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Summarizing XML Documents: Contributions, Empirical Studies, and Challenges

by

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DBIS
Datenbanken und Informationssysteme

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Declaration of Authorship

I, José de Aguiar Moraes Filho, declare that this thesis titled 'Summarizing XML Documents: Contributions, Empirical Studies, and Challenges' and the work presented in it are my own. I confirm that:

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"Do you want to know how to shrink a tree? The answer is simple: Bonsai."

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Abstract

We tackle the problem of obtaining statistics on content and structure of XML documents by using summaries which may provide cardinality estimations for XML query expressions. Our focus is a data-centric processing scenario in which we use a query engine to process such query expressions.

We provide three new summary structures called LESS (Leaf-Element-in-Subtree), LWES (Level-Wide Element Summarization), and EXsum (Element-centered XML Summarization) which are targeted to base an estimation process in an XML query optimizer. Each of these collects structural statistical information of XML documents, and the latter (EXsum) gathers, in addition, statistics on document content. Estimation procedures and/or heuristics for specific types of query expressions of each proposed approach are developed.

We have incorporated and implemented our proposals in XTC, a native XML database management system (XDBMS). With this common implementation base, we present an empirical and comparative study in which our proposals are stressed against others published in the literature, which are also incorporated into the XTC. Furthermore, an analysis is made based on criteria pertinent to a query optimizer process.

Subject: *XML summarization*

Keywords: *XML summary, statistics, structural summary, content-and-structure summary, XML query estimation*

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Abbreviations

ASPE	**A**xes **S**ummary **P**er **E**lement
BH	**B**loom **H**istogram
DPC	**D**istinct **P**ath **C**ount
EB	**E**nd-**B**iased histogram
EB-MVBD	**E**nd-**B**iased histogram with **M**in.**V**ar. **B**ucket **D**escriptor
EH	**E**qui-**H**eight histogram
EW	**E**qui-**W**idth histogram
EXsum	**E**lement-centered **X**ML **Sum**marization
HNS	**H**ierarchical **N**ode **S**ummarization
LESS	**L**eaf-**E**lement-in-**S**ubtree **S**ummarization
LWES	**L**evel-**W**ide **E**lement **S**ummarization
MOSEL	**M**ultiple **O**ccurrences of the **S**ame **E**lement name in a **L**evel
MT	**M**arkov **T**able
PS	**P**ath **S**ynopsis
PT	**P**ath **T**ree
RL	**R**ecursion **L**evel
XSeed	**X**ML **S**ynopsis based on **E**dge **E**ncoded **D**igraph

Chapter 1

Introduction

There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.
Niccolo Machiavelli, Italian writer and statesman, 1469 – 1527. In: The Prince.

1.1 The Advent of XML and Semi-Structured Data

Since the early ages of computer science, particularly in the information systems area, scientists and practitioners struggle with data models. A data model is a representation of real-world entities based on a particular view. Hence, an abstraction of the real world is provided by a data model and as abstraction only the most relevant aspects of the real-world entities are considered. The other non-relevant aspects of the world (under the data model's point of view) are not considered. For instance, the Entity-Relationship Model sees the world as a set of entities, with their attributes and the relationships among entities.

Data models allow the user to (easily) manage of the complexity of a knowledge domain, enable the comprehension of the domain and further provide a base for applications to be developed. In addition, and most importantly, they provide a description of the data which is called, generically, metadata or schema.

The degree of detail in a data model can be used to classify it into a conceptual data model, which represents the world with no concern as to how this representation should be materialized. Logical data models are more directed to the data

materialization. For example, the Entity-Relationship Model can be considered conceptual. Physical data models play a key role in databases and, in general, in data management systems. We can cite three well-known logical data models which have been used for years in databases.

The Hierarchical Model (HM) [LHH00, JKM+02] only recognizes record type, as a representation of a world entity, and 1-to-n record type relationships. The CODASYL-DBTG (or *networked*) Model [TF76, Oll78], in turn, is more flexible to permit n-to-m relationships among record types.

The Relational Model (RM) [Cod83, Cod90] sees the world entities as relations — a tabular structure, table, for short, compound of columns representing the attributes of entities. Several relationships among tables can be represented in RM, e.g., 1-to-1, 1-to-n, and n-to-m.

A common characteristic of these data models is that they require a database designer to store the schema first, and all (raw) data instances coming after must strictly adopt the metadata provided. It means that, when an evolution (modification) in the data structure is necessary, the schema must be modified and data instances unloaded and then reloaded with the new schema. Therefore, these data models are considered structured. In the structured data models, it is not possible to have, in the database, a data instance which does not completely satisfy the schema (metadata).

Structured data models present true advantages. The schema information may be used for typical database tasks such as transaction processing and query processing. For example, the data type information in the schema may be used for query parse and optimization tasks. The relationships among entities represented may be useful as synchronization information in concurrency control providing a kind of meta-synchronization.

The actual high demand for information in several application areas such as enterprise systems integration, the World Wide Web, data streams and mobile environments, has led to a need for a more flexible data model in which it is permissible for some data instances residing in a database to not strictly obey the schema. In other words, the schema should not be a barrier but a driver for data storage and manipulation. This is the so-called semi-structured data model that has the XML (eXtensible Markup Language) as its representative exponent.

1.1.1 XML—A Brief History

In the 1970's, a group of researchers (Charles Goldfarb — considered the "father" of XML, Ed Mosher, and Ray Lorie) working at IBM invented the GML, a way to mark up technical documents with structural tags. GML stands for Goldfarb-Mosher-Lorie, and this acronym was given specifically to highlight the markup capability. Later on, GML became SGML (Standard Generalized Markup Language) and, in the late 1980's, it had presented benefits for dynamic information display as realized by digital media publishers. SGML was added to W3C (The World Wide Web Consortium) in 1995 by Dan Connolly.

The first sub-product of the SGML — as a simplification of it and, in fact, a SGML application, has been HTML (Hyper-Text Markup Language) that has been applied to render content pages — whether to the World Wide Web (WWW) or to digital documents. However, HTML has suffered a lack of a discipline as software companies (e.g., Microsoft and Netscape) have created their own dialects of the original HTML proposal.

SGML being too complex, and HML not suitable for structured data, in the late 1990's, a group of people including Jon Bosak, Tim Bray, James Clark, and others came up with XML, or eXtensible Markup Language, which is also a sub-set of SGML, meant to be readable by people via semantic constraints; application languages can be implemented in XML. The W3C immediately set about reshaping HTML as an XML application, with the result being XHTML. The first XML working draft was released by the W3C in November, 1997 and a W3C recommendation for XML — called XML 1.0, in February, 1998.

The key point is that using XML the industry can specify how to store almost any kind of data, in a form that applications running on any platform can easily import and process[1].

1.1.2 XML-related Technologies

The XML technology has produced several related products and specifications, all of them managed by the W3C. Here, we indicate some of them.

[1] We cannot state, though, that XML is "self-describing" in the sense that it is understandable for any hardware/software platform. Under the database point of view, however, XML brings together, in a mixed way, value and structure interleaving them in a unit called *XML document*.

- **XML Namespaces** enable the same document to contain XML elements and attributes taken from different vocabularies, without any naming collisions occurring.
- **XInclude** defines the ability for XML files to include all or part of an external file.
- **XML Signature** defines the syntax and processing rules for creating digital signatures on XML content.
- **XML Encryption** defines the syntax and processing rules for encrypting XML content.
- **XPointer** is a system for addressing components of XML-based Internet media.
- **XSLT** is a declarative, XML-based document transformation language.

Under the database technology point of view, two XML-related products have had a profound impact in the database industry, whether for researchers or practitioners: XPath and XQuery.

- **XPath** makes it possible to refer to individual parts of an XML document. XPath expressions can refer to all or part of the text, data, and values in XML documents.
- **XQuery** is to XML and XML databases what SQL is to relational databases: ways to access, manipulate, and return XML. In fact, XQuery uses XPath as its sub-language.

1.1.3 The XML Document

The unit in which the XML specification is materialized is called XML document (or document, for short). In the structure of an XML document, we find two kinds of construct: element and attribute. Elements are disposed in a hierarchical (nested) way and have names. Hence, the *order of the elements*[2] matters in a document. They are represented by start-tags (<>) and end-tags (</>). For instance, an element called *Kaiserslautern* is represented by <*Kaiserslautern*>... </*Kaiserslautern*>. Attributes are a set of name-value pairs annotated in an

[2]Also called ***document order***. Accordingly, the internal structure of an XML document is commonly referred to as *document tree*.

element start-tag. For instance, if *Kaiserslautern* has two attributes called *zip* and *abbrev*, it is represented as *<Kaiserslautern zip=67655, abbrev=KL>... </Kaiserslautern>*. Attributes in an attribute list are separated by comma and the order is irrelevant among attributes.

An XML document has two levels of correctness, in ascending order of correctness: Well-formed and Valid.

1. **Well-formed.** A well-formed document conforms to the XML syntax rules; i.e., each start-tag must appear with a corresponding end-tag. This is the minimum correctness criteria provided for XML. A document not well-formed is not an XML document. This means that it is not accepted to be processed.

2. **Valid.** A valid document conforms additionally to semantic rules, defined by the user through an XML Schema or DTD (Document Type Definition).

XML Schema and DTD may be considered as metadata of XML, because they describe an XML document. The difference is that XML Schema yields more expressiveness than DTD, allowing data type definition in addition to the structure. However, XML Schema and DTD cannot be taken in the same meaning as a database metadata. Being semi-structured data, an XML document can vary in its level of correctness, permitting tags in the document to be different than the specification. For example, one can start to make a valid document regarding to a specific schema and later on, insert some tag into it which was not defined originally in the schema, thus downgrading the correctness level of the document. It is worthwhile to note that, different from relational databases, this is not considered a schema violation, rather a common characteristic of XML and of semi-structured data in general.

If only a well-formed document is required, XML is a generic framework for storing any amount of text or any data whose structure can be represented as a tree. The only indispensable syntactical requirement is that the document has exactly one root element (also known as the document element or document root), i.e. the entire document must be enclosed between a root start-tag and a corresponding root end-tag.

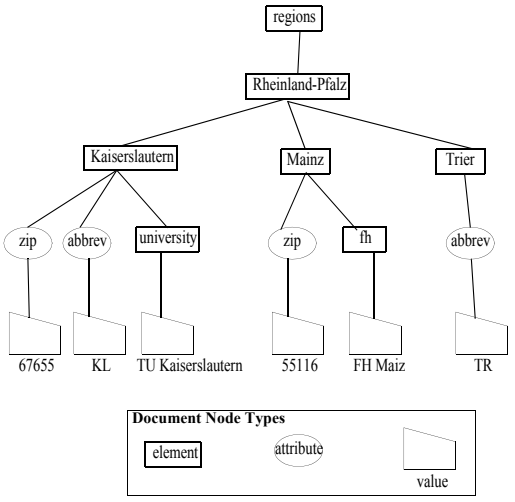
Under each tag, as leaf nodes of a document tree, it may contain data values. Theoretically, any data type can be nested under a tag. For example, if a university is called TU Kaiserslautern, we can represent it as *<university>TU Kaiserslautern*

</university>. Here, the (text) value "TU Kaiserslautern" is the value part under *university*.

In summary, an XML document tree is compounded by document nodes which can represent a tag, attribute (structural part) or a value. A sample XML document together with its graphical tree representation is given in figures 1.1(a) and 1.1(b), respectively.

```
<regions>  % The document root
 <Rheinland-Pfalz>  %  an element
  <Kaiserslautern zip=67655, abbrev=KL> % an element with attributes
   <university>
    TU Kaiserslautern     % a value
   </university>
  </Kaiserslautern>
  <Mainz zip=55116> % another element
   <fh>
    FH Mainz
   </fh>
  </Mainz>
  <Trier abbrev=TR>
  </Trier>
 </Rheinland-Pfalz>
</regions>
```

(a) Human intelligible.



(b) Document tree.

FIGURE 1.1: An XML document in both representations

1.1.4 Processing XML Documents

An XML document may be stored as a plain file in a file system of any operating system as well as in a database management system (DBMS) in native mode, i.e., keeping the native tree structure; or in shredded mode, i.e., mapping the document to another underlying structure (e.g., relational tables and columns).

In addition to typical database processing techniques, there are three ways to process an XML document using a programming language.

- SAX (Simple API for XML), an API in which the processing is made on a tag-at-a-time basis without the need to load the entire document into memory.
- DOM (Document Object Model), an API in which the document is first entirely loaded into memory and then processed.
- A transformation language such as XSLT.

While the transformation way can be built on top of SAX or DOM, these two ways have advantages and disadvantages. SAX normally requires less memory space than DOM to process a document. However, SAX processing is limited to only one-way direction. In SAX, when an element/attribute is processed, there is no way to return to it. In contrast, DOM can navigate throughout the document, in both forward (root-to-leave) direction and reverse (leave-to-root) direction. DOM will require, however, a memory space proportional to the document size which may not be suitable in many practical situations. SAX processing, in turn, gets the same memory space regardless of the document size.

1.2 XML Data Management

Both shredded and native database processing of XML documents also have advantages and disadvantages. For shredding processing, a relational database engine is normally used. In this case, a document is mapped to (a set of) tables and columns, thus breaking its native structure. For instance, a row may contain a document node and each column can store information regarding the document node (e.g., element/attribute name and/or value). Using a relational engine, one can benefit from proven features of the relational database management systems such as transaction management and query processing and reuse them. An additional software layer should be provided to enable document mapping and unmapping. This layer should provoke a non-negligible burden because, as the XML document is broken (shredded) to enable its use in a relational storage, it must be reconstructed as a result of a query. Nevertheless, a shredded document is processed as relational data, not taking into account the specific needs and idiosyncrasies of a native XML data management. Instead the processing unit being a document, it is a table. A document query in a shredded scenario is made with SQL language or SQL/XML, an extension of SQL enabling specific document operations and (a limited form of) XPath/XQuery expressions.

Pure XML data management systems (XDBMS), in turn, store an XML document, keeping its entire tree structure. Normally, B-trees are used as supporting structure to hold the *document order*[3]. In XDBMS, the document is the processing unit and tailored techniques for transaction and query processing are designed. An XDBMS uses XPath and/or XQuery for querying stored documents. Query results are also XML documents which are sent back to the user with no need for remapping. XDBMS tailors transaction techniques to support a multi-user

[3]The document node ordering generated by a depth-first traversal of the document tree

processing of a document and also query processing techniques to support the particularities of XQuery and XPath languages.

Over the last few years, hybrid data engines with the capability of storing natively both relational tables and XML documents have appeared in the database market. The most recent versions of the IBM DB2, Oracle's Oracle and Microsoft SQL Server bring this capability.

Nevertheless, in any case, all database engines have a common requirement, which is the method of uniquely identifying a document node. Note that, different from relational databases in which a tuple ID identifies a tuple in the database, for XML document nodes a node ID has to be devised and this node ID is independent from the element/attribute name. This means that two elements with the same name have mandatorily different node IDs.

1.2.1 Identifying Document Nodes

Identifying document nodes for shredded and native storage is accomplished by a Labeling Method. Whatever the labeling method is, the basic idea is to assign a unique numbering system to each document node assuring the document order. There are several labeling methods published in literature that we can classify into two categories: *range-based* and *prefix-based* labeling.

The *range-based* labeling method is designed for static XML documents, i.e., document which are not expected to have updates, and for each document node a triple of *(DocID, LP:RP, Level)* is assigned. *DocID* identifies the document; *LP:RP* describes the labeling range of each node with its subtree. *Level* is the document level in which the node resides. Range-based labeling can derive ancestor-descendant and parent-child containment (relationship) information by comparing the label of two nodes. Hence, given two nodes n_1 with label $(DocID_1, LP_1{:}RP_1, Level_1)$ and n_2 with label $(DocID_2, LP_2{:}RP_2, Level_2)$, one can say that n_1 is ancestor of n_2 (vice-versa, n_2 is descendant of n_1), if and only if, $LP_1 < LP_2$ *and* $RP_1 > RP_2$. For parent-child relationship, the additional condition is applied $Level_1 = Level_2 - 1$.

Figure 1.2 depicts an example of application of the *range-based* method for the document in Figure 1.1.

To enable dynamic XML documents, i.e., to allow insertions, deletions and updates in the document, *prefix-based* methods have been designed. The main idea is to encode each node with a string S such that,

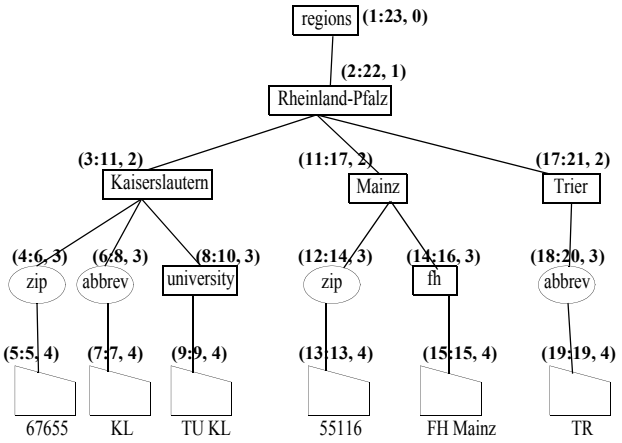


FIGURE 1.2: Range-based labeling method for an XML Document

- $S(v)$ is before $S(u)$ in lexicographic order if and only if node v is before node u in document order.
- $S(v)$ is a prefix of $S(u)$ in lexicographic order if and only if node v is an ancestor of node u.

The prefix-based scheme follow the idea of Dewey Classification used in libraries. Thus, a node with a label **1.1.1** and a node **1.1.2** are siblings (in the same subtree) and **1.1.1** comes before **1.1.2**. They have the parent and ancestor nodes **1.1** and **1**, respectively[4].

Figure 1.3 depicts a possible application of the *prefix-based* labeling method for the document in Figure 1.1.

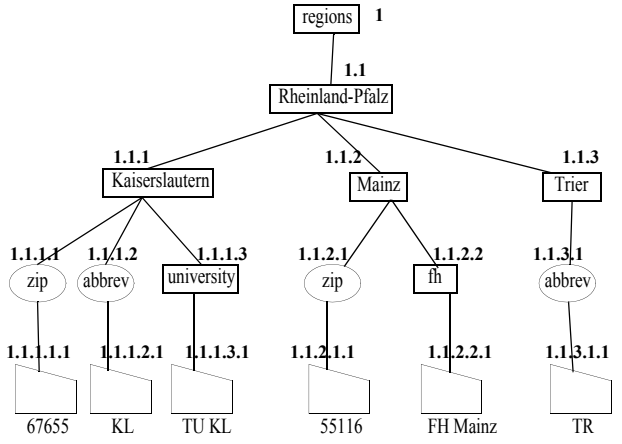


FIGURE 1.3: Prefix-based labeling method for an XML Document

[4]Consistent with the definition of *prefix-based* labeling, parent and ancestor nodes always come before a specific node as their labels come, in lexicographic order, before the label of the node. That is **1** comes before **1.1** which in turn comes before **1.1.1**, and so on.

Both methods, *range-based* and *prefix-based* labeling, maintain the document order and easily derive the computation of parent/ancestor nodes. Range-based methods, however, do not yield immutable labels when updates come, provoking a relabeling in such cases. Prefix-based labeling, on the other hand, guarantees that a label is immutable for the lifetime of the nodes. Nevertheless, both methods support declarative query processing with XQuery/XPath languages.

1.2.2 Querying XML Documents

Since declarative query languages (XQuery/XPath) for XML documents have been proposed and recommended by the W3C, the database community has now to face the challenge of how to derive appropriate query engines to effectively process XPath/XQuery queries.

Some best practices learned from relational databases have to be applied and adapted for querying XML documents. For example, the derivation of an algebraic representation of the query expression, the optimization (algebraic and/or cost-based) of the query execution plans (QEP), and the physical operators.

XML algebras have been proposed, such as XAT (XML Algebra Tree) [ZPR02], TAX (Tree Algebra for XML) [JLST02], NAL [MHM03] and NAL-STJ [Mat07], and others [SA02, NZ06]. None, though, have qualified to become a standard XML algebra, leaving an open issue of how to find a suitable algebraic representation for XML queries[5].

Several physical operators (also called Path Processing Operators, or PPO) have appeared. Structural Join (STJ) [AKJP+02, WPJ03, MHH06] was the first proposal and processes a query by a set of joins. Each join corresponds to a part of the query expression. The Twig Join family [LCL04, BLS07] evaluates a query by building a query pattern (twig) and finds matches in the document to this twig. Holistic Twig Join (HTJ) [BKS02] was an improvement on the idea of tree-pattern matching in which the twig is evaluated as a whole, without any partial pattern match. Some variations of HTJ exist, for example, Index Twig Join (ITJ) [JWLY03], Optimal Twig(O-HTJ) [FJSY05], and HTJ for OR-predicates [JLW04]. In any case, there is already room for new operators to be proposed[6].

[5] XQuery has been verified to be a Turing-complete language [Kep04]. Such finding complicates the design of an appropriated algebraic representation of XQuery even more.

[6] HTJ has produced a plethora of HTJ-based algorithms, normally focusing on a specific issue of HTJ. We have omitted these here and refer only the main algorithms of the HTJ family.

While STJ has a simple execution model — inherited from relational the nested-loop join operator, and lends itself to be modeled as a (simple) cost formula; Twig join algorithms, specially HTJ, are hard to model. This means that a cost model for enabling cost-based XML query processing is still a long way off, there is a plethora of opportunities to develop a proposal. However, one empirical cost model has already been proposed in [WH09].

Whatever the cost model adopted, statistics on documents are fundamental in order to derive, as accurately as possible, node cardinality/selectivity factors to enable appropriated cost-based decisions on which QEP should be considered the best plan. XML document statistics are normally gathered in a (generic) structure called *summary*. An XML summary congregates, in a condensed form, all document node cardinalities along with their relationships to provide estimations of query expressions or even parts of the expressions. The representation of an XML summary is based on element/attribute (node) names rather than node IDs.

1.2.3 Motivation for this Work

Over the past ten years, several proposals of XML summaries [GW97, AAN01, FHR+02, LWP+02, PG02, PG06, WJLY04, ZÖAI06] have appeared in the literature. Regarding the degree of a summary's document coverage, approaches can be classified into two categories: Structural summaries and Content-and-Structure (CAS) summaries.

Structural summaries [GW97, AAN01, FHR+02, LWP+02, WJLY04, ZÖAI06] summarize only the structural part of a document, not considering the (text) value distributions. CAS summaries [PG02, PG06] try to condense both structural and value distributions modeling dependencies between value and structure. The majority of publications focus on a statistical coverage of structural relationships among document nodes. In addition, some works [AAN01, FHR+02, WJLY04] apply compression techniques (e.g., histograms [Ioa03]) to the summary structure.

Collecting document statistics implies maintenance tasks for them. Summary updates have to take place when the document is changed by a user application to preserve the close correspondence of document and related statistics. This aspect, however, is hardly addressed in XML summary proposals. Only [LWP+02] and [WJLY04] claim to provide some solution. Most proposals assume (explicitly or tacitly) off-line summary update by re-scanning the entire document periodically.

A methodical weakness of many publications is the insufficient basis of experimental data. Frequently, they only rely on a few documents, often very small and/or with synthetic data. Furthermore, they do not provide any clues on their use with a query optimizer. Except for quality estimation results, important items such as:

- the space needed to store the summary,
- the necessary memory footprint to be used in the estimation process, and
- how fast the access to the summary is — so as to not impact query optimization time

are normally not presented in the publications.

1.3 Thesis Overview

This thesis tackles the hard problem of summarizing an XML document. This problem is so difficult due mainly to the mixed nature of an XML document which encompass varying distributions in its structural part and in its value part. Furthermore, the structural recursion allowed (and sometimes frequently) in a document complicates the summarization process.

1.3.1 Our Contributions

Trying to overcome the drawbacks of published XML summary works, and as the main contribution of this thesis, we have proposed three new XML summary structures called: **LESS** (Leaf-Element-in-Subtree Summary), **LWES** (Level-Wide Element Summarization) [AMFH08a, AMFH08c], and **EXsum** (Element-centered XML summarization) [AMFH08b]. The former two are basically structural summaries, whereas the latter is a CAS summary.

LESS and **LWES** follow the "conventional" method of summarizing documents in the sense that they mirror somewhat the document structure. **EXsum**, in turn, puts aside the strict document order structure and inaugurates a new way to summarize XML documents.

Furthermore, we have made the following contributions.

- We have created an extension to the End-Biased histogram [IP95] called **EB-MVBD** which makes suitable the use of histograms in the XML estimation process, and applied EB-MVBD to compress LESS and any other structure that needs such a feature.
- We have made the application of histograms in XML summaries flexible, so that the application is tailored according to a specific query workload [AMFH08c].
- For the cases, in which histogram application is not profitable, we have proposed a (simple) bit-list compression method.
- We have designed estimation procedures and/or heuristics for all proposed summaries.

A (hopefully extensive) set of experiments is also included with a set of documents of varying characteristics and sizes to stress and cross-compare our approaches with the competing ones. For that,

- we have constructed a *Query Workload Generator* tool which generates several types of XPath queries. This tool can be extended to generate XQuery queries.
- Additionally, a *Query Workload Processor* has been implemented which executes the query workload against the XTC XDBMS.

The analysis of the empirical results has been directed by the effective summary use for the query optimizer. Therefore, we have elicited three criteria which impact the optimization process and have evaluated all summaries (proposed and competing ones) under these criteria.

- **Sizing**. Further divided into the following sub-criteria.
  - *Storage Space* needed to persist the summary structure in the XDBMS[7].
  - *Memory footprint* required by the summary to estimate queries.
- **Timing**. Further divided into the following sub-criteria.

[7]Note that, because all summaries have been implemented into our XDBMS (see Chapter 6), we have used its Metadata Component. The *Storage Space* criterion, however, takes only net size of the structure into account, thus disregarding the specific information overhead of the Metadata's underlying structure.

  - *Building Time* is the time needed to construct the summary which includes the time for the document scan — done normally through a SAX parser, and running the respective building algorithm.
  - *Estimation Time* is the time necessary to estimate queries.

- **Estimation Quality** translated quantitatively into an error metric in which the lower error is, the higher the estimation quality provided.

1.3.2 Structure

This thesis is structured as follows. In Chapter 2, we present all necessary terminology, basic concepts and definitions which will be used throughout the thesis. Chapter 3 studies the existing XML summary approaches and, at the end, makes a qualitative discussion and comparison. Chapters 4 and 5 introduce our XML summary proposals. For each proposed summary, we detail its general idea, the building algorithms, and the estimation procedures. The empirical study comes in the Chapter 6. The set of document considered are presented, the query workload is detailed, and the analysis based on the aforementioned criteria is performed. This thesis is concluded in Chapter 7 in which, additionally, some future research directions are pointed out.

Chapter 2

Preliminaries: Terminology, Basic Concepts, and Definitions

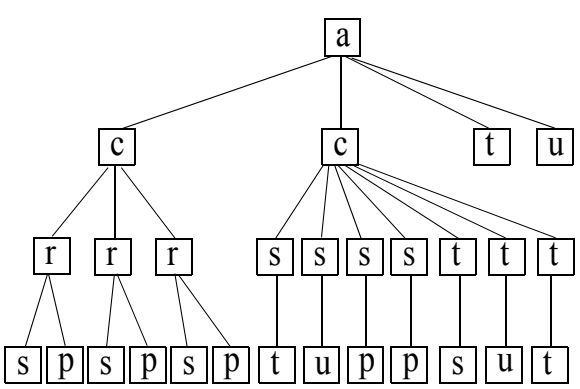
The words printed here are concepts. You must go through the experiences.
Saint Augustine, African Bishop of Hippo Regius, Doctor of the Church, 354 – 430

2.1 Overview

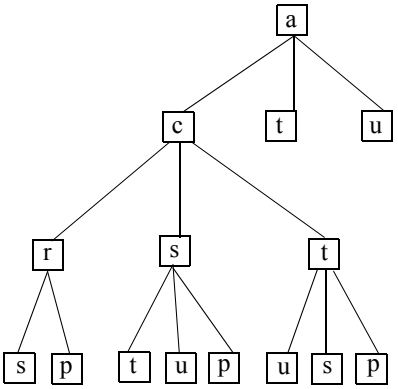
This chapter introduces the definitions and concepts that will be used throughout the thesis. Section 2.2 defines terms used throughout the remainder of this document. Some references to well-known XML documents – e.g., *dblp*, *nasa*, and *treebank*, are made in this chapter and in Section 6.2.1 we show in detail their physical characteristics (in tables 6.1(a) and 6.1(b)). Section 2.3 exhibits the basic definitions of XML summarization. We give, in Section 2.4, the details on what should be considered as the most trivial XML summary, called HNS. Section 2.5 concludes this chapter. Figures 2.1(a), 2.1(c) and 2.2(a) depict sample documents which will be used as running examples throughout this thesis.

2.2 Terminology

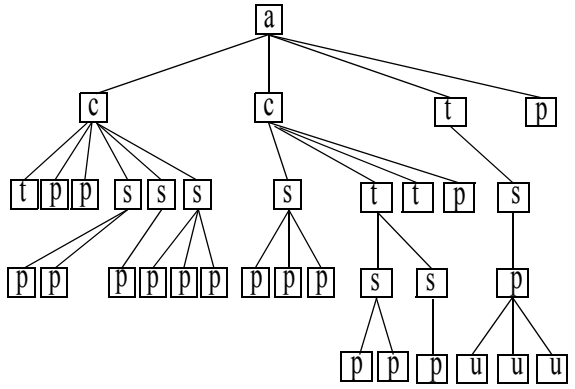
When speaking of XML summaries, we should define terms clearly in order to keep from provoke a misunderstanding. We call a summary node simply a **node**. When referring to nodes in an XML document, we use the expression "document



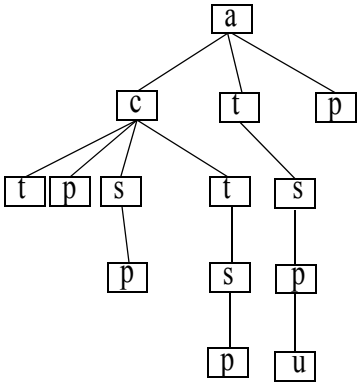
(a) A very Regular Document.



(b) The corresponding PS.

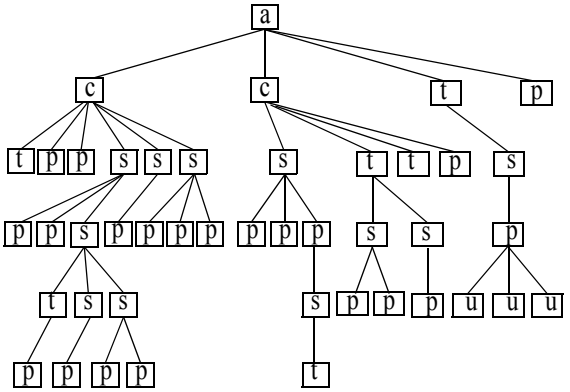


(c) A Document with some structural variability.

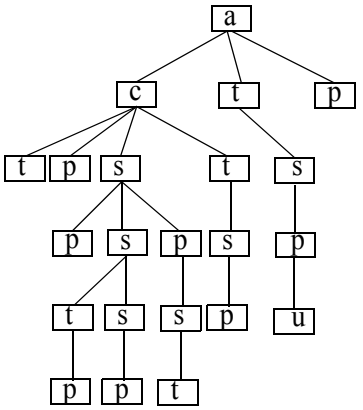


(d) The corresponding PS.

FIGURE 2.1: Recursion-free XML documents and their respective Path Synopses



(a) Recursive document.



(b) The corresponding PS.

FIGURE 2.2: Recursive XML document and path synopsis

node". General references to a document node name, i.e., a set of document nodes with the same name, are termed **element names**. Accordingly, **attribute name** is used generically to refer to document attribute names.

2.2.1 Terms in XML Query Languages

Path expressions are the base for declarative XML languages. In fact, XPath and XQuery use them as a sub-language. Therefore, it is necessary to define terms used when referring to path expressions.

Definition 2.1. *Path expression*: A path expression is a set of *location steps* (also called path steps or steps, for short) and, optionally, predicates.

Definition 2.2. *Location Step (Step)*: A location step is a compound of the following three items, in this order:

1. *Context Node*: the context under which the *node test* should be verified. In most cases, it is implicitly determined.
2. *Axis*: One of the possible axes in the XML document. For example, child (/), parent (*parent* ::), ancestor (*ancestor::*), descendant (*descendant::*), self (.), descendant-or-self (//), following sibling (*following-sibling::*), preceding sibling (*preceding-sibling::*) and so on. We can further classify axes as:
   - Forward axis: it follows the document nodes in a top-down fashion, i.e., root-to-node way. Child (/), descendant (*descendant::*), self (.), descendant-or-self (//) and following sibling (*following-sibling::*) are examples of forward axes.
   - Reverse axis: it follows the document nodes in a bottom-up fashion, i.e., node-to-root way. Parent (*parent::*), ancestor (*ancestor::*) and preceding sibling (*preceding-sibling::*) are examples of reverse axes.
3. *Node test*: A reference to a document node name to be verified under a pair context/axis.

More intuitively, a path expression has a format: $/v_1/v_2/\ldots/v_n$, where v_i are node tests, /'s represent axes and context nodes are as follows: *document root* for the step $/v_1$, v_1 for the step $/v_2$, $\cdots$, and $/v_{n-1}$ for the last step $/v_n$. As a concrete example drawn from our sample document (see Figure 2.1(c)), we may have $/a/c/t$ representing the retrieval of all document nodes whose name is t that are children (/) of c nodes which are in turn children of a.

It is worthwhile to note the declarative characteristic of path expressions. A path expression says what should be retrieved, but not how it is to be retrieved. They state, in addition, restrictions (or order), represented by the axes, to retrieve nodes. A more complex example is $//p/parent :: s/ancestor :: c$ getting all nodes c which are ancestors of s as parents of all sub-trees rooted by a document node p[1].

Definition 2.3. *Predicates*: A predicate is an expression enclosed into brackets ([ ]) occurring in any place in a path expression. Predicates can be further classify into

- Existential Predicates, which allow only path expressions inside the brackets. For example, $//c/t[./s]$.
- Value Predicates which check for value contents. For example $//c/t[text() =' XML']$.

Predicates can use AND/OR logical connectors. For example, $//c/t[./text() =' XML'$ *or* $contains(.,'document')]$. Note also that functions as defined in [W3C07] may take place. Predicates place a filter on the result. In this example, we want to retrieve t nodes being children of every subtree rooted by c that additionally have either the vale "XML" or contain a string called "document" under them.

The variability of path expressions and predicates involved may be so rich that a single auxiliary structure (as complex as conceivable) for an XML summary would not solve all query estimation/optimization problems. Moreover, the more sophisticated a summary is, the more maintenance overhead would be needed. Hence, a practical XML summary is necessarily confined in its scope, but should be expressive enough to capture the most important structural properties of XML data and flexible enough to deliver, as accurate as possible, the most frequently requested cardinality estimates for cost-based XQuery/XPath query optimization.

We are aware that some path expressions—including their predicates, if they exist—can be rewritten linguistically or algebraically[2]. Nevertheless, on purpose of gathering statistics and the estimation process, we should provide support, as widely as possible, to estimate them. However, we do not claim that our proposals cover all possible path expressions. To the contrary, we are focused on the most important kinds of path expressions. Therefore, we make an observation that child and descendant axes are considered first-class citizens, and parent and

[1] In other words, retrieving all nodes c having a descendant s as a parent of every sub-tree rooted by p.

[2] For example, rewriting path expressions to favor forward axes and then to try to "standardize" the expression in the first tasks of query processing.

ancestor axes deserve a second-class citizenship. The other axes are considered less important for all practical situations.

In any case, we need to define some basic concepts before we dive into details of the approaches.

2.3 Basic Concepts

In XML documents, as illustrated by our sample documents, many path instances only differ from each other in the leaf values, and in the order they occur in the documents. Therefore, their structural part can be represented by a single unique path, called *path class*. Taking advantage of this observation, DataGuides [GW97] was the first approach to XML summarization aimed at providing a structural overview for the user and a data structure for storing statistical document information, thus enabling the query optimization. Later proposals, called path synopses (PS), are similar to DataGuides, but are used as a query (document) guide and a compact structure view in the first place (see figures 2.1(b), 2.1(d) and 2.2(b)). Other applications are possible for a PS. For example, document structure virtualization, concurrency control, and support of indexing and query processing [HMS07, SH07, BHH09]. This synopsis has to be complemented with a summarization structure for statistical information concerning elements and axis relationships [AMFH08b, AMFH08a].

A cyclic-free XML schema captures all information needed for the path synopsis; otherwise, this data structure can be constructed while the document (sent by a client) is stored in the database. Typical path synopses have only a limited number of element names and path classes and can, therefore, be represented in a small memory-resident data structure. As shown in the following, such a concise description of the document structure is a prerequisite for effective query optimization.

Definition 2.4. *Path Class*: A representation of all path instances of the document having the same sequence of element names.

Definition 2.5. *Path Synopsis*: A tree structure capturing all path classes existing in a document.

Definition 2.6. *Unique Element Name*: An element name that occurs only once in the path synopsis.

Definition 2.7. *Homonyms*: Element names occurring more than once in the path synopsis, but not in the same path class.

Definition 2.8. *Recursive Path*: Occurs when element names appear more than once in a single path class.

An *unique* element name such as *a*, *c*, or *u* in our sample path synopses results in an unambiguous summarization, which makes path expression estimation very simple in some cases. In turn, a homonym-free document has only unique element names in its path synopsis, and it is non-recursive by definition, but may be an exception. In the typical case, a document containing a varying degree of homonyms may have most (or even all) of its paths without any level of recursion, i.e., homonyms do not occur in the same path class[3] (see Figure 2.1).

In contrast, we have to deal with *recursion* in a document as soon as an element name occurs more than once in a single path class, e.g., in paths *(a,c,s,s,s,p)* or *(a,c,s,p,s,t)* (see Figure 2.2). Highly recursive XML documents such as *treebank* (see Table 6.1(a)) are exotic outliers and not frequent in practice; therefore, they do not deserve first-class citizenship. However, some degree of recursion may be anticipated in a small class of documents. Thus, we analyze recursiveness for reasons of generality and evaluate summarization structures that support documents exhibiting a (limited) kind of structural recursion, too.

The concept of recursion level (RL) was introduced in [ZÖAI06] as a way to better represent structural recursion in XML documents and explained the case where only a single element name could recur in a path. Recursion levels were defined as follows.

Definition 2.9. *Recursion Level (RL)*: Given a rooted path in the XML tree, the maximum number of occurrences of any label (element name) minus 1 is the path recursion level (PRL). The recursion level of a node in the XML tree is defined to be the PRL of the path from root to this node.

Thus, given path *(a,c,s,s,t)*, the second *s* node has RL=1 and all other nodes have RL=0, whereas the PRL of this path is 1.

[3] *dblp* has 41 element names where 32 are homonyms resulting in 146 nodes for the path synopsis. Hence, the avg. repetition of a homonym is more than 4. The numbers for element names, homonyms, and path synopsis nodes are (100, 6, 264) and (70, 12, 111) for *swissprot* and *nasa*, respectively. Because *nasa* has only a share of 6% homonyms, the estimation procedure should be particularly simple and accurate. In all cases, the data structure for the path synopsis remains very small.

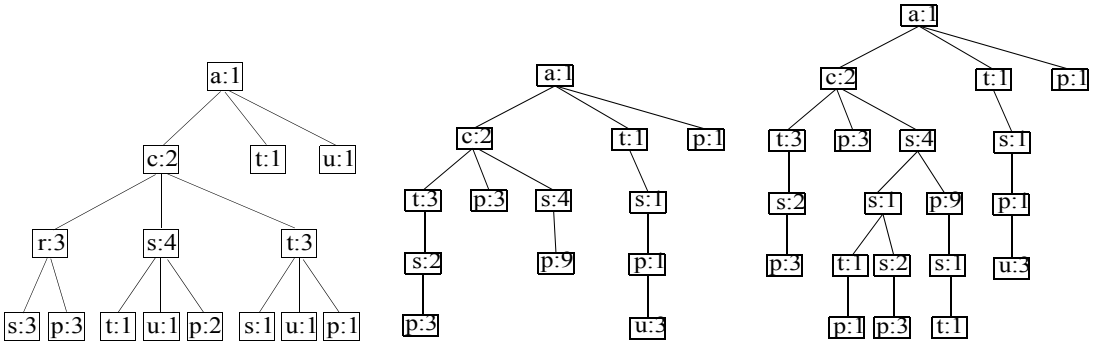
Recursion can also occur in query expressions, making the estimation even more difficult (and, often, more imprecise). For recursive path expressions, we follow the definition in [ZÖAI06].

Definition 2.10. *Recursive Path Expression*: A path expression is recursive with respect to an XML document if an element in the document could be matched by more than one node test in the expression.

Thus, it is easy to see that path expressions only consisting of /-axes (or parent axes) are not recursive. However, *//s//s* is a recursive path expression on the XML tree in Figure2.2a, because a recursively occurring *s* node could be matched by both node tests. Hence, recursive path expressions always involve at least one //-axis (or ancestor axis) and are usually applied to recursive documents.

2.4 HNS—Hierarchical Node Summarization

Hierarchical Node Summarization (HNS) embodies a structural summary of all (sub-) paths of the document where each node is related to an element/attribute name *unique* under the same parent, as illustrated in Figure 2.3[4].



(a) For the regular document. (b) For the recursion-free document. (c) For the recursive document.

FIGURE 2.3: HNS structures

An HNS is a top-down structure, where the same element/attribute names under the aggregated parent are counted. This information is depicted by a node labeled with *element:frequency*, where *element* is the element/attribute name and

[4]We do not claim that HNS is our contribution because it is a trivial form of an XML summary and some proposals ([AAN01, AMFH08c]) compress it to come up with a new summary. Nevertheless, roughly speaking, an HNS can be viewed as a PS specifically aimed at query processing support, because it preserves typical aspects of the PS structure and the related document.

frequency is the number of its instances (document nodes) under the same (aggregated) parent. Thus, HNS construction is recursive. For example in Figure 2.1(c), we have two elements c under parent a and 3 elements p under the two parents c. These elements are represented in the HNS in Figure 2.3 by an aggregated node c with frequency 2 (c:2) and by an aggregated node p with frequency 3 (p:3), respectively. It turns out that such an HNS precisely preserves the frequency information of all (sub-) paths of the original document. If we need the frequency of a path, we just traverse this path in the HNS from the root and the frequency kept in the final element addressed by the path delivers this information, e.g., path expressions such as */a/c/t/s* and */a/c/s/p* yield 2 and 9, respectively.

HNS has strong positive points. First, it delivers accurate cardinalities for all path expressions only containing child and descendant axes. For example, the path expression *//c//t* matches three nodes in the given HNS; hence, we can add the frequencies recorded in these nodes and immediately return 5 as the number of qualified document nodes (together with the fully specified paths). Recursive path expressions of the same kind can also be accurately computed using an HNS. After locating the qualified HNS nodes for a path expression, e.g., *//s//s*, their frequencies are accumulated and deliver the requested cardinality, which is 4 for the example. Second, all path classes in a document are preserved by an HNS, which prevents false positive errors. Third, HNS is memory efficient for documents exhibiting a certain degree of uniformity.

However, HNS has also negative points. The number of HNS nodes may be high for deeply-structured documents. If the HNS tree has to be fully traversed (e.g., for descendant and ancestor axes), the number of nodes may negatively impact the estimation process. For deeply-structured and highly-recursive documents, HNS may consume enormous storage space which could impede cardinality estimation and, in turn, the entire query optimization. Furthermore, query expressions containing axes such as parent, ancestor and siblings are not estimated accurately in all the cases. For example, consider querying the document in Figure 2.1(c) with an expression *//c/p/following-sibling::s*. It results 3 nodes while estimating such a query in the corresponding HNS (Figure 2.3(b)) yields 4.

Because of these drawbacks, pruning methods [AAN01, GW97] or compression techniques are normally applied to the HNS (e.g., histograms) [AMFH08c]. DataGuides [GW97] prune an HNS without taking statistical properties of the pruned part into account. Path Tree [AAN01], in turn, recovers some information of pruned paths by averaging their frequencies. However, this technique is not suitable when skewness is present—as reported in [AAN01]. A suitable compression approach for

an HNS tree is called Level-Wide Element Summarization (LWES) [AMFH08c], which captures the element distributions per tree level by applying histograms.

2.5 Conclusion

The concepts introduced in this chapter form a necessary background for the discussions in the following chapters. Furthermore, we have introduced a trivial kind of summary structure called HNS. HNS has served as a base structure to come up with several other summaries published in the literature — including two of our proposals.

However, before we introduce our proposals in Chapter 4 and Chapter 5, we review the existing summaries in the literature and then make a qualitative discussion of each of them in the next chapter.

Chapter 3

Existing Summarization Methods

Study the past if you would define the future.
K'ung fu-tsu (Confucius), Chinese philosopher, 551 BC – 479 BC. In: Anaclets.

3.1 Overview

In this chapter, we present a non-exhaustive list of summarization approaches published in literature. We detail each work in its respective section describing the main idea, building process, and estimation procedures (Section 3.2 to Section 3.4). For each class of our qualitative comparison (and discussion), in Section 3.5, we have chosen one representative summary and study each one.

3.2 MT—Markov Table

Markov Table [AAN01] is a structural summary which is built by mapping document paths together with their frequencies into two-column tables. One column represents the document paths of a specified length, whereas the second column provides the frequencies of the corresponding paths. Note that document paths may be retrieved from an HNS (see Section 2.4).

Markov Tables (MT) compress the HNS by pruning paths up to length n, where n is a parameter set by the user. The pruned part is approximated by the application of both: a Markov model and some statistical information on a generic path called *star-path*—indicated in [AAN01] by $*$ or $*/*$. In other words, if $n = 2$, MT

prunes (deletes) low-frequency paths of lengths 1 and 2 and discards also paths with lengths >2. Based on pruning and *star-path*, MT provides three compression techniques: *suffix-star*, *global-star* and *no-star*. The latter technique does not apply a *star-path*, but just relies on pruning.

3.2.1 Building and Compressing MT

Building MT is driven by two parameters: the pruning parameter n and a memory budget. The latter can be translated into a maximum size in bytes of the entire MT structure or in a maximum number of entries in MT. The former specifies the number of tables to be created. For example, for $n = 2$, there will be two tables, one with paths of length=1 and another with paths of length=2.

MT building proceeds in such way that, for $n = 2$, all paths of length 1 will be in the MT-Path-Length-1 table and all paths of length 2 will be in the MT-Path-Length-2 table. For example, in MT-Path-Length-1 table, we have entries: (*/a:1*), (*/c:2*), (*/t:4*), (*/s:7*) and so on. For MT-Path-Length-2 table, we have: (*/a/c:2*), (*/a/t:1*), and so on. Note that MT-Path-Length-1 table corresponds to the number of occurrences of each distinct element name in the document. At this point, because the memory budget is normally exceeded, compression techniques take place. In general, these compression methods recursively delete entries in MT tables substituting them with *star-paths*, until the memory budget is reached.

TABLE 3.1: MT tables (*n=2, budget=4 entries*) for the sample document in Figure 2.2(a).

(a) Suffix-* compression

MT-Path-Length-1	Freq
$*$	2
s	11
p	21
t	6

MT-Path-Length-2	Freq
$*/*$	2.2
$s/*$	2.5
s/p	16

(b) Global-* compression

MT-Path-Length-1	Freq
$*$	2
s	11
p	21
t	6

MT-Path-Length-2	Freq
$*/*$	2.35
s/p	16

To exemplify the application of these methods, consider the parameter $n = 2$ applied to our document. For the *suffix-star* method, we have a path $*$ representing all low-frequency paths of length 1, and a path $*/*$ representing all low-frequency paths of length 2. When paths of length 1 are deleted, their average frequencies are included in path $*$. The summarization process for low-frequency paths of length 2 is more complex. For a generic length-2 path x/y to be summarized,

MT looks for all length-2 paths starting with x in a table. If there exist a path, say x/z, both paths x/y and x/z are presented in the MT as a path $x/*$ and the frequencies of both are averaged to represent the frequency of $x/*$. Note that this process iterates recursively such that the very path $x/*$ may become a candidate to be summarized. If such a situation happens, the path $*/*$ is added to the MT where an averaged frequency is recorded.

Global-star and *no-star* compression methods are simpler than suffix-star in terms of computation. *Global-star* does not permit more than one *star-path* in each table, i.e., one $*$-path in MT-Path-length-1 tables e one $*/*$-path for MT-Path-length-2. Thus, low-frequency paths are directly represented by these two paths in MT tables and their respective frequencies are averaged. *no-star* does use any $*$-path, simply discarding low-frequency paths. An example of *global-star* compression is given in Table 3.1(b).

3.2.2 MT Estimation Procedure

The estimation method for MT follows a Markov process of order 1 in which a "short memory" assumption is applied, i.e., assuming that an element name in any path only depends on the *m-1* elements preceding it to be estimated. Formally, given an path expression in the format $/v_1/v_2/\cdots/v_m$ the following formula is applied [AAN01].

$$Est(/v_1/v_2/\cdots/v_m) = f(/v_1/v_2/\cdots/v_n) \times \prod_{i=1}^{m-n} \frac{f(/v_{1+i}/v_{2+i}/\cdots/v_{n+i})}{f(/v_{1+i}/v_{2+i}/\cdots/v_{n+i-1})} \quad ,$$

where $f(/v_1/v_2/\cdots/v_n)$ is a frequency of the path $(v_1, v_2, \cdots, v_n)$ obtained from a lookup in MT tables, and n is the pruning parameter.

Concretely, in our suffix-star MT of Table 3.1(a), to estimate the path expression $/a/c/s$, we apply the formula: $(a/c) \times \frac{f(c/s)}{f(/c)}$, where the fraction $\frac{f(c/s)}{f(/c)}$ may be interpreted as the number of s elements contained in all a/c paths and the factors: a/c, c/s and s are taken from an MT lookup. The factors a/c and c/s match the $*/*$ entry and the factor c matches the $*$ entry. Hence, the estimated cardinality of $/a/c/s$ is 2.22. Note that, for longer path expressions, the fractional part of the formula is extended by multiplying each part of the expression greater than n. For instance, $(/a/c/s/s)$ yields $(a/c) \times \frac{f(c/s)}{f(/c)} \times \frac{f(s/s)}{f(/s)} = 0.55$.

Note, in addition, that, because of the "short memory" Markovian assumption, MT summaries support the estimation of path expressions containing only child axes.

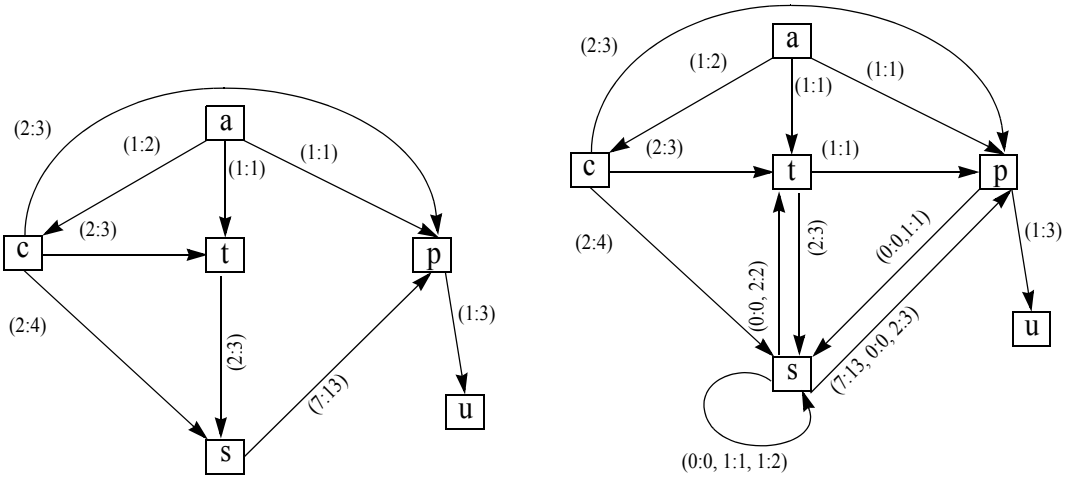
3.3 XSeed—XML Synopsis based on Edge Encoded Digraph

XSeed [ZÖAI06] summarizes XML data using a directed graph (called XSeed kernel) in which each node represents a distinct element/attribute name of the document. Each edge, in turn, represents a parent-child relationship and is labeled with a list of counter pairs (p_i:c_i), i≥0, where p_i and c_i are called parent counter and child counter, respectively. Each pair indicates that, at recursion level RL_i, parent-child relationships between two element names ($u \rightarrow v$) u and v exist, where p_i elements u and c_i elements v are involved. RL is thus applied in XSeed to capture parent-child relationships in recursive paths.

3.3.1 Building XSeed

XSeed building is based on an event-driven XML parser (SAX parser) which scans the document and maintains a stack[1]. When an opening-element event is detected, this element is pushed onto the stack. The kernel is then searched to possibly insert a new node together with its current list of out-edges. Each edge in the list contains, in turn, the RL information calculated from the rooted paths ending with this edge. The calculation of recursion levels is supported by an auxiliary data structure called "counter stacks", which is a list of stacks implemented as a hash table. The operations on counter stacks are similar to that of the main stack, i.e., in the opening (closing)-element event, an element is inserted into (removed from) the data structure. The path recursion level is indicated by the number of non-empty entries in the counter stacks minus 1. When a closing-element event is reached, then, for each out-edge in the list, RLs as well as parent and child counters are calculated and recorded in the corresponding edge in the graph. The element is then popped from the stack, its related entries in the counter stacks are also popped, and the process iterates over again when a new element comes from the parser. Processing all elements of Fig. 2.2a results in an XSeed summary as shown in Fig. 3.1(b).

[1] In other words, XSeed summary does not rely on a former HNS to be constructed.



(a) XSeed for our recursion-free document. (b) XSeed for our recursive document.

FIGURE 3.1: XSeed summary

3.3.2 Estimating Path Expressions with XSeed

To estimate cardinalities of queries containing /- and //-axes and queries with predicates, XSeed applies the concept of forward selectivity (*fsel*) for the former and backward selectivity (*bsel*) for the latter. Predicates can be estimated by XSeed only in the last step of a query.

Intuitively, given a path expression $/v_1/v_2/\ldots\ /v_n/v_{n+1}$, *fsel* is a fraction of v_{n+1} nodes (obtained from the child counters) that are contributed by the path (v_1,v_2,...,v_n) (obtained from parent counters). In other words, the estimated cardinality of a path expression containing only child axes is the estimated cardinality of its last step. Given a path expression $/v_1/v_2/\ldots/v_{n-1}/v_n[v_{n+1}]$, *bsel* captures the fraction of v_n nodes that: (1) are contributed by the path (v_1,v_2,...,v_{n-1}); and (2) have a child v_{n+1}. Note that, by the definition in [ZÖAI06], *fsel* (and *bsel*) makes the independence assumption, i.e., the probability of v_i having a child v_{i+1} is independent of v_i's ancestors. Due to this assumption, *fsel* (*bsel*) can also be calculated for all sub-expressions. For example, for each step of the path expression */a/c/s/s/t*, cardinality estimations as well as *fsel* and *bsel* values are provided as follows: [/a: 1,1,1], [a/c: 2,1,1], [c/s: 5,1,1], [s/s: 2,1,0.4], [s/t: 1,1,0.5]. For the fifth step (*s/t*), the counters with RL=1 are used to calculate *fsel* and *bsel*.

Another example illustrating the use of RL is *//s//s//p*. The estimated result for this query is exactly the sum of child counters in all RL>0 of the edge s→p. Therefore, path steps with //-axes need to traverse the XSeed kernel and compute *fsel* (and *bsel*) at each node visited. Here, because of the graph structure of XSeed, false positive hits may worsen the estimation. In other words, some

paths that can be derived from the summary may not exist in the document. Thus, path expressions as *//s/s/s/s* may be estimated in XSeed delivering a non-zero cardinality while the actual result is zero. To mitigate such situations, the traversal algorithm prunes the graph search based on a tuning parameter (called *card_threshold*). When the estimation process calculates a cardinality which is equal to *card_threshold*, the search stops and the cardinality of the step is set to the estimate calculated so far. This is clearly a time/accuracy trade-off. Lower values of *card_threshold* allow for more accurate results at the expense of longer estimation times.

However, the assumptions made in the XSeed estimation procedure break, as stated in [ZÖAI06], when the underlying graph structure (or parts of it) presents a "honeycomb" shape (as illustrated in Figure 3.2). This case corresponds to homonyms happening in several subtrees of the document and, most probably, in several levels as well. In such cases, XSeed tends to provide low quality estimations.

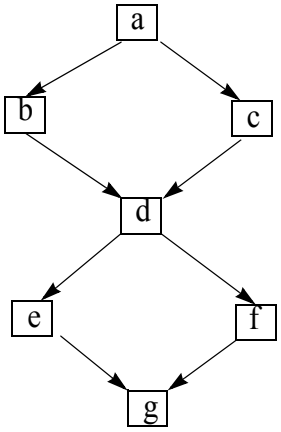


FIGURE 3.2: Situation in which XSeed breaks

The XSeed summary supports only cardinality estimations of path expressions containing child and descendant axes and expressions with predicates.

3.4 BH—Bloom Histogram

The idea of Bloom Histograms (BH) [WJLY04] is to construct a *path-count table*, mapping each of the paths in the document to a corresponding count or frequency describing the number of occurrences of that path. A path is considered to be, for a single element, a sequence of child steps that lead from the root element to the one considered. The resulting table then gives room for compression, e.g., by applying histograms, where an approximation of the distribution is based on path elements and their frequencies.

TABLE 3.2: Path-count table and Bloom histogram for our recursive document.

Path-count table

Path	Freq
(a)	1
(a, p)	1
(a, t)	1
(a, t, s)	1
(a, t, s, p)	1
(a, c, s, s)	1
(a, c, s, p, s)	1
(a, c, s, s, t)	1
(a, c, s, p, s, t)	1
(a, c, s, s, t, p)	1
(a, c)	2
(a, c, t, s)	2
(a, c, s, s, s)	2
(a, c, t)	3
(a, c, p)	3
(a, c, s, s, s, p)	3
(a, c, t, s, p)	3
(a, t, s, p, u)	3
(a, c, s)	4
(a, c, s, p)	9

Bloom histogram

Bloom filter bucket	Freq
BF((a), (a,p), (a,t), (a,t,s), (a,t,s,p), (a,c,s,s), (a,c,s,p,s), (a,c,s,s,t), (a,c,s,p,s,t), (a,c,s,s,t,p))	1
BF((a,c), (a,c,t,s), (a,c,s,s,s))	2
BF((a,c,t), (a,c,p), (a,c,s,s,s,p), (a,c,t,s,p), (a,t,s,p,u))	3
BF((a,c,s), (a,c,s,p))	6.5

The histogram generated from the *path-count table* is also structured as a table. The difference from the original one is that instead of keeping a single table entry, or mapping, for each (distinct) path, a frequency value is associated to a *set of paths*, originated by grouping paths with similar values in the distribution. In histogram terminology, each set of paths, which represent a single entry in the histogram table, is considered to be a *bucket*. The proposal of BH is to use Bloom filters [Blo70] to represent paths contained in each bucket of the histogram. Table 3.2 shows the path-count table and a sample 4-bucket histogram for the paths in the recursive sample document of Fig. 2.2. The notation $BF(p_1, ..., p_n)$ is used to describe the Bloom filter generated for the paths p_1 to p_n. The frequency value of each bucket is the average of the frequencies of the paths in the associated Bloom filter.

3.4.1 Constructing BH

BH building is a two-phase process. In the first phase, the *path-count table* is to be constructed. It can be done by traversing an HNS structure, if it exists, or scanning the entire document. Whatever the method used, the *path-count table* needs to be sorted on its *frequency* column (see column "Freq" in Table 3.2). This process has a time complexity of $O(nlogn)$, where n is the number of table entries[2].

The second phase is to compress the *path-count table* by using a histogram. The histogram construction technique proposed by BH uses a dynamic programming algorithm which has a time complexity of $O(n^2b)$, where n is the number of *path-count table* entries and b is the number of buckets chosen[3]. The histogram application obtains the correct number of histogram buckets boundaries (with the least error in each bucket) to be used according to a desired error metric. After constructing the histogram, Bloom filters are applied in the set of paths in each bucket and the building process of BH is finished.

3.4.2 BH Estimation Procedure

BH inherits the probabilistic nature of the Bloom filter. Consequently, some ratio of false positives are allowed and this ratio is directly related to the parameters used for the Bloom filter[4].

In other words, some buckets can report $True$ for a path containment test/ verification even if the path is not present in the bucket. To overcome such situations, the BH estimation procedure always returns the *average of bucket frequencies*, if more than one bucket signalize $True$ in a histogram table lookup. Therefore, to estimate a path expression, BH needs always to scan the entire BH table and test the bloom filter at each bucket. Additionally, the augment of the number of buckets in BH does not provoke an increase in estimation quality, rather, it is possible to lead to a lower quality.

In summary, the user has to control and make trade-offs between the number of buckets and the sizes of Bloom filters in order to adjust BH to produce quality

[2]The number of *path-count table* entries is exactly the number of distinct paths in a document, i.e., the number of path classes in PS (or HNS). As an example, *dblp*, *nasa*, *swissprot* and *treebank* documents have 136, 161, 264, and 338,749 path classes, respectively.

[3]Because of this quadratic mechanism and, in addition, the sort needed for the first phase, the BH building time may become, in some cases, prohibitive.

[4]Basically, the number of bits, the error ratio allowed, and the number of hash functions used.

estimations. Another restriction to the BH structure is related to the support of path expressions, which is limited to path expressions with only child axes.

3.5 Discussion and Qualitative Comparison

After having studied the most important summaries published, it is necessary to have a discussion, comparing them qualitatively. To accomplish this, we must first find some classification criterion as well as some comparison criteria.

3.5.1 Classification

For this propose, we separate the existing approaches into two different classes: probabilistic methods and non-probabilistic approaches which we further refine based on their structural characteristics, i.e., their shapes: tree-based, graph-based and table-based. Hence, MT and BH are classified as non-probabilistic/ table-based and probabilistic/table-based, respectively. XSeed is classified into non-probabilistic/graph-based and Path Tree (PT) [AAN01] is a non-probabilistic/ tree-based approach (see Table 3.3)[5]. A probabilistic classification is considered if a summary structure, by its own virtue, allows false-positive and/or false-negative hits. The opposite case is the non-probabilistic methods.

As an example, we have classified MT as non-probabilistic, although MT uses a Markovian model to estimate expressions. However, the MT structure does not allow false positive/negative hits. XSeed, on the other hand, allows inexistent paths to be derived from its structure, i.e., the structure can evaluate path expressions that have an empty result as a non-empty expression result. This is clearly a false-positive hit. Therefore, we have classified XSeed as a probabilistic method.

3.5.2 Comparison

Table 3.4 summarizes and compares the characteristics of the summary approaches discussed so far in a qualitative way. The criteria compared are *scalability*, *estimation*, *loading*, *pruning*, and *support for path axes*.

[5]Aboulnaga et al. [AAN01] have proposed both PT and MT. The only difference between them is: the format – PT is tree-structured and MT is table-structured – and the estimation procedure – PT estimates based on a tree traversal and MT estimates based on a Markovian assumption. However, PT and MT rely on similar compression techniques. We have referred to PT here for sake of completeness of our qualitative comparison.

Table 3.3: Classes to compare summary approaches

Class	Shape	Approaches
Non-Probabilistic	tree	PT
	table	MT
Probabilistic	graph	XSeed
	table	BH

Scalability is the ability of the structure to keep its uniformity regardless of the document to which it applies. In our analysis, only graph-based methods are considered to be scalable, since their underlying structures maintain size and complexity even for huge and non-uniform documents. This is not the case for tree structures, because they reflect the document structure in a compressed way, or for table structures, where the number of rows strictly depends on the number of path classes in the document.

Table 3.4: Qualitative comparison among summary approaches

Class	Shape	Scalability	Estimation	Loading	Pruning	Path Axes
Non-probabilistic	tree	no	tree traversal	heavy	building	child, descendant, predicates
	table	no	table lookup	heavy	building	child
Probabilistic	graph	yes	graph search	light	estimation	child, descendant, predicates
	table	no	table lookup	heavy	no	child

Estimation describes the basic method of the path estimation process. Because it operates on the underlying storage structure, it directly affects the performance and complexity of the estimation process.

Loading addresses the memory requirements of the structure. We consider it a combination of two different measures: disk space requirements to store the structure inside the database, and the ability of loading partial structures into main memory, given the specific needs of a path expression to be estimated. Tree- and table-based structures are considered heavy, because they require the whole structure to be loaded in memory. For some methods of the tree-based class, this issue may be compensated by load-on-demand where only parts of the structure are loaded to the main memory during path expression estimation. As for the storage requirements, tree-based structures consume large amounts of space due

to the fact that they preserve the tree structure of the document. This is not the case for tables, but, because of their bad scalability, we cannot generally assume low space requirement. Graph structures, on the other hand, have a light load, as they are scalable and have a high degree of compression. However, the graph-based class does not allow load on demand.

Pruning a summary structure can be performed during structure building and cardinality estimation. Pruning in the building phase consists of setting boundaries for the document navigation and is usually done by specifying a maximal number of (upper) levels up to which the structure keeps the accurate numbers of occurrences, while for lower levels only guesses can be derived for them from the summary (normally, based on a statistical model). For tree-based structures, this corresponds to a standard tree pruning, where the summary has the same limitations concerning the number of levels as those used for the document navigation. Pruning can also be applied to table building, where the sizes of the paths stored are restricted by the given level boundary. The second type of pruning applies to the estimation process and, in our analysis, only to graph-based structures. The technique aims to set a limit to graph navigation, thereby avoiding unacceptable estimation times, however, at the expense of estimation accuracy. In the XSeed study made in Section 3.3, this is done by the "card_threshold" parameter which controls the trade-off between estimation time and accuracy.

For the flexibility, expressiveness, and usefulness of a summary class for cardinality estimation and, in turn, query optimization, *support of path axes* is decisive. Our rating in Table 3.4 records the path axes supported for cardinality estimation of path steps and whether a summary enables selectivity estimation for predicates[6]. Note, however, that some approaches are so restrictive in the use of path axes (e.g., table-based) and even if their underlying structures would allow estimation of specific axes, they do not provide such a support. As a matter of fact, most of the evaluated methods only deliver cardinality estimations for (/) and (//) axes. Estimation techniques for parent and ancestor axes have been missing in the proposals.

[6]We have stated that tree-based approaches allow descendant axes and predicates in path expressions by virtue of the underlying structure. In the original publication, however, no support to such expressions is given.

3.6 Conclusion

We have presented published XML summary workings, highlighting their ideas, strengths, and weaknesses in a comparative way.

Trying, humbly, to keep the positive points and overcome the negative points of published works studied so far, we introduce, in the two next chapters, our proposals for XML summarization. Chapter 4 presents two of them, LESS and LWES, which basically apply techniques to compress a HNS in a tailored fashion, thus following a "conventional" way. Chapter 5 details the EXsum approach which, in turn, follows a completely different way to summarize XML document.

Chapter 4

Following the Conventional—The LESS and LWES Summaries

Either you repeat the same conventional doctrines everybody is saying, or else you say something true, and it will sound like it's from Neptune.
Avram Noam Chomsky,American Linguist and Activist, b.1928

4.1 Introduction

In this chapter, we detail Leaf-Element-in-Subtree (LESS—Section 4.3), and Level-Wide XML Summarization (LWES—Section 4.4) structures (their ideas, building algorithms, applying compression methods and estimation procedures). As both structures rely on histogram compression techniques, we introduce first the fundamental concepts of histograms in Section 4.2.

4.2 Histograms

The element names occurring in an HNS tree are not continuous and have no natural ordering[1]. Instead, we have to deal with non-ordered discrete data spaces. Therefore, parametric distributions [MCS88] can not be applied. However non-parametric estimation techniques, e.g., histograms, may be suitable for the compression of *element:frequency* lists.

[1]To favor statistic information, the document order is somewhat broken in the HNS as compared to the respective PS.

Various forms of histograms [Ioa03]—all observing the standard assumptions of *uniform element/value distribution* and *element independence*—have been proposed so far; we sketch the most important ones. According to [Ioa03], a histogram on a set X is constructed by partitioning the data distribution of X's elements into $\beta(\beta \geq 1)$ mutually disjoint subsets called buckets and by approximating frequencies and values in each bucket in some common fashion, normally by averaging frequencies. This definition allows a degree of freedom in which we can both: (i) adapt the histogram definition to our needs, and (ii) use the types of histograms proposed in the literature.

There are, of course, several types of histograms. Four of these well-known types are: Equi-width (EW), Equi-height (EH) [PSC84], End-biased (EB) [IP95] and Biased histograms [PHIS96]. To illustrate these histograms, consider a set $\aleph$ of elements with five elements ($|\aleph| = 5$) as depicted in Table 4.1(a), where each element is annotated with its frequency (freq.), i.e., its number of occurrences[2].

TABLE 4.1: Different types of histograms for a sample set of elements

(a) Set of elements

Element	Freq
author	10
editor	3
price	5
title	1
year	19

(b) Equi-width histogram

Bucket	Estim.Freq
author–editor	13
price–title	6
year	19

(c) Equi-height histogram

Bucket	Estim.Freq
author–editor	13
price–year	13
year–year	12

(d) End-biased histogram

Bucket	Estim.Freq
min.var.elemts.	3
author	10
year	19

(e) Biased histogram

Bucket	Estim.Freq
author–author	9
author–tiltle	9
year	19

This set could represent a complete subtree or a set of element names at a specific level of a document and has to be mapped onto β buckets ($\beta \leq |\aleph|$). In our illustrations, we use three buckets to represent such a set.

While keeping the alphabetical order, an EW histogram (Table 4.1(b)) groups $|\aleph| / \beta$ elements together with their sum of frequencies in a bucket (with the left-over in the last bucket). Each bucket is then labeled with a start element and an end element, where the start element is the first entry in the bucket and the end

[2]This set is also called *frequency vector*, in statistic/histogram terminology

element is the last entry in the bucket. If a bucket holds only one entry, it will have equal start and end elements.

In contrast, EH computes the sum S of the individual element frequencies and sets $S/|\aleph|$ as an equal height. With this criterion, the entries of the original set are partitioned in an order-preserving way into buckets (Table 4.1(c)). If the frequency contribution of the end element is not fully contained in the bucket frequency (est. freq.), this element will appear as the start element in the subsequent bucket thereby spanning two (or more) buckets (see price–year and year–year buckets in Table 4.1(c)).

The biased histogram types try to emphasize particular elements while they approximate the remaining elements. Some degrees of freedom are conceivable, e.g., emphasizing elements with highest or highest/lowest frequencies or averaging elements with minimum variance. In our example in Table 4.1(d), EB selects $|\aleph| - (\beta - 1)$ elements which exhibit the minimum variance and represents them by a single bucket with their average frequency. The remaining $\beta - 1$ elements are represented by individual (singleton) buckets. Here, the EB histogram isolates the elements author and year and averages the remaining elements (min. var. elemts) in a bucket.

A Biased histogram (Table 4.1(e)) isolates the element with the highest frequency (year) and approximates the remaining elements in an EH way.

The direct and straightforward application of histograms may not be appropriate in all cases for XML data. In fact, some special situations exist in which histograms cannot contribute to further compression. These cases are described and dealt with as follows.

4.2.1 Histogram Application for XML

The first observation we have is that histograms have been originally designed to numeric data and element names in an XML document are character strings. Hence, we need a way to map element/attribute names to a numeric representation. Let us call it *vocabulary*. A *vocabulary* is a list of pairs "element-name:number" which maps each distinct element/attribute name to a number. Because the number of distinct element/attribute names in an XML document is normally small,

we only need one byte for the representation[3]. The number representing an element/attribute name is called VocabularyID (VocID). A *vocabulary* is thus a prerequisite to apply histograms in XML documents. With a *vocabulary*, buckets can now be represented by numbers.

The second observation is that for certain types of histograms (e.g., EB) some buckets are not appropriately described. Almost every bucket is described by its boundaries (e.g., author–editor and price–year). However, the "min.var.elemt." bucket in an EB histogram represents a set of elements with no explicit description. In the other words, it is assumed that elements that are not in the singleton buckets are in the "min.var.elemt." bucket. However, for estimating path expressions, this may be a problem for certain axes (e.g. descendant axis) and provoke a low quality estimation.

For example, consider a path expression *//a/b*. To estimate such an expression, we need to scan a summary looking for all sub-trees rooted by a and probe a b as a child. If the children of these sub-trees are presented by an EB histogram, it may happen that for one (or more) sub-tree with no b, the corresponding histogram will report a non-zero estimation due to the semantic of "min.var.elemt." bucket. This is clearly a case of false-positive probe during the estimation process[4]. Therefore, so as not to derive bad estimates we need, in this case, an explicit descriptor. Let us call it MVBD – Min.Var. Bucket Descriptor.

The computation of MVBD is quite simple. Having a *vocabulary* and the list of singleton buckets, we can build a (compressed) bit list of all elements inside of the "min.var.elemt." bucket. Additionally, we need the first and the last element (in fact, their VocIDs) for MVBD. For example, consider that we have 3 elements to be represented in the MVBD: j(VocID=10), o(15), and t(20). The MVBD is, in this case, formed by (10:20,10000100001). Each bit position between 10 and 20 is represented by "1" if the element is in the MVBD, or "0", otherwise[5]. The resulting EB histograms with the MVBD is called EB-MVBD.

The last observation is related to very irregular HNS structures. In such HNS, it is a common case to have one or two element names per sub-tree or level. The effective application of histograms in such cases depends completely on the element frequencies. If there exist varying frequencies (e.g., one element with a

[3]In our experiments, only *treebank* reaches 251 distinct element names, while other documents normally have a *vocabulary* varying from 40 to 170 entries. Therefore, one byte suffices to represent element/attribute names of an XML document.

[4]This should be avoided because the estimation error will tend to be high.

[5]For any practical implementation issue, we need only the last VocID and the bit list. In any case, bit compression techniques can be applied.

frequency of 20, and another one with 2,000), histograms cannot help so much under compression and accuracy point of views. Applying an EB histogram with one bucket is equivalent to averaging the frequencies—giving 1,010—which might yield a very low estimation quality. Applying a two-buckets EB histogram would correspond to, strictly speaking, no histogram at all, but rather a "bar graph". In this case, we would have accurate estimations with no savings in storage. If we use an EH histogram with a number of buckets greater than two, the waste of storage space would be even higher, and accuracy might also suffer as well.

To remedy such a situation, a re-scan in the HNS or in the entire document—depending on the approach implemented—is necessary to decide, based on the number of subtrees with one or two element names and on their frequencies, which histogram configuration to use. This is obviously the ideal method but it incurs an excessive extra time to be computed turning out a parametric method. Therefore, to cope with these cases in a pragmatic way, we do not apply histograms on subtrees/levels with only one or two element names. We apply instead the same bit list compression method used for MVBD and record the respective frequencies, i.e., without averaging them.

4.3 LESS—Leaf-Elements-in-Subtree Summarization

LESS [AMFH08a] is a structural summary in which histograms are applied in subtrees, specifically in their leaf elements. Histograms are annotated in every root element of subtrees.

4.3.1 The Main Idea

The observation that child sets having the same element name as their parent frequently exhibit a similar element distribution led to the development of the LESS method. It assumes a certain stable repetition (reasonably uniform distribution) of such patterns of parent-child sets. Hence, this property serves to save storage space.

The resulting LESS can be considered as a tree consisting of the inner HNS nodes and specific compacting structures. LESS can derive histograms which approximate the distribution information of child sets. In this sense, a child set is a

compound of a parent element and its child elements, but not of the related elements at lower levels.

The construction of a LESS summary requires an HNS structure to be built first. Therefore, the overall process to develop a LESS summary is two-phased. In the next section, we explain the second phase, i.e., the specific construction of a LESS structure given an existing HNS.

4.3.2 Building LESS

The LESS building process is based on an algorithm (see Algorithm 4.1) which recursively traverses the entire HNS, computing and applying the respective histograms/bit lists to the nodes of the LESS structure.

Algorithm 4.1: Building a LESS structure

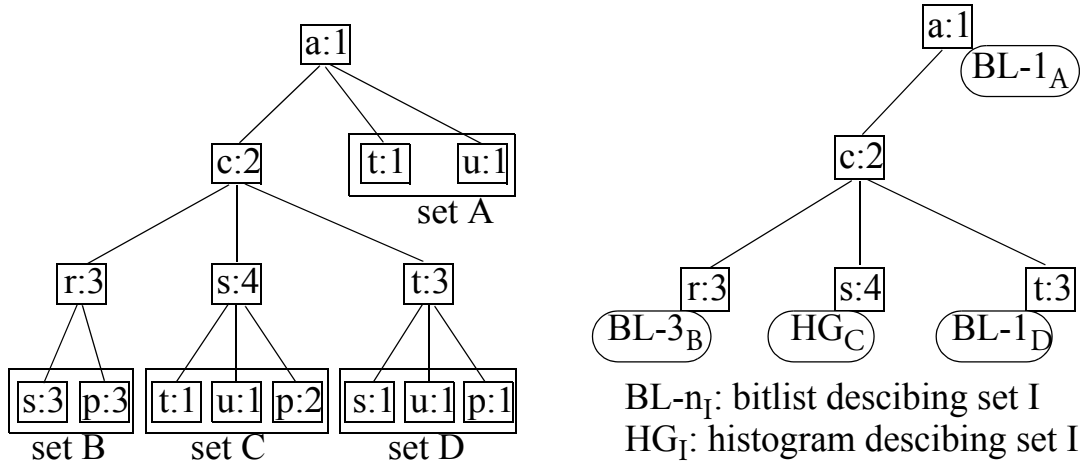
Input: An existing HNS tree, a histogram type
Output: The LESS summmary

```
1  begin
2  |  initialize an empty LESS Structure ;
3  |  HNSnode ← getRootNode(HNS) ;
4  |  BuildLESS(HNSnode, HistogramType);
5  end
6  Procedure BuildLESS(HNSnode, HistogramType) begin
7  |  leaves ← getLeafChildren(HNSnode) ;
8  |  inner ← getNonLeafChildren(HNSnode) ;
9  |  LESSNode ← addNodeToTree(HNSnode, LESS) ;
10 |  if leaves.size() > 2 then
11 |  |  histogram ← createHistogram(leaves, HistogramType) ;
12 |  |  annotate histogram to LESSNode ;
13 |  else if leaves.size() = 2 then
14 |  |  bitList ← createBitLits(leaves) ;
15 |  |  annotate bitList to LESSNode ;
16 |  else
17 |  |  addNodeToTree (leaves.getNode(), LESS) ;
18 |  endif
19 |  foreach node ∈ inner do
20 |  |  BuildLESS(node, HistogramType) ;
21 |  endfch
22 end
```

To illustrate the execution of the Algorithm 4.1, we use the HNS of the Figure 2.3(a) which we have, for sake of clarity, repeated in Figure 4.1.

The algorithm starts in lines 2–3. We first initialize an empty LESS structure, get the root node of the corresponding HNS tree and call the procedure *BuildLESS* passing the arguments: HNS root node and histogram type[6]. With the histogram type chosen, it will be applied throughout the LESS structure. Note, however, that it is possible to make a tailored application of histograms based on an anticipated knowledge of the workload on certain parts of the LESS tree, as pointed out in [AMFH08c].

Following the algorithm, we compute *leaf* and *inner* sets which are the set of leaf nodes and non-leaf nodes of the subtree rooted by the *HNSnode* passed as parameter (lines 7–8). For the current HNS tree, these sets are compound by nodes: $(t : 1, u : 1)$ and $(c : 2)$, respectively. The HNS root node, together with its frequency, is then inserted into the LESS tree as its root node (line 9). The processing of leaf set is made in lines 10–18. Our current *leaf* set has 2 nodes, and because of that we apply the bit list (line 14) and annotate this bit list into the LESS node (line 15). This operation is graphically shown as "BL-1_A" under LESS node a in Figure 4.1(b).



(a) HNS tree. (b) LESS structure.

FIGURE 4.1: Deriving the LESS structure.

Going further, lines 19–21 recursively traverse the HNS tree using the *inner* set. Then, the next HNS node $c : 2$ is visited. For $c : 2$, the *leaf* set is empty and the *inner* set has: $r : 3$, $s : 4$, and $t : 3$ nodes. The node $c : 2$ is inserted into the LESS structure (line 9) and the algorithm recurs again. For the HNS node $r : 3$, we find an empty *inner* set and a *leaf* set with $s : 3$ and $p : 3$ nodes. Node $r : 3$ is inserted into the LESS tree (line 9) and a bit list is once again applied (lines 13–15, also see "BL-3_B" in Figure 4.1(b)). When the algorithm reaches node $s : 4$,

[6]Histogram type can be one of those histograms studied in Section 4.2, e.g., EH, EW, EB, Biased and EB-MVBD.

its *inner* set is empty, but its *leaf* set has three nodes: $t:1$, $s:1$, and $p:2$. Here, a histogram is applied (lines 10–12) after inserting node $s:4$ into the LESS (see "HG_C" in Figure 4.1(b)).

When a *leaf* set has only one node, this node is directly inserted into LESS (line 17). After traversing completely the HNS tree in Figure 4.1(a), the algorithm finishes and the corresponding LESS structure is depicted in Figure 4.1(b). The LESS building algorithm has a time complexity of $O(n)$, where n is the number of nodes of the corresponding HNS tree.

4.3.3 LESS Estimation

To estimate cardinality of path expressions with LESS, we need to traverse the LESS tree and get the estimated cardinality by using the *GetCard* function for each location step. The *GetCard* function obtains the cardinality from a LESS node or from a histogram, whichever matches to a location step.

For example, an expression */a/c/r* is estimated, using the LESS structure in Figure 4.1(b), as follows. First, we start from the LESS root node to get the cardinality of the first step (*/a*), giving the accurate value of 1. Then, we look at the children of a to probe c (for the second step */c*). This yields a cardinality of 2. For the last step (*/r*), we go down in the LESS tree and look for an r among the children of c. Node r produces an accurate cardinality of 3 which is the estimated cardinality for the expression. Note that the estimation process of LESS, in addition to estimating the cardinality of an expression, can also estimate the cardinality of individual steps in such expression.

Another example is *//c//s*. For this expression, we, most probably, have to make a complete traversal of the LESS summary. For the first step (*//c*), and starting from the LESS root node, we look down in the tree seeking for c nodes. The cardinality of this step is then the sum of cardinalities of the c nodes found. In our case, there is only one c node with cardinality of 2. To continue the estimation process, we take each LESS node c found in the previous step and make another traversal probing s nodes which are descendants of c. In this case, we have to probe two bit lists, under nodes $r:3$ and $t:3$, and the node $s:4$ itself and apply the *GetCard* function to them. The estimated cardinality for this step is calculated as $4+3+1=8$.

The expression */a/c//p* follows the same estimation process. In this case, for the estimation of the last step *//p*, we collect every p in the descendant axis of c and

apply *GetCard* function. This function acts on two bit lists (BL-3_B, BL-1_D) and one histogram (HG_C). Assuming that an EB-MVBD histogram is constructed and that it delivers $p = 2$ as the estimated cardinality for p, the estimated cardinality for the expression is $3 + 2 + 1 = 6$.

In summary, the estimation process of a LESS structure traverses the LEES tree and is directly related to the number and type of the histograms annotated in the nodes of the tree.

4.4 LWES—Level-Wide Element Summarization

While the application of histograms in LESS is restricted to subtrees, LWES [AMFH08c] extends this application to every level of an HNS tree, transforming effectively the resulting structure into a graph. The LWES approach is an alternative solution which tries to deal with recursion in XML documents such as *treebank*, but it may also be beneficial for others, e.g., *dblp*[7].

4.4.1 The Idea Behind LWES

A way to compress an HNS tree is to capture the distribution of elements of a tree level by applying histograms. For example, Figure 4.2(a) shows two nodes s in level 2, one $s : 4$ under c, and another $s : 1$ under t. Let us call such situation Multiple Occurrences of the Same Element in a Level (MOSEL, for short). In this case, MOSEL of s in level 2—*MOSEL(s,2)*. LWES represents each MOSEL by using a single histogram. In a similar way, this rule is applied to all other HNS nodes, e.g., *MOSEL(s,3)*, *MOSEL(s,4)*, *MOSEL(p,3)*, and *MOSEL(p,5)* of Figure 4.2(a).

Nodes in an HNS tree with only one occurrence in a level are not compressed. Rather, they are directly inserted into the LWES (e.g., nodes t and p in levels 1 and 2). After applying histograms to MOSELs, the LWES summary is created (see Figure 4.2(b)).

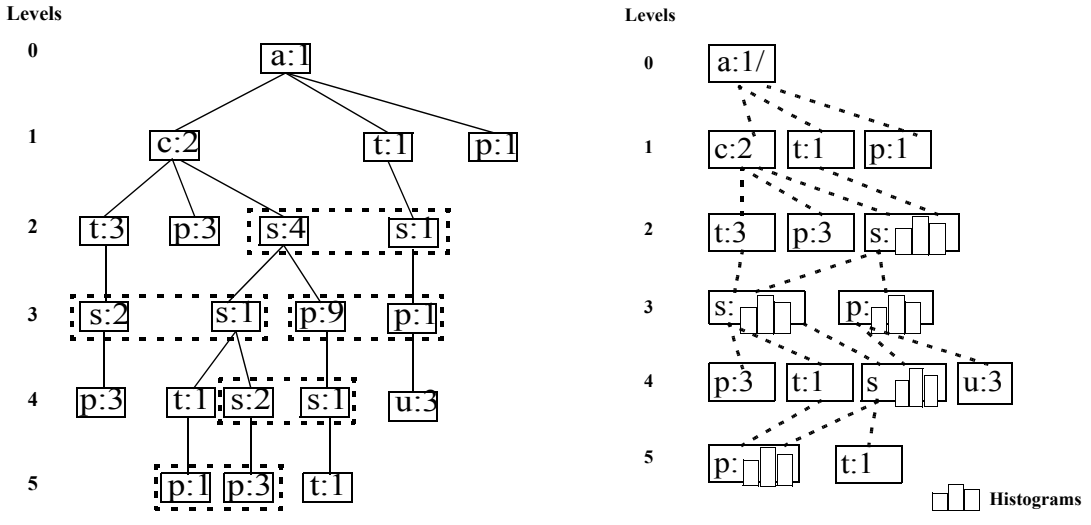
[7]The *dblp* document has several element names repeating in every level of its structure. Documents with such a characteristic can also benefit from LWES summarization.

In addition to the histograms, LWES maintains, for each compressed MOSEL, a list of parent pointers—represented in Figure 4.2(b) as dashed lines—which has a twofold goal[8]:

- it properly captures the hierarchy (parent-child relationships) of the document, and
- it helps to distinguish each node occurrence of an element. In other words, a histogram bucket may have one or more parent pointers to one or more elements/histogram buckets in the level immediately above it.

Both uses of parent pointers are exploited during the cardinality estimation process. Parent pointers explicitly represent all elements in the buckets, eliminating thus the need to use special types of histograms. Hence, there is no reason to use an EB-MVBD histogram in LWES.

Additionally, LWES has at least one advantage over LESS. An element name (node) at a level is represented by only a single histogram in LWES. LESS must possibly use more than one histogram to represent an element at a level. This fact makes LWES more space-effective than LESS.



(a) HNS tree. (b) LWES structure.

FIGURE 4.2: LWES structure for our recursive document.

[8]A MOSEL compressed by a histogram is represented in the LWES by the element name and the histogram buckets (see Figure 4.2(b)).

4.4.2 LWES Building Algorithm

Similar to LESS, the LWES building process requires an HNS tree to be previously computed, i.e., it is also a two-phased process. In the following, we illustrate the running of the Algorithm 4.2 with the HNS of Figure 4.2(a).

Algorithm 4.2: Building a LWES structure

Input: An existing HNS tree, a histogram type
Output: The LWES summmary

```
1  begin
2      initialize an empty LWES Structure ;
3      initialize an empty occurrenceList Structure ;
4      HNSnode ← getRootNode(HNS) ;
5      level = 0 ;
6      BuildLevelOccurrenceList(level, HNSnode) ;
7      BuildLWES(occurrenceList, HistogramType);
8  end
9  Procedure BuildLevelOccurrenceList(level, HNSnode) begin
10     occurrenceList.add(level, HNSnode) ;
11     children ← getChildren(HNSnode) ;
12     foreach node ∈ children do
13         BuildLevelOccurrenceList(level + 1, node) ;
14     endfch
15 end
16 Procedure BuildLWES(occurrenceList, HistogramType) begin
17     foreach level ∈ occurrenceList do
18         MOSELListsAtLevel ← occurrenceList.getMOSELLists(level) ;
19         if MOSELListsAtLevel is empty then
20             insert occurrenceList.getNodes(level) into LWES at level;
21         else
22             foreach MOSEL ∈ MOSELListsAtLevel do
23                 histogram ← createHistogram(MOSEL, HistogramType) ;
24                 adjust parent pointers ;
25                 annotate histogram to MOSEL ;
26                 insert MOSEL into LWES at level ;
27             endfch
28             commonNodes ← occurrenceList.getNodes(level);
29             foreach node ∈ commonNodes do
30                 insert node into LWES at level;
31             endfch
32         endif
33     endfch
34 end
```

To build an LWES summary, we need to first collect all nodes at each level of the HNS tree. This is performed by procedure *BuildLevelOccurrenceList* (lines 9–15). Starting with the HNS root node, this procedure recursively creates an *occurrenceList* for each level. Each *occurrenceList* contains all HNS nodes (line 10) at the respective level and is able to detect existing MOSELs in the level.

After creating *occurrenceList*s by traversing the HNS tree, we then have all the data to summarize and construct an LWES structure (procedure $BuildLWES$ in lines 16–33). First of all, for each level in the *occurrenceList*, we must detect an existing MOSEL in order to apply histograms and insert the MOSEL compressed by a histogram into the LWES. The variable $MOSELListsAtLevel$ stores all MOSEL at a level retrieved by method $getMOSELLists$ of *occurrenceList*. This variable is, in fact, a list of MOSELs (line 18). If $MOSELListsAtLevel$ is empty, we can directly insert all nodes of *occurrenceList* into LWES, because there is no possibility to apply a histogram (lines 19–20).

Therefore, at level 0 of the HNS tree (4.2(a)) there is only the root node which is inserted into LWES level 0. The *occurrenceList* of level 1 has no MOSEL, just common nodes which are also directly inserted in level 1 of LWES (see levels 0 and 1 of 4.2(b)).

However, we must apply histograms in existing MOSELs (lines 22–26). For that, we create a histogram of a $HistogramType$ for each MOSEL found in $MOSELListsAtLevel$, In addition, parent pointers must be adjusted (line 24) to reflect the correct relationship between the histogram buckets and their respective parents in the level above. Then, we insert the MOSEL together with parent pointers into LWES (line 25–26).

The remaining nodes, i.e., nodes not belonging to a MOSEL, must also be inserted into LWES (lines 28–30). MOSEL happens firstly at level 2 of the HNS tree. In this case, there is a $MOSEL(s, 2)$ and two common nodes $t : 3$ and $p : 3$. Consequently, in level 2 of LWES there are three nodes: t, p and $MOSEL(s, 2)$. The latter is represented by the element name (s), the respective histogram and parent pointers. In level 3 of the HNS tree, for example, there are two MOSELs. Therefore, the corresponding level in LWES has also two nodes. This process continues to be illustrated in levels 4 and 5 of the HNS tree.

After iterating throughout the levels, the algorithm finishes and the LWES summary is built as depicted in Figure 4.2(b). The LWES building algorithm has a time complexity of $O(2n)$ and a space complexity of $O(n)$, where n is the number of nodes of the corresponding HNS tree.

4.4.3 Estimating Path Expression with LWES

The estimation process of LWES is based on a search in the LWES structure. Similar to LESS, the *GetCard* function is also used to get the estimated cardinality of a path expression and the individual location steps of such an expression, whether directly from common nodes or from histogram buckets annotated to the compressed MOSELs. Therefore, for certain axes in a location step (e.g., //-axis), the LWES structure should be, in the worst case, entirely traversed.

As an example, consider the expression */a/c/s/s* posed on our recursive document of Figure 2.2(a). This expression consists of location steps with only child axes. The first step */a* has a context node which is the document root. Then, we probe the level 0 of the LWES for an a and obtain directly the step cardinality of 1. For the second step */c*, the level 1 is checked for a node c whose parent pointer points to a. It is found with a cardinality of 2. The third step */s* looks for a node s in level 2 with a parent pointer to c. This node s is a compressed MOSEL with a histogram. The parent pointers link each histogram bucket to the respective parent node in the level above. Hence, assuming that 2-bucket EB histograms were applied to the LWES of Figure 4.2(b), we can find that the estimated cardinality for this step is 4. For the last step, another */s*, the level 3 must be probed and the cardinality is also obtained from a histogram. In this case, the cardinality of the step is 1 which is the estimated cardinality of the expression[9].

Therefore, for path expressions consisting of only child axis, the cardinality of the expression is the cardinality of the last step. More formally, we have

$$Estim(/v_1/v_2/\cdots/v_n) = GetCard(/v_n) \tag{4.4.1}$$

Now assume that a user wants to get all nodes p in a document. The corresponding path expression is *//p*. This expression has a descendant axis and, in this case, the estimation process triggers probes in every level of the LWES. In the other words, the entire LWES structure is searched. At each level, a node p is probed and the estimated cardinality is gathered (*GetCard* function applied). The estimated cardinality for this expression is the ***sum*** of all *GetCard* application results. For our example, the result is 20, if we use 2-bucket EB histograms[10].

[9] If a 1-bucket EB histogram is applied to the LWES of the Figure 4.2(b), the estimated cardinalities for the third and the last steps are 2.5 and 1.5, respectively. In this case, the estimated cardinality of the expression is 1.5.

[10] The result would be 15, if we had used 1-bucket EB histograms.

Putting it in a more general way, we may say that every time a location step with a descendant axis has to be estimated, the estimation result is the sum of the partial results of every application of the *GetCard* function to the probed nodes. More formally,

$$Estim(//v) = \sum_{i=1}^{n} GetCard(v_i) \tag{4.4.2}$$

where v_i is each probed node of v[11].

To demonstrate the application possibilities of the Equation 4.4.1 and the Equation 4.4.2, we use the following expression */a/c//p/s*. For the first two location steps */a/c*, Equation 4.4.1 applies directly, i.e., the estimated cardinality is the cardinality of the second step which is 2. The application of Equation 4.4.2comes with the third step (*//p*). Here, we must probe p nodes in LWES levels below the level of node c, i.e., from level 2 down. For each node p that qualifies for the location step, we sum its cardinalities to come up with the step cardinality which is 18. Note that, for histograms—*MOSEL(p)*—buckets qualify if their parent pointers track to c. In the last step */s*, Equation 4.4.1 cannot be applied directly, because the previous step contains a //-axis. In fact, we must look for an s in the level immediately below and whose parent pointer points to one of the nodes gathered in the previous step. Thus, */s* has an estimated cardinality of 1.

4.5 Discussion

After having detailed our first two proposals on structural summarization of XML documents, and in light of the points raised in Section 1.2.3, we must discuss important issues related to them.

As positive points, we can highlight that LESS and LWES do not prune any document path and the application of histograms better capture node distributions in a document. This is in direct contrast to MT, which applies pruning, and PT which prunes and averages frequencies of document nodes.

On the other hand, LESS and LWES may not scale for deeply structured documents in both storage size and estimation time. The possible reason is that LESS and LWES summaries mirror somewhat the document tree structure thus making

[11]Note that, Equation 4.4.1 and Equation 4.4.2 apply also to the LESS estimation and, in general, to all tree and graph structures to estimate these kinds of path expression. Here, we present a simple formalization of an intuitive knowledge.

a correlation between the document structure and the summary structure. To estimate //-axes, the estimation procedure must search most of the nodes of the summary. The interplay of /and //-axes in a path expression makes the LWES and LESS to memorize (save) some nodes for the next step estimation, thus augmenting the space (also most probably the time) complexity of the estimation process.

Another negative point is that LESS and LWES can hardly estimate reverse axes (parent and ancestor) or at most the estimation of such axes tend to yield a very low estimation quality. The reasons for that is the coalescing of HNS nodes to reflect their frequencies in parts of the document. Additionally, for ancestor axes the memorization of nodes in the estimation process also applies.

Last point to be evaluated is the two-phased construction process, i.e., build the HNS structure first and then the respective summary. Because of that, building times may tend to be high for huge document sizes (see, for example, *psd*7003 and *uniprot* documents in Table 6.1(a)).

On the other hand, for most practical cases[12], LESS and LWES present themselves (hopefully) as solutions for structural summarization of XML documents.

[12]Documents not deeply structured (e.g., up to 5 levels) and with a low degree of both structural recursion and homonyms.

Chapter 5

EXsum—The Element-centered XML Summarization

It is not only old and early impressions that deceive us;
the charms of novelty have the same power.
Blaise Pascal, French Mathematician, Philosopher and Physicist, 1623 – 1662. In: Thoughts

5.1 Introduction

This chapter presents EXsum, an Element-centered XML Summarization technique. In contrast to all approaches studied so far, EXsum does not follow the strict tree hierarchy of an XML document. Rather, it concentrates on relationships among element names (called *spokes* in EXsum) which capture the concept of axes in a document and enable a direct (and simple) application in the estimation process of path expressions.

This chapter is structured as follows. In Section 5.2, we introduce the motivation which has driven the EXsum's design. Section 5.3 presents the core idea and the definition of EXsum structure. The EXsum construction algorithm is detailed in Section 5.4 and the estimation procedures are studied in Section 5.6.

5.2 Motivation for EXsum

The design of EXsum has been motivated by three factors, in addition to accuracy: *fast access* to the EXsum structure—avoiding a complete traversal to estimate location steps, *load on demand* of parts of the structure—lowering the memory footprint needed for the estimation process, and *extensibility*—which can be understood as the facility to easily aggregate more summarized data (e.g., parent and ancestor axes summarization), and devise new estimation procedures.

These factors have been thought to be an answer to drawbacks found in the published approaches and apply the lessons learned from the summarization structures (basically, histograms) used in relational databases.

Relational databases allow summarization structures which are very concise and have fast access. For example, consider a table with 20 columns having histograms on 15 of them. To estimate a query referring to only 2 out of 15 columns, the estimation process just needs to load 2 histograms into memory, lowering thus the memory footprint necessary to estimation. Histograms, in turn, have fast access—at most a binary search takes place—to deliver the estimated cardinality of an expression. Therefore, we want to bring these important characteristics to the XML summarization.

In all approaches published, one must traverse the corresponding structure to gather the estimated cardinality of a location step (e.g., with descendant and/or ancestor axes). This means that possibly the structure is searched many times to get the final estimation result, hence, impacting the time for estimation and, most likely, the overall optimization time. We want to avoid this behavior and substitute it for a direct access to the summary whatever the axis estimated. In other words, we want to limit the summary accesses to the number of location steps in a path expression.

Last but not least, the majority of published summary structures are concerned with the estimation of path expressions with /and //-axes, giving no room to extend them to capture other axes or value distributions in XML documents. We want a summary to be able to easily extend its structure in face of new summarization needs.

After all, the structure with all these desirable characteristics must be as accurate as possible to yield quality estimations. With these motivations in mind, we define the EXsum structure in the next section.

5.3 The Gist of EXsum

To dive into the main idea behind EXsum, we need a little introspection and to recall the basic definition of a tree. An XML document is a nodes' hierarchy which is represented by a tree in an XDBMS. Therefore, we assume the following (recursive) definition of the tree [Här96][1].

Definition 5.1. *Rooted Tree*: An oriented rooted tree, or simply a rooted tree, is a collection T of nodes which may be empty, otherwise it has the following characteristics:

1. In T, a distinguished node exists r called *root*.
2. The $T-r$ nodes form a set $S = S_1, S_2, \cdots, S_n$ where each S_i is also a (rooted) tree and is connected to r by an edge.

Each S_i is called a *subtree* rooted in i. Each edge connecting two nodes a and b correspond to a parent-child relationship between them, i.e., node a is called parent (super-ordinate) of b—vice-versa, b is child (subordinate) of a. A tree with n nodes has $n-1$ edges. A *leaf node* is a node with no children.

We can derive from Definition 5.1 the following possible relationships (called axes in XML terminology) among tree nodes, in addition to the parent-child relationship.

- *Ancestor*: A node a is an ancestor of node b if a can be reached from b by following the parent relationship.
- *Descendant*: A node a is an descendant of node b if a can be reached from b by following the child relationship.
- *Sibling*: Two nodes a and b are considered siblings if they are children of a common parent node.

The definition of the structure of an XML document described in [W3C98, W3C06] and the path expressions syntax studied in Section 2.2.1 are compliant with the Definition 5.1, which additionally defined two other axes: *following::* and *preceding::*. Therefore, we can reach the following observation.

[1] Translated into English and rephrased by the author.

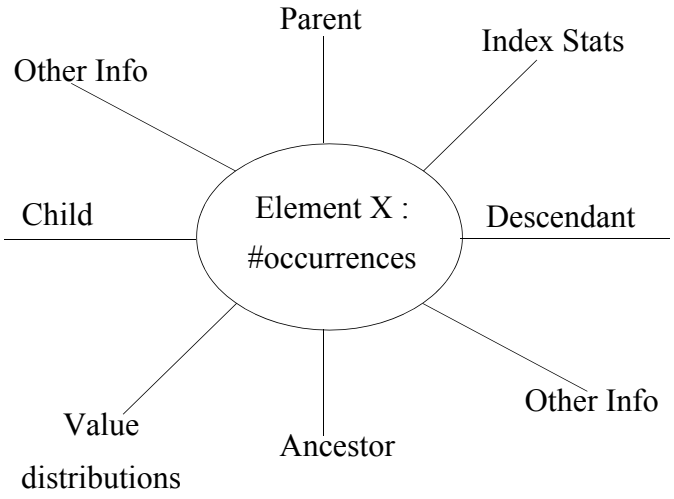


FIGURE 5.1: Sketch of an ASPE node structure

Remark 5.2. The core "entity" of a tree is a node—indeed, a tree with only one (root) node is considered a tree. In addition, a node has relationships with other nodes.

Based on this observation and making an abstraction, we can realize a new way to summarize an XML document. Instead of mirroring the complete (document) tree hierarchy, we take the distinct element/attribute names together with their frequencies (i.e., their number of occurrences in a document) and make for each one a node of our summary. Furthermore, for each summary node we capture the frequency distributions regarding the relationships between the element name and the other element names in (possibly all) axes. This is the gist of EXsum.

Definition 5.3. *EXsum—Element-wise XML Summarization.* An EXsum structure is defined as a set of ASPE (Axes Summary Per Element) nodes, where one and only one node exists for each distinct element/attribute name in an XML document. These nodes are independent from each other, in the sense that all the information regarding an element name is sufficiently encompassed by its correspondent ASPE node.

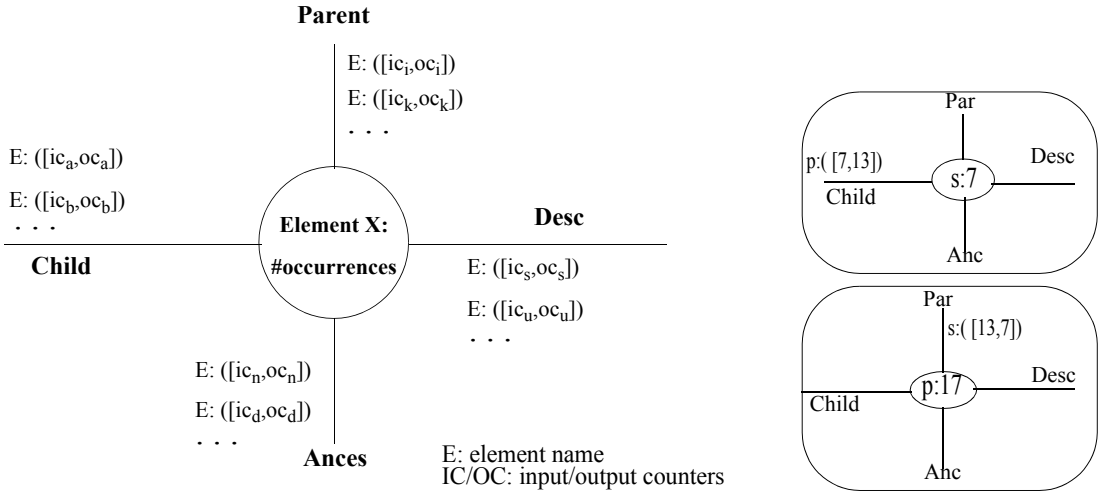
The structure of an ASPE node holds the total frequency of the element being tracked and the cardinalities of all other elements that relate to it, grouped by relationship type. The type of relationship is an abstraction which serves to model many concepts such as axis relationships, value distributions and other information related to the element. In an ASPE node, a relationship type is called ***spoke***. Thus, an ASPE node resembles a "spoked wheel" as sketched in Figure 5.1.

5.4 Constructing EXsum

Before deeply detailing the building algorithm and estimation procedures of the EXsum summary, we will smoothly introduce important concepts and features which are part of it. We start to consider the non-recursive document in Figure 2.1(c) and then in Section 5.4.5 we study the EXsum's building for documents containing structural recursion.

5.4.1 Counters on Axis Spokes

For each axis relationship between two element names, ASPE nodes maintain two counters called *Input Counter (IC)* and *Output Counter (OC)*, which register the cardinality occurring between the elements (see Figure 5.2(a)). They are used in the path expression estimation process to derive cardinality estimates on path steps.



(a) Format of an ASPE node for non-recursive documents.

(b) Partial EXsum structure.

FIGURE 5.2: ASPE node format and EXsum summary (cut-out)

To illustrate these counters, consider a *parent-child relationship* between element s and element p in our recursion-free document. Thus, there are two ASPE nodes: ASPE(s) and ASPE(p) registering respectively 7 and 17 as the frequencies of element names s and p. ASPE(s) has a child spoke in which there exists a p with (IC=7, OC=13). It means that, for the child relationship $s \rightarrow p$, we find in the document 7 elements s as parent of p and 13 elements p as children of s. Conversely, in the parent spoke of ASPE(p), there is a s with (IC=13, OC=7) indicating that for parent relationship $p \rightarrow s$ there is the same number of elements,

now counted in a reversed way. Therefore, the *IC* and *OC* counters capture the fan-in and fan-out of a relationship, respectively.

Note that IC and OC counters are somewhat replicated across ASPE nodes. This feature enables estimates of arbitrary long path expressions. Without loss of generality, we have implemented ASPE nodes with five spokes representing the four main important (XPath) axes (parent, child, ancestor and descendant—as pointed out in Section 2.2.1)—and a spoke for (text) value distributions. In the next section, we detail the structural summarization algorithm of EXsum.

5.4.2 EXsum Building Algorithm

The building process of the EXsum structure is done on-the-fly, while parsing the XML document. This can happen on two occasions: when the document is being loaded into an XDBMS, or later, when it is already stored. In both cases, the EXsum building algorithm is the same, as long as the system provides a parsing interface which abstracts the particularities of these two occasions.

The building process relies on a document scan, which is performed by an event driven parser. We manipulate two specific events raised by the parser: *Start Element* and *End Element*. The former happens when the parser visits an element/attribute name in the document, and the latter occurs when the parser leaves the element name, reaching a "close tag". Through this section, we discuss how we can build the element summarization in EXsum based on this parsing method.

The main idea is to maintain a stack S of elements/attribute names while processing the document. Elements are pushed into this stack at the occurrence of a *Start Element* event, while occurrences of *End Element* events cause already processed elements to be popped out. All the possible states of the stack are equivalent, therefore, to all possible rooted paths in the document. In other words, the stack S represents, at any point in time, the tree path that leads from the root to the current element being visited.

Algorithm 5.1 describes what happens when the *Start Element* and *End Element* events are signalized. Attribute names come attached to elements on *Start Element* events. They are, however, considered as "subordinate" nodes in an XML tree, as described in the XML specification [W3C06]. Accordingly, we have established that, under the EXsum perspective, attribute names are also considered as regular ASPE nodes, just like elements (lines 4-8 of Algorithm 5.1). The core process

for building EXsum is accomplished by the *BuildEXsum* procedure described in Algorithm 5.2.

Note also that, at *End Element* events, we pop out the element name and release all auxiliary structures that were used in the *BuildEXsum* procedure (lines 10-12 of Algorithm 5.1).

Algorithm 5.1: Handles the occurrence of a element name when parsing the document

Input: An existing XML document
Output: The EXsum summmary

```
1  EventHandler START ELEMENT begin
2  |  stack_S.push(node) ;
3  |  BuildEXsum(stack_S) ;
4  |  foreach attribute ∈ node.attributeList() do
5  |  |  stack_S.push(attribute) ;
6  |  |  BuildEXsum(stack_S) ;
7  |  |  stack.pop() ;
8  |  endfch
9  end
10 EventHandler END ELEMENT begin
11 |  stack_S.pop() ;
12 end
```

For each configuration of the stack S, we need to compute axis relationships between all the elements inside it, and count their occurrences in the correspondent ASPE nodes. For this computation, we take the recently pushed element, the *Top Of Stack (TOS)*, as reference. Under the TOS perspective, we need to count occurrences in the following axes:

- Parent axis. From the TOS to the $TOS - 1$ element.
- Child axis. From the $TOS - 1$ element to the TOS.
- Ancestor axis. From the TOS to every other element in the stack.
- Descendant axis. From every other element in the stack to the TOS.

These are, therefore, the relationships that have to be registered for every observed configuration of the stack S and, consequently, in every call of the *BuildEXsum* procedure.

To register these relationships, however, we need to be careful with the many particularities of each axis, in order to avoid repetitive counts of the same relationship. The repeated invocation of *BuildEXsum* causes a lot of redundancy in the observed configurations of the stack S, and some precautions must be taken to avoid repeated counts of an element. Figure 5.3 illustrates the case where redundancy becomes an issue. In the left hand of Figure 5.3, there are three p node siblings, children of the same parent s, whereas in the middle of Figure 5.3, the three p nodes are not siblings because they are in different subtrees. For the former, the correct counts for the child relationship $s \rightarrow p$ are [IC=1, OC=3], since we have a single element s having three distinct p's as children. The latter has the counters [IC=3, OC=3]. The parser, however, does not provide this kind of context information, and the building process by itself cannot distinguish between the subtrees in Figure 5.3, since they produce the same set of stack configurations. We explain how to handle such a situation in the following section.

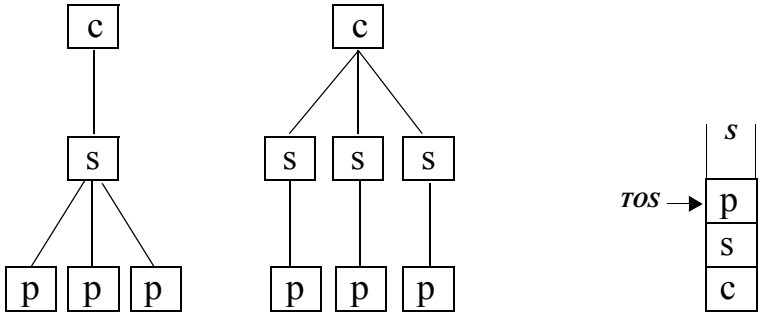


FIGURE 5.3: Subtrees producing the same stack S configuration

5.4.3 Correctly Counting Element Occurrences

To overcome issues related to different tree shapes producing the same stack S configuration, we have introduced an auxiliary list for each element in the stack S, to keep a history of the different paths produced by the stack during the parsing. This list is called *Elements in SubTree* (EST), and it maintains, for each element e in the stack S, a list of all the distinct elements that were pushed over it, or, in other words, all distinct elements that were visited by the parser under the subtree rooted by e. This means that every time a *Start Element* event occurs, the EST list of each element in the stack is updated, to signalize an occurrence of the current TOS under their subtrees.

With EST lists, we can now correctly count child and parent relationships, which, as seen earlier, occur between TOS and TOS-1 in a single configuration of the stack S. The child relation from TOS-1 to TOS has its OC incremented by one,

while the IC is only incremented if the EST list of TOS-1 does not contain TOS. If it contains TOS, it means TOS has a sibling with the same name which was already visited, and the occurrence of their parent in the relationship (IC) was already registered. The procedure for the parent axis is the same, except that, in this case, the IC is always incremented, while the OC must pass through the EST test.

For counting ancestor and descendant axes, the procedure is the same as when counting parent and child, respectively, except that relationships are registered between every node in the stack and the TOS. However, another issue regarding ancestor axes is raised when a recursive path is being processed. We discuss this issue later in Section 5.4.5, where we take a look at recursion. The maintenance of EST lists is performed by the *isFirstOccurrence* function (line 5 in Algorithm 5.2).

5.4.4 The Non-Recursive Case

The building techniques discussed so far, making use of EST lists, are illustrated in Figure 5.4. We take different subpaths of the document in Figure 2.1(c) and explain the behavior of *BuildEXsum* when processing those paths. We also indicate which relevant parts of Algorithm 5.2 are performing the actions.

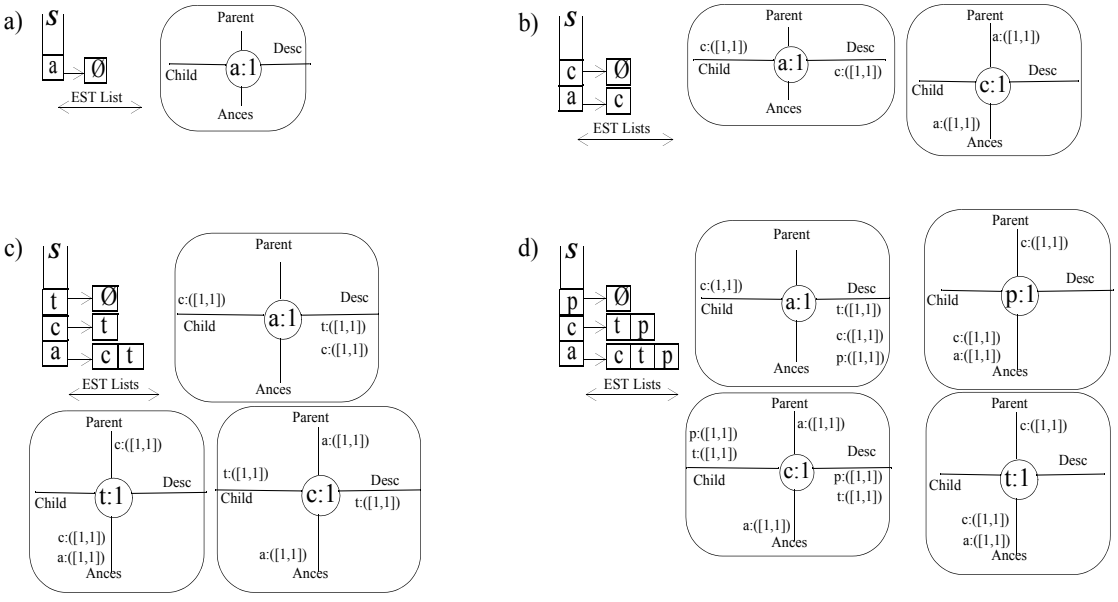


FIGURE 5.4: Configurations of EXsum and stack S (partial scan)

When the document root element is visited, its element name a is pushed into S, becoming the TOS. Furthermore, it causes the allocation of ASPE(a) and the setting of 1 as the total frequency of a in the document. This value is incremented

Algorithm 5.2: Processes a new path to be added to EXsum structure

```
1  Procedure BuildEXsum begin
2      n ← stack.size() ;
3      totalFreq(n) = totalFreq(n) + 1 ;
4      for i = 1 to n − 1 do
           /* maintains EST lists */
5          setOppositeCount ← isFirstOccurrence(stack[i], stack[n]) ;
6          computeRL ;
7          add descendant spoke from stack[i] to stack[n] with recursion level
           descRecLevel ;
8          add ancestor spoke from stack[n] to stack[i] with recursion level
           ancRecLevel ;
9          if i = n − 1 then
10             add child spoke from stack[i] to stack[n] with recursion level
               descRecLevel ;
11             add parent spoke from stack[n] to stack[i] with recursion level
               ancRecLevel ;
12         endif
13     endfor
       /* extension to support more statistical information and
          estimation procedures */
14     ComputeDPC(stack);
15 end
   /* extension to capture structural recursion */
16 Procedure ComputeRL begin
17     ancRecLevel ← 0;
18     for j = 1 to i − 1 do
19         if stack[j] = stack[i] then
20             ancRecLevel + + ;
21         endif
22     endfor
23     descRecLevel ← 0 ;
24     for j = i to n − 1 do
25         if stack[j] = stack[n] then
26             descRecLevel + + ;
27         endif
28     endfor
29 end
```

for the TOS in every execution of *BuildEXsum*, as seen in line 13 of Algorithm 5.2. After that, an empty EST list is allocated for a. The current state of the EXsum summary is shown in Figure 5.4(a).

In the next step, a node with element name c is reached and pushed into S. Because ASPE(c) is not present, it is created and the related axes information is added to a and c as follows. The algorithm needs to adjust IC/OC counters in ASPE(a) and in ASPE(c). Since this is the first time that c appears under a, the EST list of a includes c and signalizes that it was not present before (*isFirstOccurrence* in line 3). The function *isFirstOccurrence(x,y)* checks if this is the first occurrence of the node y under the subtree rooted by node x, by looking for the node y in the EST list of x. If no occurrence is found, it adds y to the list and returns *true*. In our case, since the function returns *true*, both IC and OC are set, resulting in [IC=1, OC=1] for $a \rightarrow c$ in child and descendant axes. Similarly, $c \rightarrow a$ ends up with [IC=1,OC=1] in the parent and ancestor spokes. The summary now looks like the one in Figure 5.4(b).

It is important to note that every child relationship is also a descendant one, and the same is valid for parent and ancestor. This comes from the XPath specification [W3C07], where a descendant axis relationship is defined as *"the transitive closure of the child axis; it contains the descendants of the context node (the children, the children of the children, and so on)"*, and the definition of ancestor follows in a similar way[2]. Therefore, when registering child and parent relationships, EXsum also considers them as descendant and ancestor.

Continuing the document scan, a node with element name t is now visited ($S = [a, c, t]$) (Figure 5.4(c)). Again, t is pushed into S, ASPE(t) is created, and the axis relationships between t and the other path elements c and a are updated. Note that child and parent will only be set between t and c. The EST lists of a and c now contain a t, and again both lists report that it is the first occurrence. Thus, the counts [IC=1, OC=1] are registered for ancestor and descendant axes of $a \leftrightarrow t$ and $c \leftrightarrow t$ (lines 5 and 6). Additionally, child and parent are also set with the same values for $c \leftrightarrow t$ (lines 8 and 9).

Since t has no children, an *end_element* event is signalized and t is popped out from S. This process is iterated when the scan reaches the fourth element p ($S = [a, c, p]$) and counters are adjusted in $a \leftrightarrow p$ and $c \leftrightarrow p$, in the same way as

[2] According to the XPath specification [W3C07], the ancestor axis is defined as *"the transitive closure of the parent axis; it contains the ancestors of the context node (the parent, the parent of the parent, and so on)"*

in the previous step. EXsum and stack S configurations thus far can be viewed in Figure 5.4(d).

The effect of EST lists is highlighted when the process visits the fifth element (another p, resulting in $S = [a, c, p]$). Here, ASPE(p) is already allocated and there is already a p in the EST lists of c and a. Thus, it is not the first occurrence of p under the subtrees rooted by c and a (line 3, $setOppositeCount = false$). This causes the increment of only OC in the child ($c \rightarrow p$) and descendant ($a \rightarrow p$ and $c \rightarrow p$) axes. Likewise, parent ($p \rightarrow c$) and ancestor ($p \rightarrow a$ and $p \rightarrow c$) axes have only the IC value incremented. This mirrors the subtree structure in which there is only one c as parent of two p and consequently, one a as ancestor of two p. By proceeding so, we have the correct values of IC/OC counters when the processing of a subtree finished.

To conclude our explanation, EXsum records axis relationships regarding an element/attribute name in the document with counters IC/OC. Given a relationship $a \rightarrow b$, the structure records how many times the relationship occurred in the document tree. This is captured by each pair IC/OC, in which is recorded how many instances of a and b are present in this relationship. The total number of occurrences of a given relationship is, therefore, given by the calculation of $max(IC, OC)$.

The complete EXsum structure for the document in Figure 2.1(c) of Section 2.1 is given in Figure 5.5.

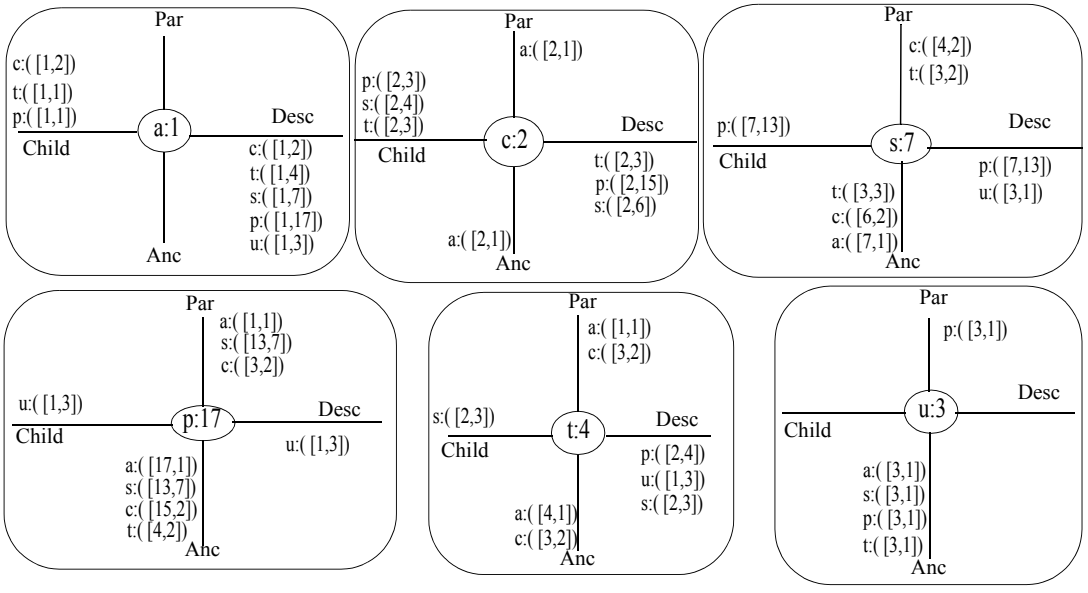


FIGURE 5.5: EXsum structure for our recursion-free document in Figure 2.1(c)

5.4.5 Dealing with Structural Recursion

Although highly recursive documents like *treebank* are not frequent in practical situations, some degree of recursion may be anticipated in a small class of documents. Thus, we deal with recursiveness for reasons of generality and support summarization on documents exhibiting a limited kind of structural recursion. General recursion, however, seems to be elusive and does not allow for a meaningful estimation process, which could deliver approximations of sufficient quality.

EXsum relies on the concept of Recursion Level (RL) to cope with recursion in document paths (see Section 2.3). So far, we have only worked with values of zero in recursion levels (RL=0), since our sample document has been a recursion-free one[3]. From now on, we study recursive path summarization using the recursive sample document in Figure 2.2(a)a of Section 2.3. To cope with recursion in the EXsum summary, we need to extend the ASPE format to register IC/OC counters for each RL found. Therefore, the extended ASPE node format is sketched in Figure 5.6.

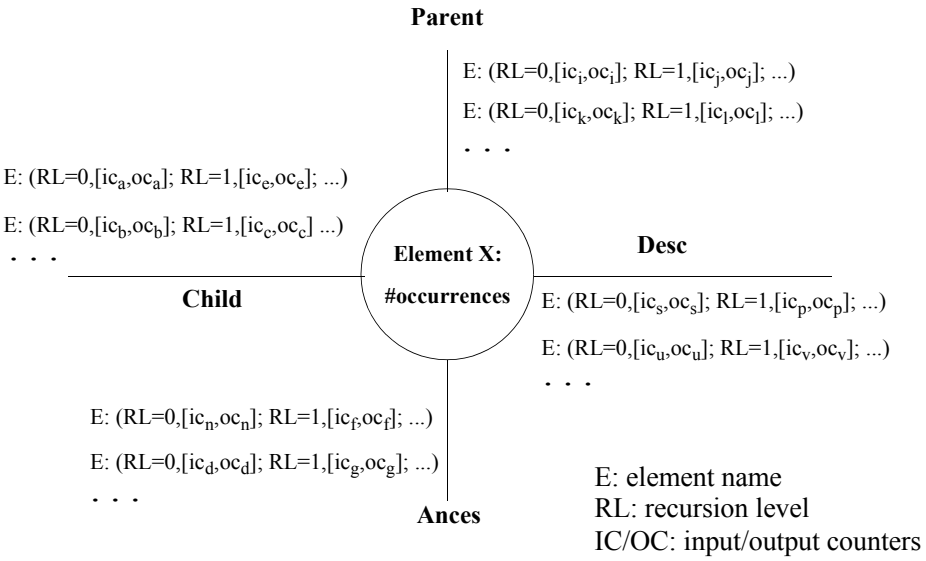


FIGURE 5.6: Format of an ASPE node for recursive documents

5.4.5.1 Calculating RL

The original proposal of the RL concept [ZÖAI06] was restricted to parent-child relationships in a document. We have extended this concept to encompass ancestor

[3]The RL=0 counter has been omitted in previous sections for sake of clarity. Nevertheless, the RL=0 assumption is applicable in former cases. In fact, based on a prior knowledge of the document, the DBA can drive EXsum to produce (or not) RLs counters. This is also a flexibility feature of EXsum.

and descendant axes. The calculation of RLs is embodied in the building algorithm (line 6) and performed in procedure *ComputeRL* in Algorithm 5.2—lines 16–29). For each axis relationship inside ASPE nodes, we calculate RL and, for each RL, the IC/OC counters. EXsum is, in its general format (see Figure 5.6), a recursion-aware summary, and two kinds of recursion are involved, which are forward-path recursion and reverse-path recursion (see Figure 5.7).

The forward-path recursion is considered when navigating downwards through the path, from the document root element to the current element. This kind of recursion is considered when dealing with child and descendant axes. The reverse-path recursion is gathered in the opposite direction, i.e., from the current element to the document root. Similarly, reverse-path recursion is used in parent and ancestor spokes of ASPE nodes.

In order to calculate the proper values of forward and reverse recursion for a relationship, one must analyze the path in which this relationship occurs. Given a path with n elements, represented as a stack like that seen in the building process, we need to calculate the recursion levels between an arbitrary element in position i ($0 < i < n$) and the TOS, located in position n. The forward-path recursion is given by the number of occurrences of the element i in the sub-path $(0, \cdots, i-1)$ (lines 23-28 of the procedure *ComputeRL* in Algorithm 5.1), while the forward path is equivalent to the number of occurrences of n in $(i+1, \cdots, n-1)$ (lines 17-22). In other words, for a given relationship $a \leftrightarrow b$, where b is contained in the subtree rooted by a (b is descendant of a), the forward recursion level represents the repetitions of a when traversing, through the path, from the root until reaching b, while the reverse one considers a bottom-up traversal, from b until a. We show an example of this calculation later in this section.

To illustrate the processing of a recursive path, we give a step-by-step walkthrough on the execution of *BuildEXsum*, just like we did earlier for the recursion-free document. Considering the document in Figure 2.2, we take the state of the summary just after processing the eleventh element, which is the t in the path (a, c, s, s, t). This path is the first occurrence of recursion when parsing the document, as we can notice the repetition of the node s before reaching t. Figure 5.8 illustrates the summary state at this point, and we can notice the counters with $RL = 1$ in the spokes of s. Starting from this point, we detail the processing of the twelfth element, which brings additional levels of recursion.

When the document reaches the twelfth element, an s, the configuration of the stack S is $[a, c, s, s, s]$ (see Figure 5.7(a)). This is the path to be processed, and we need to update all the relationships involving the element s, i.e., the TOS and

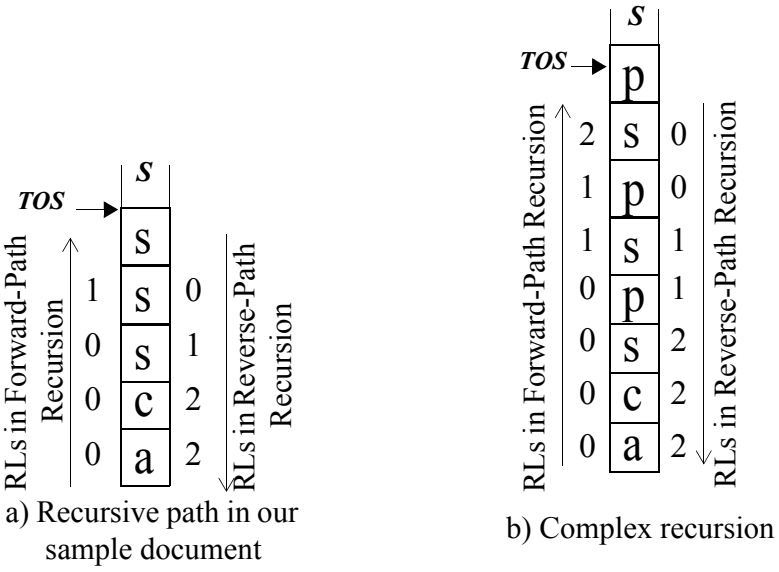


FIGURE 5.7: Calculating RL for recursive paths

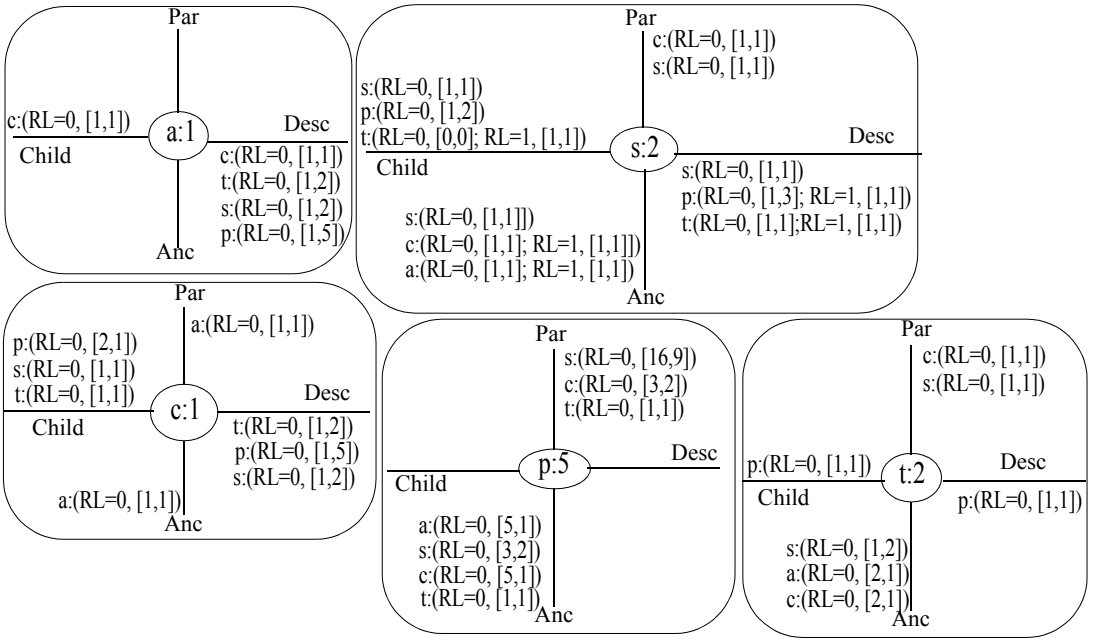


FIGURE 5.8: EXsum state before processing the 12^{th} element in our recursive document

the other elements in the stack. The procedure is the same as for the other non-recursive paths seen for now, but we detail the RL calculation, as it will return values greater than zero in this case.

The values for forward recursion in this path are as follows: a:(RL=0); c:(RL=0); s:(RL=0); s:(RL=1). The last s before the TOS presents a recursion level of 1, since the sub-path that reaches it from the root ($[a, c, s]$) contains one occurrence

of s. All these values of RL will be registered in descendant relationships between those elements and s, with the addition of a $RL = 1$ in the child axis of $s \rightarrow s$.

Reverse-path recursion values for the elements in the path are: a:(RL=2); c:(RL=2); s:(RL=1); s:(RL=0). Starting from the root element a, we notice the occurrence of two s's between this element and the TOS, which is also a s. The RL in this case is, thus, 2, and the value maintains until the first s is reached, when the count of occurrences would drop to 1. The RL of the ancestor axis in $s \rightarrow s$, for this first s in the path, is therefore 1. Reaching the element right before the TOS, we find another s, so the count is again decremented, resulting in RL=0 for the parent and ancestor axes between this element and the TOS.

Figure 5.7(a) illustrates the example path and shows both forward and reverse recursion values for all the elements in the stack. A more complex example of path recursion and RL calculation (not related to the document in Figure 2.2(a)) is given in Figure 5.7(b).

When the bulding process leaves the twelfth element s, the resulting EXsum state is depicted in Figure 5.9, and the changes made to the summary since the last state are highlighted in bold.

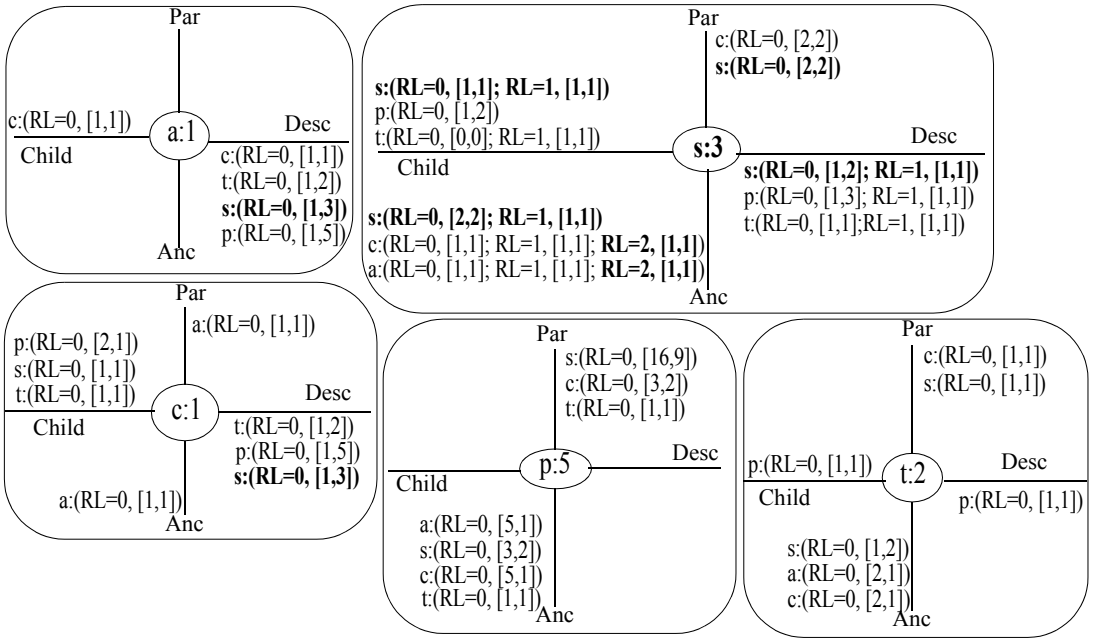


FIGURE 5.9: EXsum state after processing the 12$^{\text{th}}$ element in our recursive document

When the document in Figure 2.2(a) of Section 2.3 is completely scanned, the corresponding EXsum structure is given in Figure 5.10.

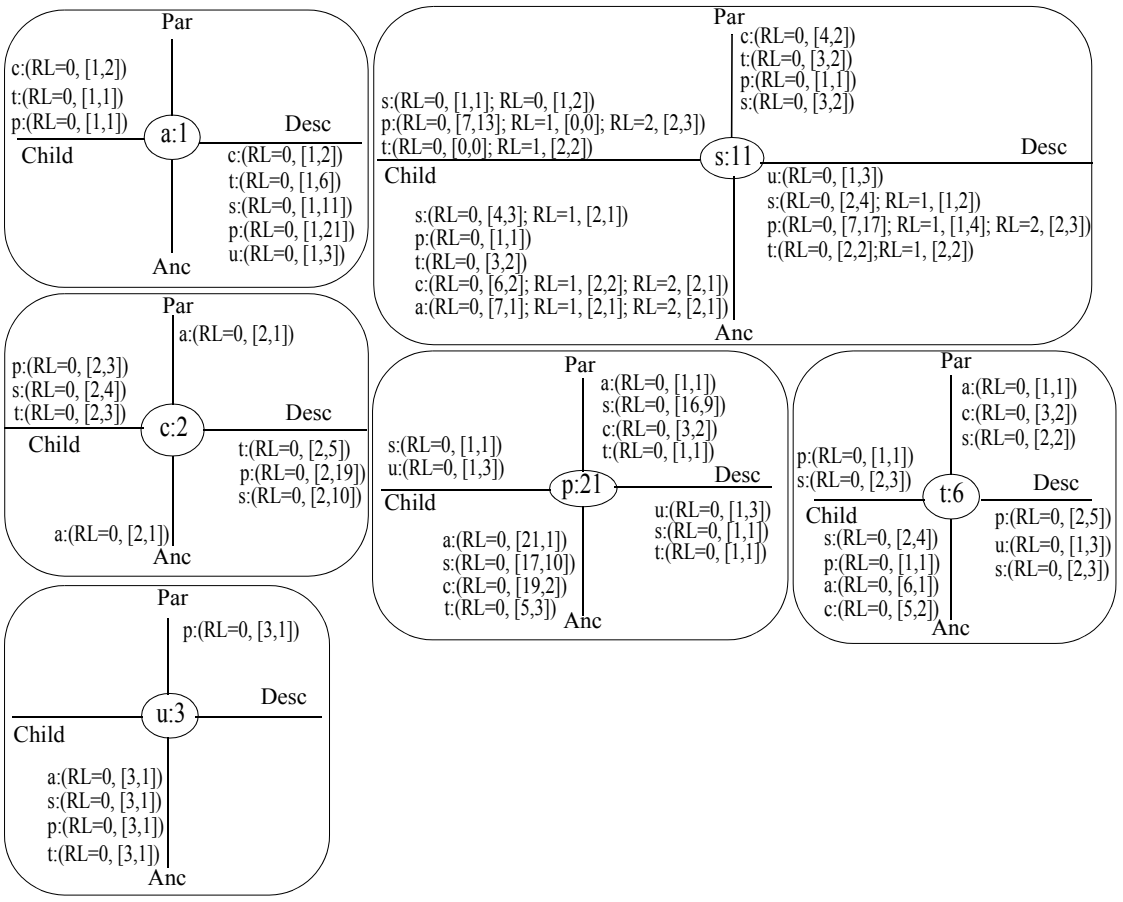


FIGURE 5.10: EXsum for recursive paths

5.4.6 Extending EXsum—The Distinct Path Count

In Section 5.6, we study an estimation procedure called **DPC Division**. This procedure needs, for estimating some axis relationships (child and descendant), the number of distinct paths that reach a specific relationship from the document root node. In other words, if we have a relationship $s \rightarrow p$, we need to know how many distinct rooted paths lead to the element s in this relationship. We refer to this count as the *Distinct Path Count (DPC)*.

We need to extend the ASPE node structure to encompass DPC counters. Up to now, in each spoke, we have a list of triples $(RL, [IC, OC])$ (see Figure 5.6) for each relationship inside spokes. Now, we add another counter to child and descendant spokes, resulting in 4-tuples with $(RL, [IC, OC, DPC])$. Note that the concept behind DPC is suitable only for forward axes, as the document navigation is done in a forward direction, i.e., top-down.

Recursion also plays a role in the DPC extension. As seen earlier, we have tuples of $(RL, [IC, OC, DPC])$ in the counters inside spokes. Accordingly, we should

register the correct DPC value for every recursion level. To do so, we associate a RL to each sub-path inserted in the child and descendant sets. The computation of this RL is done in the same way as when we obtain forward-path RLs to update IC's and OC's, i.e., by counting, inside the sub-path, the occurrences of the element at the right side of the relationship.

To compute the DPC, we need to maintain a set of all distinct rooted paths for each relationship. To do so, we call on the procedure *ComputeDPC* (line 14 of *BuildEXsum* in Algorithm 5.2). We can implement this procedure in two ways. First, given a relationship $s \rightarrow p$, we can traverse a path synopsis, seeking the specific rooted paths we need, and repeat this traversal for each relationship computed. If a path synopsis exists, this traversal has a time complexity of $O(nlog(n))$, where n is the number of nodes of the path synopsis.

In the absence of a path synopsis for the document, we have designed the self-contained procedure *ComputeDPC* given in Algorithm 5.3. It processes every rooted path occurrence, represented by the *Stack* argument given by the *BuildEXsum* procedure. For every pair of related nodes, we maintain two sets, one for child (child set) and the other for descendant (descendant set) relationship.

Algorithm 5.3: *ComputeDPC*. Computes the distinct paths for child and descendant spokes

```
1  begin
2      n ← stack.size() ;
3      if n > 2 then
4          for i = 2 to n − 1 do
5              recLevel ← 0 ;
6              for j = 1 to i − 1 do
7                  if j = i then
8                      recLevel + + ;
9                  endif
10             endfor
11             add the sub-path stack[1 .. i − 1] with RL=recLevel to the
               descendant set of (stack[i]; stack[n]);
12             if i = n − 1 then
13                 add the sub-path stack[1 .. i − 1] with RL=recLevel to the child
                   set of (stack[i]; stack[n]) ;
14             endif
15         endfor
16     endif
17 end
```

To explain how this algorithm works, we take a practical example. Consider the path (a, c, s, s, t) in the recursive document in Figure 2.2. The TOS element in this case is t. The procedure starts by assigning the size of the path to n, which in this case is 4. Then, we check for the value of n. The procedure is only executed for values of n greater than 2 (line 2), because a path with two nodes contains only one child relationship and, therefore, no preceding distinct paths. Then, for every node i in the path—below the TOS—we add an occurrence of the subpath that leads from the root to the descendant relationship between i and the TOS (line 10). The proper RL value is calculated by counting the occurrences of i in this sub-path (lines 4-9). For the particular case of the relationship between TOS and the element right before it, the path is also added to the child set (line 12). So, in the given example, the procedure starts with element c (position 2). Then, we take the descendant set of the relation from c to t, denoted as a pair $(c; t)$, and add an occurrence of the path $/a$, with RL=0. The child set will be left untouched, as c is not at position $TOS - 1$. Because sets are used, no duplicate elements will be added, and only distinct paths will populate them. When going to the first s element, the path to be added is $/a/c$, also with RL=0. Reaching the second s, we need to add the path $/a/c/s$ to the relationship $(s; t)$. This time, since one occurrence of s is found in the preceding path, it will be inserted with RL=1. Moreover, it will also be added to the child set, as the element is positioned right before the TOS t. Figure 5.11 illustrates which relations and paths are computed.

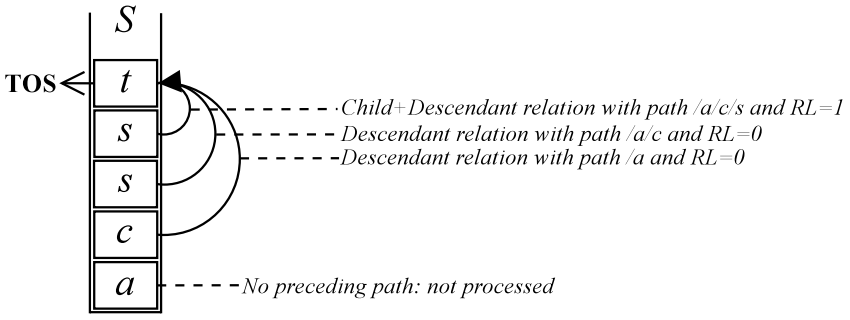


FIGURE 5.11: Distinct path computing for a sample path stack

When the scan of the document is finished, we have, for every child and descendant relationship in the document, the sets with the preceding distinct paths. The distinct path count is, for each relationship and each recursion level, the cardinality of the elements with the same RL inside the corresponding set. This procedure has a space complexity of $O(p)$, where p is the number distinct paths in the document[4].

[4]To place some numbers in evidence, the numbers of distinct paths for documents *dblp*, *swissprot*, and *nasa* are 164, 264, and 111, respectively

Figure 5.12 shows the extension of EXsum with DPC counters for our recursion-free document. Figure 5.13 depicts the correspondent EXsum structure for our recursive document of Figure 2.2(a).

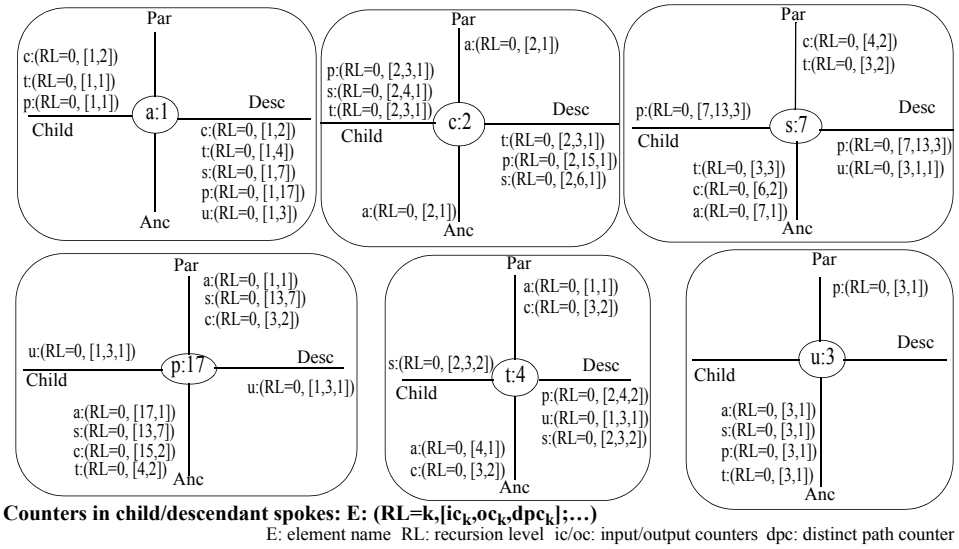


FIGURE 5.12: EXsum extended with DPC (recursion-free document)

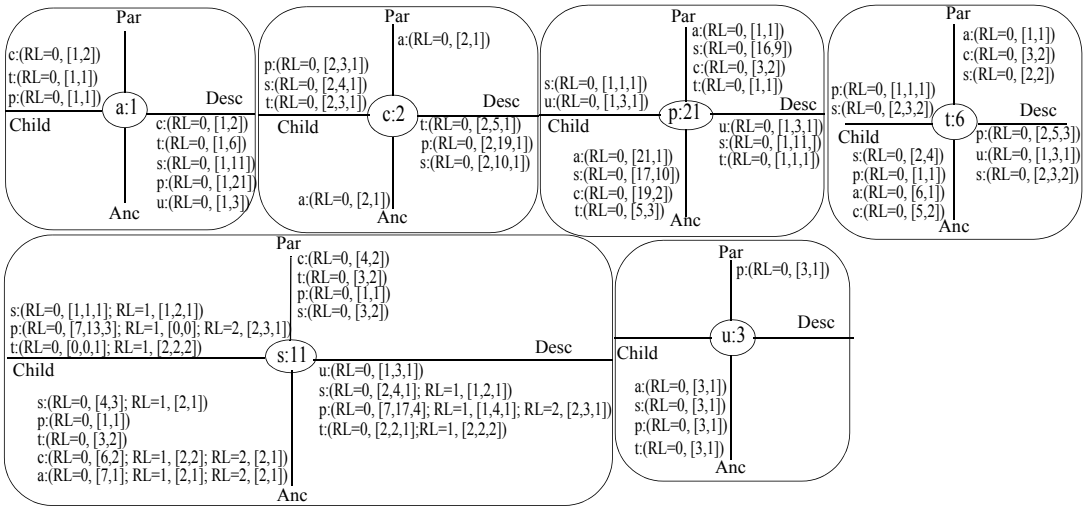


FIGURE 5.13: EXsum extended with DPC (recursive document)

5.5 Capturing Value Distributions

In this section, we introduce an extension to the EXsum structure to enable the summarization of XML text nodes and, consequently, the estimation of path expressions with value predicates. The methodology used for the actual summarization of text contents is also easily extensible to produce good results with

information retrieval and compression techniques. Therefore, to introduce the idea, we first consider the storage of full text contents and, later in this section, we discuss possible methods to summarize the text contents themselves.

While the structural part of a document is very repetitive, we cannot say the same about the value part. The number of possible values of varying data types in a single subtree is so huge that a single method to condense all particularities referring to both value and structure of a document will most probably be unpractical. For example, we may have values such as numbers, dates, and text strings with varying numbers of occurrences, which do not follow the same variation of the structural part in a subtree. Furthermore, the set of possible predicates in XQuery is so rich and complex that a single structure would not suffice to encompass all possibilities.

Basically two kinds of predicates may appear in XQuery statements: value predicates and path predicates where both are represented in brackets ([]). The former has the traditional meaning inherited from relational databases in which techniques as histograms (see Section 4.2) and q-grams [CGG04] can be applied. The latter is a novel feature of XQuery. Of course, XQuery allows for the coexistence of both kinds of predicates in a path expression.

Existential predicates may contain one or more path expressions, e.g., */a/c[./s]/t* and *//s[./s and .//s/t]*. A path expression qualifies a path instance only, if the included predicate evaluates to *true*. If the predicate, in turn, contains several path expressions logically connected by AND, then all path expressions must be evaluated to *true*.

Value predicates may also contain functions related to the data type. For example, the expression */a/c[./text()='XML']* retrieves all c nodes under a that have a text string equal to "XML". Other functions are provided in the XPath specification such as *contains*—which tests string containment—*substring*, and so on. Additionally, XPath specifies a function called $ftcontains$ enabling (recursive) full-text search in XML documents.

5.5.1 Following the DOM Specification

According to the DOM specification [W3C98], text contents inside an XML document are also considered to be nodes, and they fit into the tree model just like

elements and attributes[5]. This means the content under an element or attribute is stored as its child node. If the content contains markup tags in the middle of the text, like the italic text in the sample document in Figure 5.14, the text content is broken into three nodes: the text content before the sub-element, the element node (with the text under it as child), and the text content after the element. Figure 5.14 also illustrates the DOM tree for the document.

The first p element has a single block of text, with no elements in beneath, and therefore only one text node with all the content. The second p, although, has an i child in the middle of the text, which causes the text to be split into several nodes. Text nodes are also considered to be leaf nodes, which means no other XML node (element, attribute, entity reference, comment, etc.) can be a child of text nodes. Furthermore, the only nodes that can hold text content, or have text nodes as children, are element and attribute nodes.

The summarization process for the document is shown in Figure 5.14.

5.5.1.1 Incorporating Text Nodes into EXsum

The approach of text contents as nodes is perfectly suitable for EXsum to summarize them. We can store text nodes and create special relationships between them and the other elements and attributes in the document. We do not need, however, to consider them as elements or attributes, which means we do not create an ASPE node for each text node. Instead, we introduce a new spoke (called "text spoke") to the ASPE structure and organize related text contents inside it. Therefore, we compute relationships between document element/attribute names and text nodes, by adding a "text spoke" to the ASPE structure, thus extending EXsum to register value distributions. This is the gist of value summarization of the EXsum summary.

Each text spoke contains a list of text contents, which are associated to the element name tracked by the corresponding ASPE node, and a counter for the text nodes under it. Every new occurrence of text content makes a new text content entry to be added to the "text spoke" in the corresponding ASPE. Every occurrence of an already registered text content makes an increment to the counter. Figure 5.15 illustrates the text spoke inside the ASPE(p). Like every other spokes in EXsum,

[5] **Quotation from DOM specification.** *The Text interface represents the textual content (termed character data in XML) of an Element or Attribute. If there is no markup inside an element's content, the text is contained in a single object implementing the Text interface that is the only child of the element. If there is markup, it is parsed into a list of elements and Text nodes that form the list of children of the element.*

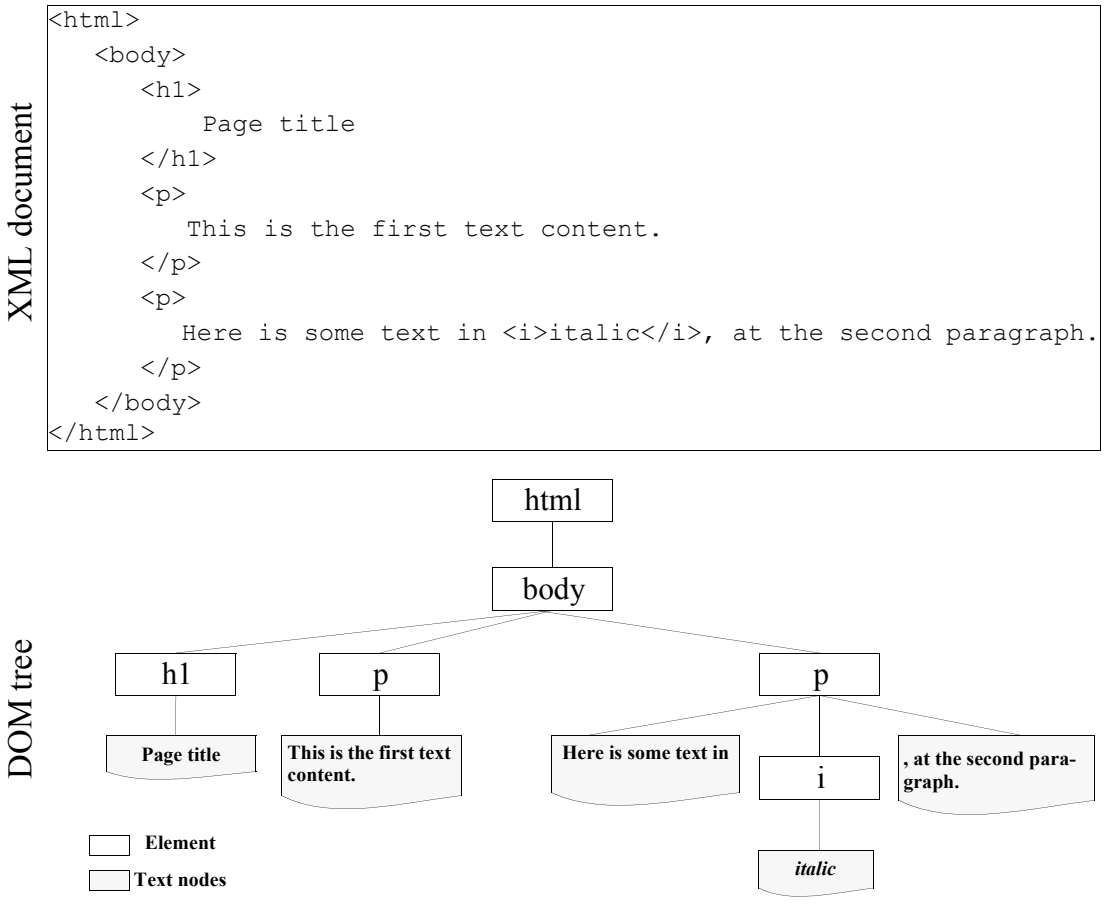


FIGURE 5.14: Example of an XML document with text nodes and DOM tree

relationships are registered independent of the physical location of the element occurrence, so all text under any *p* node is stored in the same spoke.

This approach is simple and straight-forward. However, it is not suitable for summarization purposes, because text nodes represent most of the XML data in many practical XML documents and the amount of space consumed by such an approach can be very expensive and, therefore, not affordable for query estimation. In the next section, we introduce some techniques to summarize and compress the text contents inside text spokes.

5.5.2 EXsum's Text Content Summarization Framework

In this section, we gradually introduce techniques to progressively improve the summarization of text values by compressing or rearranging the information in text spokes.

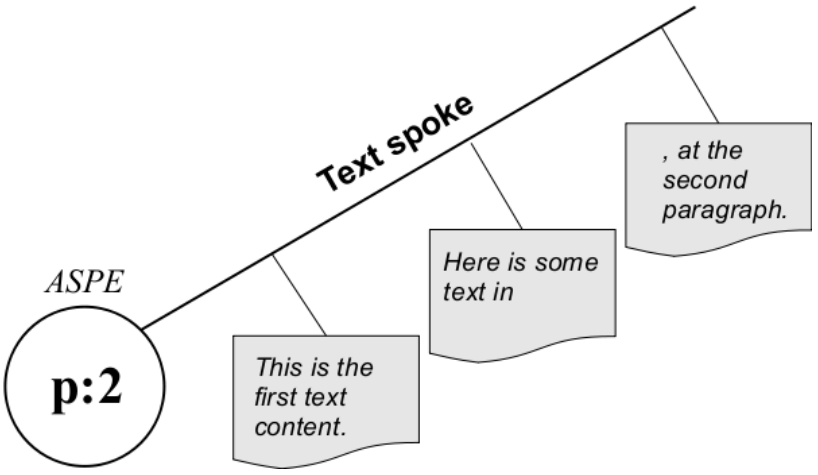


FIGURE 5.15: Text spoke of the p element in the example XHTML document

The EXsum framework for summarizing text values is flexible enough to give support to the estimation of certain kinds of predicates in a path expression. Among all XPath functions, our aim is to handle three types of predicate expressions:

1. predicates with simple (binary) comparisons (e.g., $>$, $<$, $=$, $\leq$, $\neq$, etc);
2. predicates with a *contains*() function, and
3. predicates with a limited kind of $ftcontains$ function (e.g., $[ftcontains\ 'x']$ or $[ftcontains\ 'x'\ \ ftand\ 'y']$).

As examples of path expressions of each one of these types, we may have $//i[text() =' italic']$, $//p[contains(text(),' italic')]$, and $//p[ftcontains\ 'italic']$ respectively. XPath function $text()$ retrieves all texts nodes under an element and evaluates each one against the comparison. We also support $text()$ function as a location step in path expressions as $//i/text()$.

The $ftcontains$ function is a Boolean function that, if it is evaluated to *true*, in predicate, its context node in the path expression is inserted in the query result. Otherwise, no node is returned. Accordingly, cardinality and selectivity measures should be applied (see later in this section). Although we provide support to a limited kind of $ftcontains$ function, we do not use any document-centric technique to support query estimation on XML documents (e.g., full-text search[6]). On the contrary, we use data-centric techniques. We assume (and expect) that text values

[6]For example, we cannot support: stemming information/summarization ("with stemming" clause), thesaurus ("FTThesuarus" clause), order ("ordered" and "distance" clauses), or scope ("same/different sentence/paragraph" clause).

in documents are short —at most, not so long as a half page of text—and in most of cases consisting of numerical values and nouns.

We do not claim that we present one summarization technique that is suitable for all kinds of predicates studied. Instead, the framework is able to construct any necessary structure (or set of structures), balancing compression and loss of information, to support predicates types. The novelty here is, however, the estimation method relating cardinality estimations of text values with the structural part of a path expression, which yields estimated measures on the cardinality of path expression and predicate selectivity.

5.5.2.1 The Issue of Data Type

As a common step to improve our text summary, we should consider the identification of data types in text spokes. XML schema [W3C08] provides an explicit data type information for values under an element/attribute. If we have XML schema, we derive data type information for each text spoke in ASPE nodes and drive the suitable compression technique. In the absence of schema information, we assume the existence of two functions: $isNumber()$ and $isString()$, which, applied to the values of a text spoke, give us the corresponding basic data type, whether numeric or not.

Different data types require different summarization methods. For example, histograms are useful for numeric data, whereas q-grams are suitable for text strings. Therefore, we do not claim to propose a general solution for all possible data types. Rather, we build a framework in which one can use the most suitable summarization method(s) to answer a given query workload, in a tailored way.

5.5.2.2 The Three-step Summarization

We now present a three-step summarization process which one can follow completely or partially. The result of each step is consistent, in the sense that an implementation can go only to a specific step, apply the summarization technique(s) suitable for the step, and then not go further to other steps at all. It is the responsibility of the system administrator to configure the EXsum framework to compute the necessary summarization structure(s).

Our value summarization framework is a compound of three phases. The first phase collects all the values under a specific element/attribute name applying

the respective data type functions and creating the so-called frequency vector. The frequency vector captures for each distinct value the corresponding number of occurrences (frequency). The second phase is optional and normally applied to strings. In this phase, the strings are tokenized where a token can mean a q-gram, a word, or any substring of arbitrary length. The tokenization is thus implementation-dependent. One can tailor the building of tokens according to an expected query workload. For example, if it is known that most queries search words in an XML document, tokens can be constructed accordingly, i.e., a token is any set of characters between two blank spaces. The third phase applies a suitable compression technique. For example, for numeric data, we can apply histograms.

Step 1: Create Frequency Vectors. The first enhancement is to eliminate repeated occurrences of the same text under an ASPE spoke by creating frequency vectors. This is considered to be the basic step towards a good summarization methodology. In this approach, instead of maintaining a plain list of text contents, we would have a vector with one entry for each distinct text occurrence and the number of occurrences (frequency) of the associated text set. In this case, every time a text is being added to the summary, we must first see if it is already present inside the desired spoke and, in the affirmative case, simply increment the associated counter. Otherwise, a new entry containing the text would be added to the vector.

Frequency vectors are useful to support any predicates handled by EXsum. Despite that, this technique itself does not provide a significant summarization improvement, since repeated occurrences of full text contents are somewhat rare in the majority of practical XML documents. The exception are element content or attribute values with a restricted domain, like the boolean set ($true$ or $false$) or values inside an enumeration (e.g., $male$, $female$). In other words, the frequency vector may be large.

However, we can gather at least two summary information from frequency vectors. To favor storage space to accommodate the summary, we can strip (and store for the spoke) only the number of entries in the vector (i.e., the number of distinct values) and the total frequency (i.e., sum of frequencies). Assuming uniform distribution in text values, these two pieces of information can support the estimation of predicate types 1 and 3. In fact, this information is always captured in addition to the application of any compression technique. The reason behind this is to support queries involving $text()$ function in path expressions (as a location step). Another compression technique is to store the n most frequent entries in the vector and make the uniform distribution assumption for the rest (storing, for that part,

only the number of distinct values and the total frequency). In this case, value n is determined by a tuning parameter.

Another possible task in this step is to make a statistical study on the frequency vector to obtain statistical measures such as variance, standard deviation, mean, and skewness. This information can drive the application of suitable compression techniques in Step 3, thus making them a parametric technique[7].

Step 2: Break into Tokens. Since occurrences of full text blocks tend to be unique inside a general XML document, we try to break the blocks of text in less representative information, having, therefore, a more restricted set of values. The natural way of doing that in text blocks is by splitting into tokens. Although the meaning of token varies a lot (it has several possible definitions), let us assume, for a better discussion, that a token corresponds to a word (i.e., a termed sequence of characters between two blank spaces in the text). When we take many text occurrences and break them into token occurrences, the amount of repeated values raises significantly. When creating frequency vectors over a set of tokens, we have, therefore, a much more compact structure, since repeated occurrences can be eliminated.

While providing an efficient compression of data, this method (token-based frequency vector) introduces a big loss of information, since the composition of words to form the text data is lost, and the resulting data looses much of its significance. In Figure 5.16, we illustrate the result of applying token-based frequency vectors (word splitting) to the ASPE node of p in Figure 5.15. Due to this loss, we cannot estimate type 1 predicates.

However, by applying compression techniques such as histograms or q-grams on the token-based vector, we can approximate estimations for predicate types 2 and 3. How good or bad the estimation results are with such techniques is an issue which should be empirically evaluated. In any case, if storage space is a concern, we can also apply techniques pointed out in Step 1 using the uniform distribution assumption for estimation.

Step 3: Apply Compression Methods. Whatever frequency vector we have, we can always apply compression techniques. The support of a predicate type depends on the frequency vector type (text-based or token-based). The application of

[7]Parametric statistical techniques depend on a prior knowledge of the distribution of a set to be applied. Non-parametric techniques are applied ignoring such a distribution. For example, histograms can be considered a non-parametric technique.

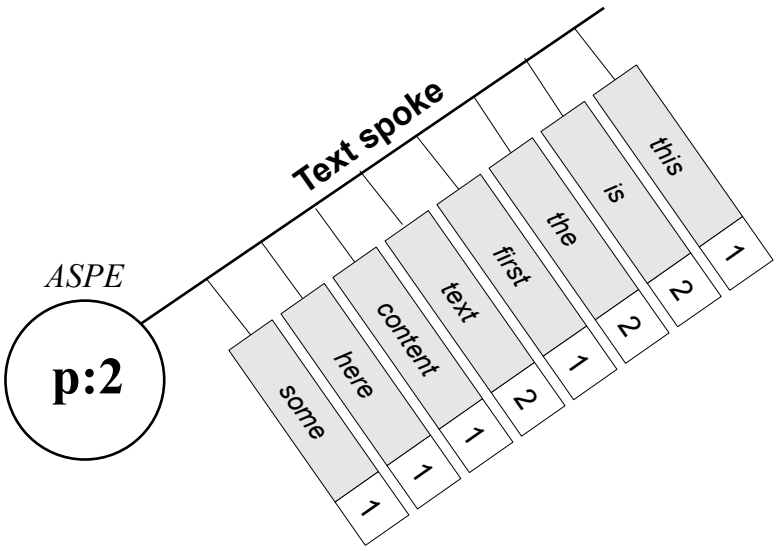


FIGURE 5.16: Text spoke of the p element after applying some summarization techniques

compression technique has an influence on the quality of the estimations. Although there are many techniques published in the literature [Ioa03, CGG04, DJL91], we are concerned here with histograms. There are also several types of histograms. For example, we may have Equi-height , Biased and End-biased histograms. The two first types provide support to predicates of type 1, while End-biased histograms are suitable for equality predicates (=) and Boolean predicates ($ftcontains$ function).

Another important part of this step, if a token-based frequency vector is used, is to remove stop words, which are words that occur very often in texts in general. They are considered to be prepositions, articles, pronouns and so on, as well as some common verbs like "to be" and "to have". Due to their high frequency of use, these words may be considered by a compression method to be very important words in the text, but they have actually very little significance for the information itself. If we ignore such words when constructing the word frequency vector and the histogram, we may achieve a higher compression and avoid "polluting" the histogram with insignificant information.

5.6 Estimation Procedures

EXsum was designed to support XML query optimization with the use of XPath and/or XQuery languages. The estimation process is part of the optimizer, in which cost information is estimated for a QEP operator. For example, we can, by

using EXsum, estimate the cost of Structural Join (STJ) [AKJP+02] or Holistic Twig Join (HTJ) [BKS02] operators in a query plan. Obviously, we are aware that a cost model is also necessary [WH09] in order to calculate the total cost of a QEP. We are not, however, concerned with the cost model, but with estimation mechanism and procedures provided by EXsum, which can be used in a full XML query optimizer process.

Basically, two kinds of information can be estimated with EXsum: path cardinality and path selectivity. The former corresponds to the number of document nodes resulting from the processing of a path expression. These nodes are given back to the user as result, with their respective subtrees. The latter comes to play when predicates are present in path expressions and it is also used in the cost model of an optimizer. We study both in this section, by using path expressions which are the base for the two main XML query languages.

As studied in Section 2.2.1, a path expression has three components. For example, a path expression such as $/x/y//z$ has three steps: $/x$, $/y$ and $//z$. For each step, context nodes are "document root", x, and y, respectively. Axes are child (/) and descendant(//). Node tests are respectively: x, y and z. The final result reveals the number of z nodes in the document satisfying this expression. Such a path expression can be operated by QEPs with a set of STJ operators, which directly mirrors the semantic of the expression itself, or with a QEP with one (or more) HTJ operators, which allows a "multi-way" join. The scope of this thesis abstracts the differences between QEP approaches, and we focus only on the information that can be provided to generate such plans.

5.6.1 Underlying Mechanism of EXsum's Estimation

The EXsum estimation mechanism of a path expression is executed step by step. It follows each location step in an expression, probes the ASPE node related to the context node, inspects the spoke related to the axis, and accesses the node test in the spoke, obtaining the cardinality estimation from the OC counter for the step (occ). This makes the EXsum estimation process heavily step-based, and understanding the process of a single step estimation is the key when figuring out how it deals with full path expressions.

The mechanism takes the three step components as arguments and returns the estimated cardinality of the node test in the result. To help in this process, we introduce auxiliary information, which can be considered as the set of all "outside"

information needed by the step estimation. This information may include recursion levels, path descriptions, and instructions for the estimation mechanism.

To understand the general estimation process, we take the example document tree given in Figure 2.1(c), as well as its correspondent EXsum sketch in Figure 5.5, and detail the estimation of an example query: $/a/c//s$. Since the first location step has a simple child axis and a is the root of the document, we access ASPE(a) and return $occ(/a)$ which is obtained directly from the number of occurrences of a. In this case, the value of 1 is returned as the cardinality of this step. Then, for the next step $/c$, we probe the child spoke of ASPE(a) for a c and find in its OC counter a value of 2 ($occ(/c)$=2), which is the cardinality for this step. Finally, we estimate the step $//s$. We proceed to ASPE(c) and probe its descendant spoke for an s. At this point, we get $occ(//s)$=7 from the OC counter of s and the process returns 7 as the cardinality of the path expression.

Note that, when a location step is estimated, its related ASPE node (and only such ASPE node) has to be loaded into memory. This feature considerably reduces the EXsum's memory footprint to estimate path expressions. In fact, in the worst case, the number of ASPE nodes to be loaded into memory is bounded by the number of location steps in the expression. In other words, we do not need to load the entire EXsum structure into memory to estimate a simple location step or even multiple-step expressions. This feature is kept for all estimation cases, whether on recursion-free or recursive path expressions.

Although a generic mechanism exists, many specific situations have to be handled, such as different characteristics of each axis, recursion levels, methods to improve accuracy, and special occasions such as root and leaf nodes. Moreover, we have to cope with cases in which EXsum delivers accurate cardinalities and cases in which an approximation has to take place. We study these issues in the following sections.

5.6.2 Cases with Guaranteed Accuracy and Special Cases

The construction principle of EXsum exactly covers two-step path expressions containing *child*, *descendant*, *parent*, and *ancestor* axes. As an important property, the element-centered summarization, therefore, delivers accurate cardinalities for them, when the evaluation starts from the root or an unique element name.

5.6.2.1 The Special Case of the First Step

The first step of an XPath expression generates a special condition in the step estimation process, since in this case we do not have an explicit context node, and all searches start from the root node. Therefore, only downward-oriented axes (/and //) are possible. If $//x$ is the first location step, then $occ(x)$ directly delivers the cardinality of $//x$, i.e., the number of document nodes having element name x. The same information can be derived by accessing the ASPE of the root element and retrieving the OC in the descendant spoke of x. Path expression $/x$ refers to the root element of a document. When accessing ASPE(x), we have to check whether its parent spoke is empty or not. If a parent is found, $occ(/x)$ is necessarily 0, otherwise it must be 1. As an example evaluated on the document of Figure 2.1(c), $//p$ and $/p$ deliver cardinalities 17 and 0, respectively. The other types of axes hardly make sense with respect to the root node and can, therefore, be neglected.

5.6.2.2 Unique Element Names

Another special case occurs when the end step of an arbitrary long path expression refers to a unique element name z. No matter what axis references occur in the path expression, we immediately inspect ASPE(z) and, after having verified that the entire path expression matches the path synopsis (which means the path actually exists), deliver $occ(z)$ as the accurate cardinality information.

For example, $/a/t/s/p/u$, $//s/p/u$ or $//t//p/u$ can be evaluated in this way and all deliver (see Figure 2.1) cardinality 3. Note that the existence of unique element names, to be verified using the path synopsis, is most valuable for cardinality estimation. When referenced in some of the intermediate location steps, it can be used to begin the estimation in the middle starting with precise cardinality information. Assume some subtrees containing the element name p are appended to the u nodes in the document of Figure 2.1; then the estimation of $//t//s//u//p$ would begin at ASPE(u) and return (for this example) accurate cardinality information.

5.6.3 Methods to Improve Accuracy

EXsum delivers accurate cardinality results for all path expressions on homonym-free documents and for path expressions with one and two location steps on recursion-free document paths. We believe that these cases, where the EXsum

TABLE 5.1: Application of estimation procedures in axis relationships.

Procedure name	Axes			
	Child	Parent	Descendant	Ancestor
Interpolation	Yes	Yes	Yes	Yes
DPC division	Yes	No	Yes	No
Total Frequency Division	Yes	Yes	Yes	Yes
Last Step Cardinality Division	Yes	Yes	Yes	Yes

structure reflects the document structure, cover the lion's share of practically all relevant estimation requests. For n-step path expressions ($n > 2$), however, EXsum cannot always guarantee accurate estimation results. The structure of ASPE nodes does not capture the complete set of root-to-leaf paths in the document. Instead, it keeps axis relationships between pairs of element names and represents their distribution on the basis of element names.

Consider a three-step path expression $//c/s/p$ addressing the document in Figure 2.1a. For the first two location steps ($//c/s$), we follow the child spoke of ASPE(c) and find that s exists for this axis and has cardinality 4. To evaluate the subsequent location step ($/p$), we have to access ASPE(s) and follow the child spoke. Only if the value of s derived from //c/s, i.e., $occ(//c/s)$, is equal to the total frequency of s delivered by ASPE(s), we know that all s elements of the document are children of c (under $//c$). Hence, we can continue with accurate cardinality determination for $//c/s/p$. Applied to the document in Figure 2.1(c), $occ(//c/s) = 4$ and ASPE(s) $= 7$, which means that three s elements are not reachable by the paths of $//c/s$.

We now introduce some techniques to compensate the loss of accuracy in these cases, and, consequently, improve the estimation results. These estimation procedures are summarized in Table 5.1 with respect to their application in axes of path expressions. Without loss of generality, we detail these procedures and motivate them with examples of non-recursive queries (i.e., queries whose RL is always 0) in the document in Figure 2.1(c).

While the interpolation method is generic enough to be applied in all types of query—value predicates included—Previous Step Division and Total Frequency Division methods are suitable to estimate value predicate expressions. The DPC-based method is oriented to produce estimation results for queries encompassing only structure [AMFHS09]. Nevertheless, in our experimental study (see Chapter 6), we test these methods, when applicable, against all query types to quantify their degree of suitability for each type. Therefore, we will have a clear idea whether using a generic method suffices or whether a specialized method should come into play.

5.6.3.1 Interpolation

In this estimation procedure, a path expression is decomposed into overlapping two-location-step fractions and a linear interpolation takes place to combine their results, assuming the uniform distribution of elements related to the "overlapped" node tests of these fractions.

To evaluate a path expression $//x/y//z$, two overlapping two-location-step fractions are considered: $//x/y$ and $y//z$. For the partial expressions $//x/y$ and $y//z$, we access ASPE(x) and ASPE(y) (whose values are equivalent to $occ(//x)$ and $occ(//y)$, respectively) and follow the ASPE spokes for the second location steps to obtain $occ(//x/y)$ and $occ(//y//z)$. Because not all y nodes of $//y//z$ find a matching partner in the y nodes of $//x/y$, we assume uniform element distribution for the y nodes to enable a straightforward combination of estimates for such partial expressions. By using the ratio $C1/C2$, we linearly interpolate the number of occurrences of the subsequent step $y//z$ to estimate $occ(//x/y//z)$. In this case, $C1$ is given by $occ(//x/y)$ and C2 by the total frequency of the element y; thus, $C1 \geq C2$ always holds. The result of step estimation is then given by:

$$\frac{C1}{C2} \times occ(y//z)$$

This interpolation could be applied step by step, such that we gain estimation heuristics for n-step path expressions. If more accurate information is present (e.g., by mining entire paths), it is used instead. Estimating $occ(//c/s/p)$ from the document in Figure 2.1a, we obtain $C1 = 4$ and $C2 = 7$, and the interpolated cardinality $C1/C2 * (occ(s/p)) = 4/7 * (13)$ (approx. 7.43), whereas the actual cardinality for the path expression $//c/s/p$ is 9.

5.6.3.2 DPC-based Estimation

The DPC-based estimation procedure relies on the assumption of uniform distribution of document paths leading to a location step. The idea is to count in how many different ways a node can be reached starting from the root node in the document (see Section 5.4.6), and divide the $occ(step)$ cardinality by this number. When using recursion, these distinct paths are also classified according to their recursion level.

Consider the path expression $/a/c/s/p$. The estimation of the step $/s$ ($occ(/s)$) is given as follows. In ASPE(c), we search the child spoke for an s and find the

OC and DPC counters. The estimation of $occ(/s) = OC/DPC$, gives us 4/1=4 as step estimation. This means that (coincidently) there is only one path leading to $c \rightarrow s$. For the next step $(/p)$, we find two distinct paths reaching $s \rightarrow p$: (a, c) and (a, c, t). Since the OC counter of p in the child spoke of ASPE(s) is 13, then $occ(/p) = 13/2 = 6.5$, which is the estimated cardinality of the expression.

The DPC is also available for descendant steps. Considering $/a/c/s//p$, the DPC for the step $s//p$ would also be 2 ($/a/c$ and $/a/c/t$), since it corresponds to the number of paths leading to s nodes which have at least one p in its subtree. Note that, for the same pair relationship $x \rightarrow y$, the DPC counter in the descendant spoke is always greater than, or equal to the one in the child spoke, since child steps are a subset of descendant ones.

5.6.3.3 Total Frequency Division

Another procedure is to get a step estimation by dividing the value in the OC counter of the node test by the total frequency of the context node. This is similar to the IC counter division method, except that it considers, for a step a/b all occurrences of a in the document—obtained directly from ASPE(a)—without considering any relationship to b nodes. The accuracy of this method is then, in the best case, equal to the one achieved by the IC counter division.

By applying this procedure to the expression $/a/c//t$, we have $occ(c//t) = 2$, and ASPE(c) delivers 2. The estimation gives us $\frac{occ(c//t)}{ASPE(c)} = 1$.

5.6.3.4 Previous Step Division

The last estimation procedure is the division by the cardinality of the previous step. This method uses two numbers: the $occ(currentstep)$ gathered from the OC counter in the ASPE spoke and the estimation result of the previous step in a expression. Dividing both numbers, the procedure yields the estimation for the current step. By iterating this calculation throughout all location steps of an expression, the estimation is produced.

This method introduces a strict dependency between the estimations of each step, forcing a sequential execution—that could be a disadvantage for certain document paths. On the other hand, it does not depend on any other information than the OC counter retrieved by the estimation mechanism, such as DPC, IC counters, or total frequencies.

For example, for estimating $//t/s/p$ we take three location steps $//t$, $/s$, and $/p$. For the first one, we get the estimation directly from ASPE(t), giving us 3. For the second step, we probe the child spoke of ASPE(t) for an s and take its OC counter. In this case, it is also 3. Then, $occ(/s) = 3/3 = 1$. For the last step $/p$, we take the OC counter in child spoke of ASPE(s) which is 13. Thus, $occ(/p) = 13/1 = 13$. Then, $occ(//t/s/p) = 13$.

5.6.4 A Look on Recursion

The ability to deal with recursion introduces an extra effort in the general process, because when looking for cardinality estimation, we must retrieve it at the right recursion level (RL). For recursion-free documents, RL for all elements in all ASPE spokes is always zero. Nevertheless, the correct RL choice for a location step in a path expression should be applied for both recursion-free and recursive documents.

When a certain spoke (axis relationship) is probed for a specific node test in a recursion-capable ASPE structure, it gives us a list of IC/OC counters for different RLs, for the required element in the spoke. Therefore, the estimation process needs to calculate the RL for the location step being analyzed, get the corresponding IC/OC counter, and apply one of the estimation procedures studied so far. To calculate the location step's RL, we apply Definition 2.9 (see Section 2.3) in two different manners.

The first one is the *step recursion level*, which is calculated by counting the number of occurrences of the context node between the first location step and the location step right before the node test being currently processed. So, for example, if we have a path $/a/b/b/c/d$, and we want to estimate the step $/c$ (with context node b), we have to count how many occurrences of b exist in the path before this step. It yields a value of 2, which by Definition 2.9 produces an RL of 1.

The second approach is the *path recursion level*, which considers the recursion level of a specific step as being the highest level of recursion reached by any node test in the path expression before it. In this case, to estimate $/d$ (context node c) in the aforementioned expression, the recursion level is 1, which is the RL reached by b, the element that recurs the most in the expression. A more complex example is the expression $/a/c/b/c/b/c/d$. In this case, the estimation of location step $/d$ takes an RL=2, because c recurs the highest number of times.

Both approaches have to internally store additional context information. The first one needs the description of the full path being queried, whereas the second

one keeps track of the highest recursion level thus far. The *path recursion level*, however, introduces an exception to the estimation process. In the example path mentioned above, it is possible that c/d has no recursion in the document, which means all nodes are under an RL of 0, and there are no occurrences on the first level. This exception is generally caused when we are looking for an RL higher than the highest one for that path, and, to deal with it, we simply take the highest possible RL and get the cardinality for it. By definition, the *step recursion level* is, however, more compliant with path expression semantics of the XPath language. Accordingly, we consider the *step recursion level* to be the default approach.

As an example of the process of estimating the cardinality of a path expression with recursion, we consider the document in Figure 2.2(a), with recursive paths, and detail the estimation process for an example expression $/a/c/s/s/p$.

The step $/a$ follows the special condition of the first step, and recursion makes no sense here. Therefore, we just retrieve the value 1. For the step a/c, we have to follow the general recursion method and count occurrences of a in the preceding path. Since there is no previous node, the level would be 0, just like in any other second step of a path. Starting from the third step, c/s, it is already possible to have recursion, but this is not the case, since c did not occur yet in the path (there is only an a for now), so again the recursion level is 0. The step s/s, unlike how it may seem, has no recursion, because the recursion is only introduced after descending to repeated occurrences. In this step, we are about to descend into a recursion, but we did not yet, and this can be confirmed by applying the method to count the recursion level, which would be 0 since there is no s in the preceding path ($/a/c$). At the step s/p, however, we will have recurred into the s node, with a level of 1 (one occurrence of s in $/a/c/s$).

Note that the results of each step estimation would actually depend on the method applied. However, the recursion does not necessarily affect the accuracy improvement method, and the process of distributing results would be the same, whether it uses recursion or not. Despite this, the methods can be modified to support recursion, and give a better result in such cases. One example would be to group the distinct paths in the DPC method by recursion level when computing a path occurrence.

5.6.5 Estimating Remaining Axes

Axes such as *preceding* (*sibling*) and *following* (*sibling*) are considered exotic and may hardly appear in real-world applications. In general, their estimation is

elusive, because these axes refer to relative positions (order) of node instances. Hence, the data structures needed would explore this order when collecting statistics for them and would not be maintainable. Indeed, nobody has ever tried to give estimates for these axes. Nevertheless, we only want to point out here that EXsum carries some information which could be used and would be helpful, at least for the upper document levels. Because the root (a) is the first node in document order, counting all relationships in ASPE(a) delivers the number of the following elements. When the expression */c/following-sibling::p* has to be estimated, we identify via ASPE(c) the parent of c and, in turn, figure out via the child spoke of ASPE(a) that there is no sibling p. Of course, we often need to apply some heuristics at lower levels. For example, expression */t/preceding-sibling::c* could be estimated by accessing the root ASPE(a) and finding in the child spoke that there is only a single t which has two c nodes as siblings. Because order information is not available, the number of c nodes in the role of the preceding/following sibling has to be guessed.

Chapter 6

Experimental Study

Be brave. Take risks. Nothing can substitute experience.
Paulo Coelho, Brazilian novelist, writer, lyricist, and political activist, b.1947

6.1 Introduction

In this chapter, we present our findings regarding the quantitative evaluation of our proposals. In addition, we comparatively analyze EXsum, LESS, and LWES against three summaries published in the literature: Markov Tables (MT), XSeed and Bloom Histogram (BH). All analyses are in regard to the three important criteria for the query optimization process. This means that in our experiments we investigate not only the accuracy of a summary, but also the storage needs and memory footprint, and building and access times.

We define the aim of each criteria throughout this chapter, but first we detail our set-up environment.

6.2 Setting up

We have implemented and incorporated our approaches and competing ones into the XDBMS XTC, a native XML database management system. All summaries have become part of the "Document Metadata" which is maintained by the Metadata Component of XTC. This means that for each document evaluated we have

attached the respective summaries to its metadata[1]. However, the results presented here regarding storage do not take into account the overhead of the underlying metadata structure, representing thus the net storage numbers for each summary.

6.2.1 Documents Considered

XML documents usually exhibit a high degree of redundancy in their structural part, i.e., they contain many paths having identical sequences of element/attribute names. To anticipate some characteristics of documents considered in practice, a well-known set of XML documents is listed in Table 6.1(a).

Table 6.1(b) depicts the structural characteristics of the considered documents. Column *#nodes* shows the total number of nodes in a document according to the DOM specification. Column *#E/A* shows the number of distinct element/attribute names. It indicates that only a few of them occur and documents typically have, therefore, a very repetitive structure. Column *max. depth* indicates the highest level that can be reached when traversing the document, while *avg. depth* shows the average number of levels in a root-to-leaf path. These last two columns give some hints on the variability of documents. For example, *swissprot* is quite a regular document, because its average depth is close to its maximum depth. In contrast, *treebank* is extremely irregular, an exotic outlier. For each document, columns *#homonyms (%PC)* and *#recursive PC (%PC)* contains the detailed numbers of homonyms path classes and recursive path classes, respectively. The %PC is the relative quantity of homonyms/recursive path classes in a PS. For example, the *dblp* document has 17.07% of homonyms in its PS and only 3.05% of its path classes are recursive, whereas the *xmark* document contains 5.48% and 19.7% of homonyms and recursive path classes, respectively. Appendix A studies in detail homonym distributions in each document considered.

We consider these documents in our comparative experiments of XML summarization structures, as shown later on in Section 6.3.

6.2.2 Test Framework

We created a set of tools to generate, execute, and collect results of XPath query workloads. We describe these tools in the following.

[1]The XTC Metadata Component has a underlying B-tree structure.

TABLE 6.1: Characteristics of documents considered.

(a) General characteristics

Doc. name	description	size (MB)	#nodes (inner/ text)
dblp	Comp.Sc. Index	330.0	9,070,558 / 8,345,289
nasa	Astron. data	25.8	532,96 / 359,993
swissprot	Protein data	109.5	5,166,890 / 2,013,844
treebank	Wall Street J.	86.1	2,437,667 / 1,391,845
psd7003	Protein data	716	22,596,465 / 17,245,756
uniprot	Protein data	1,820	81,983,492 / 53,502,972
xmark	Synthetic data	100	2,048,180 / 1,173,733

(b) Structural characteristics

Doc. name	#E/A	max. depth	avg. depth	#path classes (PC)	#homonyms (%PC)	#recursive PC (%PC)
dblp	41	7	3.39	164	28 (17.07%)	5 (3,05%)
nasa	70	9	6.08	111	15 (13.52%)	2 (1.80%)
swissprot	100	6	4.07	264	6 (2.72%)	0 (0.0%)
treebank	251	37	8.44	338,749	171 (0.05%)	328,228 (96.89%)
psd7003	70	8	5.68	97	13 (13.40%)	0 (0.0%)
uniprot	89	7	4.53	160	18 (11.25%)	2 (1.25%)
xmark	77	13	6.33	548	30 (5.48%)	108 (19.7%)

The test framework[2] consists of two isolated applications developed to integrate with the XTC system. The first one is the *workload generator*, which is implemented inside the XTC server. This application performs a scan on a given document's HNS tree, generating the set of all possible rooted paths. Then, it processes the paths on the set, using string manipulation, to generate *simplechild*, *descendant*, *ancestor*, *parent*, *negative* (i.e., paths which do not exist), and predicate XPath queries. These queries are written to workload files, simple text files with a distinct XPath query on each line, according to the types mentioned before. The user can also pass a list of XML documents, to limit the processing only to those files, instead of going through all the folders in the test directory.

The other application is called *workload processor*, and it works in a standalone fashion, making use of the XTC driver to connect to a running process of the XTC server. It processes a file system directory containing different folders filled with workload files. These folders are named according to the document name in which

[2]The test framework had its initial implementation made by Felipe Mobus. Caetano Sauer continuously led it to completion and enriched it with nice features that facilitated the tests. Most of the explanation on the test framework was drawn from Caetano Sauer's Research Report on his one-year internship at the University of Kaiserslautern, in the DBIS group.

the workload files inside it should be executed. Besides the working directory, the program also gets a list of summary structures to compare, optionally with estimation parameters. The Figure 6.1 illustrates an example of a test environment to be processed by the *workload processor*.

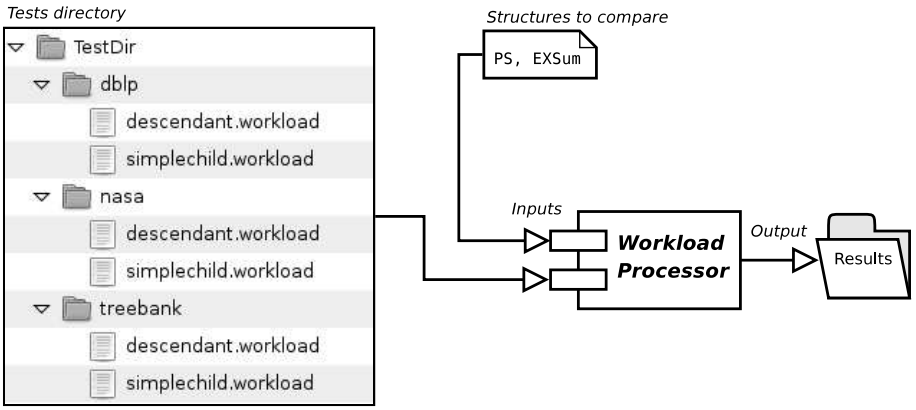


FIGURE 6.1: Illustration of a workload processor execution.

In the example of Figure 6.1, the *workload processor* will enter the working directory, named *TestDir*, and then the sub-directories *treebank*, *dblp*, and *nasa*. These are also names of the documents on which the queries will be executed, followed by the usual *.xml* suffix. Inside each sub-directory, every file with the *workload* extension will have the queries inside it executed against the *HNS* and *EXsum* summary structures. The results will also be generated for each of the workload files, listing cardinalities, and time measurements obtained from each structure.

The *workload processor* was designed with a few important factors in mind. First of all, the test on summary structures may have a very high time consumption depending on the query and document characteristics, so the application can be interrupted at any time, fully saving the state of the test execution for a further resumption. This mechanism was implemented using a multi-threaded approach, in which one thread makes the connection to the XTC server and executes the workloads, while another controls its execution and receives the user's input, to interrupt the execution when the corresponding command is given.

Another important factor is that we usually want to compare a certain summary structure against the accurate result of each query, so when processing the list of summary structures to be tested, the application considers the first one as being the reference structure. A special keyword *real* can be used to execute the query directly at the XQuery interface of the XTC system and to retrieve the cardinalities using the XQuery's *count()* function, but this is usually very time demanding, specially for heavy documents. The solution is, therefore, to use the HNS as the reference structure, since all results are accurate when using it.

However, for the cases of the parent and ancestor queries and queries with value predicates, however, one would have to use the actual query execution to obtain the cardinalities, since HNS lacks support for such queries.

The design of the *workload processor* application also considers that the documents may not yet be loaded into the XTC system and the summary structures may not be stored for them. To cope with this situation, the application makes use of the connection with the XTC server to test if all the documents provided are stored, and loading them if they are not. This check considers, however, only the name of the file, and for the automatic loading to work, the program must receive the list of documents to process as arguments, and they must include the file system path. For example, the following call of the *workload processor* would compare HNS against EXsum, processing only the documents *nasa.xml* and *treebank.xml*:

```
WorkloadProcessor
      /path/to/TestDir
      /path/to/nasa.xml,/path/to/treebank.xml
      hns,exsum
```

In this case, the documents *nasa.xml* and *treebank.xml* will be checked for existence in the XTC server, and the path given in the arguments would be used to locate and load them in case they do not exist. The *runXmlStats*[3] command would also be executed for HNS and EXSum structures if one of them is not stored in any of the documents.

6.2.3 Query Workload

Using the *workload generator* and for each document listed in Table 6.1(a), we have produced a query workload with respect to the following types of queries: simplechild, descendant, parent, and ancestor queries. Simplechild queries encompass only child (/) axes. The amount of simplechild queries produced for each document, except for *treebank*, covers all possible paths in the document. Descendant, parent and ancestor queries have been randomized.

[3]We have created four commands in the XTC system to collect and generate summaries (*runXmlStats*), view a summary created (*viewXmlStats*), delete an existing summary (*deleteXmlStats*), and list the stored summaries (*listXmlStats*). These commands compound the estimation interface of the XTC. Additionally, there are two other commands, *estimateExpression* and *estimateStep* which are designed to be integrated to the query optimizer.

For *treebank*, due to its huge number of path classes, we randomized the entire workload. Additionally, we have generated queries containing structural and value predicates. For queries with value predicates, we directed the generation of workload to a biased way. That is, we have generated value predicates with a ratio of 60:40. This means that we generated 60% of the predicates among the most frequent entries in the frequency vector and randomized the 40% remaining among the least frequent entries.

6.2.4 Configuring Parameters

For comparing EXsum, LWES, and LESS against the competing approaches: XSeed, Markov Table (MT), and Bloom Histogram (BH), we have chosen the following settings.

For Markov Tables, we have evaluated two values of the pruning parameter: 2 (MT2) and 3 (MT3). We have used the MT compression method called *suffix-star*. Additionally, we have set the memory budget (in number of MT entries) for MT2 and MT3, of 90 and 30, respectively.

For the XSeed kernel, we have set the search pruning parameter to 100 for *treebank*, 50 for *dblp*, and 20 for the other documents.

For LWES, End-biased histograms were continuously applied to all levels of the summary structure.

BH has been tested with Bloom filters of 125 bytes (1,000 bits) for all buckets using 10 hash functions, resulting in a false positive rate of approximately 10^{-6} in the majority of the cases. The number of buckets for BH has been set to 1/4 of the entries of the path-count table for all documents except *treebank*, which was set to ten[4].

6.2.5 Hardware and Software Environment for Testing

Before introducing the test results generated by the *workload processor*, we will first describe the test environment, including hardware, software, and operating system characteristics.

[4]The reason to limit the number of BH buckets for *treebank* is that its building algorithm has a quadratic complexity in the number of path classes — and *treebank* has more than 600,000 path classes. We have tested using 1/4 of the path-count table but BH building could not finish, even with a fewer number of buckets. Therefore, as we could only build BH with 10 buckets for *treebank*, we have used this configuration.

The execution of the test workloads was made on a personal laptop computer, with an Intel Core 2 Duo processor chip running at 2.2 GHz and 3 GB of DDR-2 RAM memory. The GNU/Linux operating system, with kernel version 2.6.27, was used together with the Sun implementation of the Java 6 virtual machine, at the update version 10. The XTC server process was running on the same machine.

6.3 Empirical Evaluation

In this section, we apply the criteria of sizing, timing, and estimation quality to our summaries, as well as the competing ones. Accordingly, we will show the results of this evaluation.

6.3.1 Sizing Analysis

Our sizing analysis takes into account the storage space for a summary on disk as well as the memory footprint needed to run cardinality estimations.

The storage amount listed in Table 6.2 characterizes the net size of a summary and only includes the bytes necessary to store the summary on disk. The gross size may be influenced by a specific implementation and confuse a direct comparison[5].

In Tables 6.2 and 6.3, we have shown two columns for EXsum. The reason behind this is that, as DPC is optional and used only if the DPC-based estimation procedure is applied, we assume the general format of EXsum (depicted in Figure 5.6) in column "Other", and in column "DPC" we take into account the impact of the DPC count in the EXsum summary size.

Table 6.2: Storage size (in KBytes)

	EXsum						
Document	DPC	Other	LWES	XSeed	BH	MT2	MT3
dblp	7	6	2	7	41	0.41	0.49
nasa	9	9	2	7	27	0.38	0.40
swissprot	14	13	4	15	65	0.37	0.38
treebank	168	158	3,339	160	3	0.39	0.36
pds7003	7	7	2	6	24	0.36	0.36
uniprot	10	10	3	9	40	0.37	0.40
xmark	13	12	7	8	135	0.37	0.34

[5]Recall that all summaries have been incorporated into XTC's metadata.

MT is the most compact summary outperforming XSeed, BH, EXsum, and LWES. However, as seen in Section 3.2, MT does not support queries with descendant axes and predicates. Among the summaries supporting a broader range of query types, LWES presents, in the majority of the cases, the most compact storage. However, LWES does not scale to highly recursive documents (*treebank*).

Therefore, overall, we put EXsum and XSeed in the same place as the two most compact summaries.

Table 6.3 compares the memory footprints for various estimation situations on all summaries/documents. The memory footprint verification is justified in data-centric scenarios of XML document processing. In document-centric processing, a summary is completely loaded to main memory when the document is first accessed. Then, one can argue that summaries having sizes smaller than a threshold (e.g., $\leq$ 200KB) can be kept in the processor cache. Under this argument, the majority of the approaches is suitable for a document-centric XML processing. Data-centric processing, in turn, requires that only the necessary memory footprint is used to process an XML document.

Table 6.3: Memory footprint (in KBytes)

	EXsum						
Document	DPC	Other	LWES	XSeed	BH	MT2	MT3
# location steps = ceil(average depth)							
dblp	0.65	0.62	2	7	41	0.41	0.49
nasa	0.91	0.84	2	7	27	0.38	0.40
swissprot	0.68	0.65	4	15	65	0.37	0.38
treebank	6.03	5.66	3,339	160	3	0.39	0.36
pds7003	0.60	0.57	2	6	24	0.36	0.36
uniprot	0.56	0.53	3	9	40	0.37	0.40
xmark	1.16	1.11	7	8	135	0.37	0.34
# location steps = maximum depth							
dblp	1.13	1.08	2	7	41	0.41	0.49
nasa	1.17	1.11	2	7	27	0.38	0.40
swissprot	0.82	0.78	4	15	65	0.37	0.38
treebank	24.80	23.28	3,339	160	3	0.39	0.36
pds7003	0.79	0.76	2	6	24	0.36	0.36
uniprot	0.79	0.75	3	9	40	0.37	0.40
xmark	2.16	2.05	7	8	135	0.37	0.34

We have computed the average memory size needed to estimate cardinalities for queries with two characteristics: queries whose number of location steps, whatever axes included, are equal to the document's average depth (rounded up to next integer value), and queries whose number of location steps is equal to the maximum

document depth. These cases enable us to infer whether a summary needs to be entirely or only partially loaded into memory, i.e., whether or not the memory consumption of a summary is bounded to the number of location steps in a query during the estimation. Except for EXsum, all other methods require the entire structure in memory to perform cardinality estimations. EXsum, in contrast, only loads the referenced ASPE nodes, making it the summary with the lowest memory footprint and related disk IO. Thus, although the use of EXsum implies higher storage space consumption, the estimation process may compensate it by lowering memory use and IO overhead.

6.3.2 Timing Analysis

We have computed two kinds of time measures: building time and estimation time. Building time is computed when the summary is built. It is normally accomplished on one of two occasions: loading the document into the database or scanning a stored document. The results refer to the latter.

For Exsum, the difference between "DPC" and "Other" timing, whether building or estimation, is negligible. Thus, we have reported, in tables 6.4 and 6.5, just one result depicted as $EXsum$.

Hence, building time is the time needed to scan the document, build the summary in memory, and serialize it to disk (i.e., write the summary to disk). Table 6.4 illustrates the comparative results of the building process, which are, of course, dominated by the scan time that, in turn, is directly proportional to the number of document nodes (document size). Building algorithms require just a subsecond range, from the total time, to be run. Therefore, these timings confirm their scalability even for highly recursive documents such as *treebank*.

However, the BH method is an exception. The related construction process is directly dependent on the number of path classes in the document (i.e., the number of entries in the path-count table) and on the number of buckets and this process has a quadratic time complexity on the number of path classes. Therefore, for deeply structured documents (e.g., *treebank*), BH building time tends to be high—in our experiments. It took almost 4 hours.

Moderate structural recursion as a factor that could hit the building time, has a negligible impact on constructing XML summaries. Regarding the (huge) document sizes, these numbers seem to be acceptable in practical database scenarios.

For example, the worst time verified (EXsum for a non-recursive 1GB-*uniprot* document) corresponds to 18.3 minutes, whereas the worst case for *treebank* (LWES) corresponds to 2.3 minutes.

TABLE 6.4: Building times (in sec)

Document	EXsum	LWES	XSeed	BH	MT2	MT3
dblp	121.81	86.31	135.51	217.10	85.99	85.97
nasa	10.35	5.47	5.43	11.48	5.19	5.20
swissprot	63.67	37.65	53.73	102.77	37.45	37.71
treebank	59.83	138.79	42.88	13,458.0	45.96	45.82
pds7003	941.95	653.53	715.71	1,393.82	653.56	653.52
uniprot	1,096.75	486.74	779.35	1,089.96	486.60	486.62
xmark	51.07	25.07	55.61	62.05	25.06	25.06

Estimation time refers to the time needed to estimate a query. That is, the time that the estimation process needs to get the query expression, access the summary (possibly, more than once), and report the result to the optimizer. The time considered here is an arithmetic average of the times required by every query in the workload. Table 6.5 presents the estimation times classified by query types.

EXsum delivers the superior results for all document and query types; hence, its impact on the overall optimization process is very low. XSeed and LWES have prohibitive times for queries with descendant axes in deeply structure documents, whereas, for the other documents, their times are acceptable.

The problem with LWES and XSeed is the traversal of their structures when they have to be used to estimate descendant axes for highly recursive or deeply-structured documents. Although the XSeed estimation procedures make a trade-off between estimation time and accuracy by setting a tuning parameter—thereby producing fast results at expenses of low estimation quality—LWES seems to have a costly search in its parent pointers to qualify nodes in estimating descendant axes.

6.3.3 Estimation Quality

Estimation quality refers to the accuracy of a summary, or the ability to provide cardinality estimations near the actual values and is expressed by an error metric. In our case, we used the *Normalized Root Mean Square Error (NRMSE)* which is defined by the formula: $\sqrt{\sum_{i=1}^{n}(e_i - a_i)^2}/(\sum_{i=1}^{n}(a_i)/n)$, where n is the number of queries in the workload, e is the estimated result size and a is the actual result

TABLE 6.5: Estimation times (in msec)

Document	EXsum	LWES	XSeed	BH	MT2	MT3
Simple child queries						
dblp	2.85	3.18	13.21	2.97	4.57	3.84
nasa	3.55	3.30	11.60	3.05	3.93	3.59
swissprot	2.93	2.80	17.83	3.30	3.62	3.85
treebank	3.72	5.15	7,413	3.87	4.66	3.89
pds7003	3.86	3.15	3.28	2.95	3.79	4.79
uniprot	4.24	5.23	14.76	7.86	7.92	5.17
xmark	3.81	4.56	3.78	3.08	3.83	3.67

Document	EXsum	LWES	XSeed
Descendant queries			
dblp	3.18	3.12	26.12
nasa	2.75	2.93	7.19
swissprot	2.95	3.20	20.00
treebank	3.21	27,391.0	8,588.0
pds7003	4.04	3.53	7.96
uniprot	3.62	4.34	9.06
xmark	4.12	5.22	4.45
Queries with predicates			
dblp	4.92	N/A	7.63
nasa	5.60	N/A	10.20
swissprot	11.80	N/A	24.84
treebank	7.29	N/A	6,705
pds7003	13.86	N/A	15.75
uniprot	7.48	N/A	44.84
xmark	5.46	N/A	6.01

Document	EXsum	LWES
Parent and ancestor queries		
dblp	4.39	7.00
nasa	4.42	4.50
swissprot	5.48	7.34
treebank	5.09	10.88
pds7003	4.00	3.34
uniprot	4.00	38.67
xmark	9.64	70.08

N/A: Not Applicable

size. NRMSE measures the average error per unit of the accurate result[6]. In general, the less error the metric presents, the better the estimation is and the more accurate the summary is.

Table 6.6 and Figure 6.2 show estimation quality results for only simplechild queries and Table 6.7 and Figure 6.3 deal with descendant ones. A combined estimation error for both types of query is given in Figure 6.4 and, in percent values, in Table 6.8.

MT and BH present the worst results for simplechild queries. Queries whose number of location steps largely exceed the path lengths summarized in MT tend

[6]We are aware that there are several other error metrics. However, by definition of the NRMSE metric, its expresses a suitable understanding of estimation quality.

TABLE 6.6: NRMSE error for queries with child axes

Document	DPC	Interpolation	LWES	XSeed	BH	MT2	MT3
dblp	0.163	0.011	0.170	0.001	1.416	0.076	0.284
nasa	0.377	0.043	0.044	0.044	0.779	2.482	0.640
swissprot	0.00	0.00	0.133	0.001	1.523	2.555	0,649
treebank	16.356	97.445	0.935	8.541	16.239	8.164	13.665
pds7003	0.00	0.00	0.00	0.00	0.205	1.119	0.615
uniprot	2.379	0.316	0.183	0.331	0.198	3.194	0.606
xmark	2.154	4.101	0.163	2.443	0.866	2.443	1.606

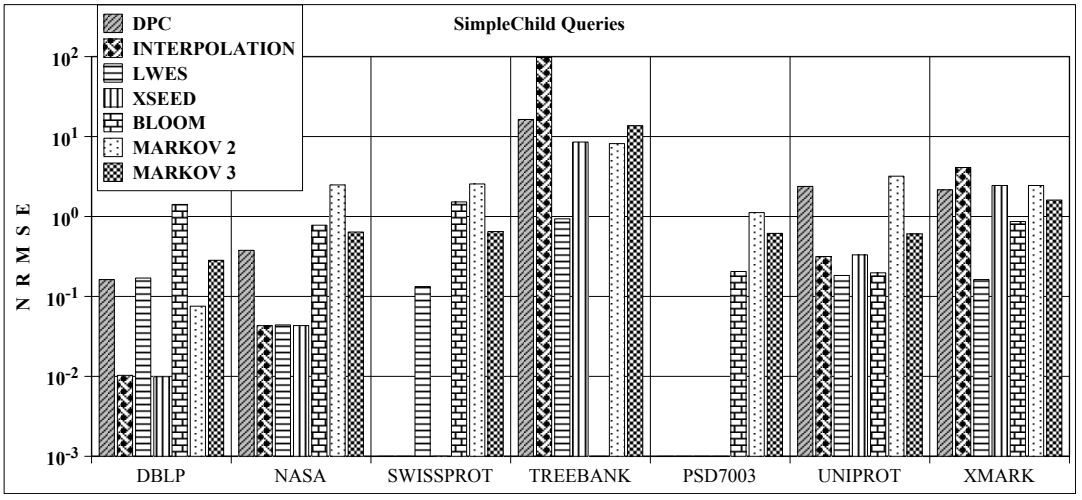


FIGURE 6.2: Comparative accuracy: child

to have a lower estimation quality, because the behavior of the Markov Model in MT is dependent on the pruning parameter. BH, in turn, presents a problem, in a BH lookup, when more than one Bloom filters report *true*. In this case, BH averages bucket frequencies which may produce bad results if two (or more) buckets have strongly varying frequencies.

None of the compared methods provides acceptable results for *treebank*[7], which means that highly recursive documents remain a challenge for summarization. On the other hand, for non-recursive documents and documents containing a lower degree of recursion, XSeed, EXsum, and LWES produce accurate estimations. In these cases, they reach at most an NRMSE error of 30% (see Table 6.8 and Figure 6.4).

Queries with descendant axes have presented the best results. Most of them with a NRMSE=0 or near to zero. This means that this kind of axis is well-represented in all summaries compared.

[7]This finding also applies to other query types. Therefore, we do not highlight it any further.

TABLE 6.7: NRMSE error for queries with descendant axes

Document	DPC	Interpolation	LWES	XSeed
dblp	0.003	0.005	0.012	0.007
nasa	0.000	0.000	0.008	0.002
swissprot	0.000	0.000	0.00	0.001
treebank	4.061	2.941	2.480	2.953
pds7003	0.000	0.000	0.000	0.000
uniprot	0.000	0.000	0.000	0.001
xmark	0.000	0.000	0.009	1.669

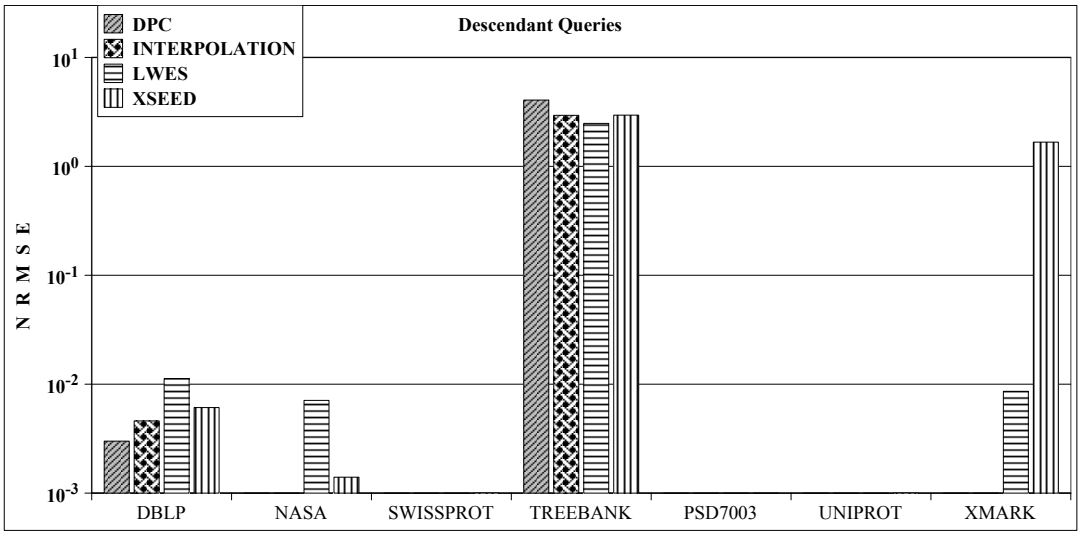


FIGURE 6.3: Comparative accuracy: descendant

XSeed has continuously presented low quality results on the *xmark* document for simplechild and descendant queries (see the combined result in Table 6.8 and in Figure 6.4) due to the homonym-related problem stated in Section 3.3. Although EXsum produces better results than XSeed, there is a big difference between "Interpolation" and "DCP-based" estimation procedures. DPC better captures the occurrences of homonyms scattered in the document. However, we cannot affirm that the EXsum numbers for this case are accurate enough. LWES arises as the "great champion" to deal with the homonym issue.

Unfortunately, not all summaries support cardinality estimation for queries with parent and ancestor axes and with predicates. Therefore, only selective accuracy results are compared in Figure 6.5 (also in Table 6.9). Even for EXsum, some estimation procedures are not applicable to such query types. Therefore, we could not make a real Cartesian comparison on all query types.

In particular, EXsum obtains very good results and, in some cases, accurate results for queries referring to parent and ancestor axes.

TABLE 6.8: Combined NRMSE error for queries with child and descendant steps (in %)

Document	DPC	Interpolation	LWES	XSeed
dblp	13.86	0.91	14.49	0.91
nasa	29.32	3.35	3.45	3.36
swissprot	0.00	0.00	12.10	0.01
treebank	591.64	429.67	361.25	441.68
pds7003	0.00	0.00	0.00	0.00
uniprot	210.32	27.94	16.18	29.27
xmark	120.46	229.30	9.47	256.73

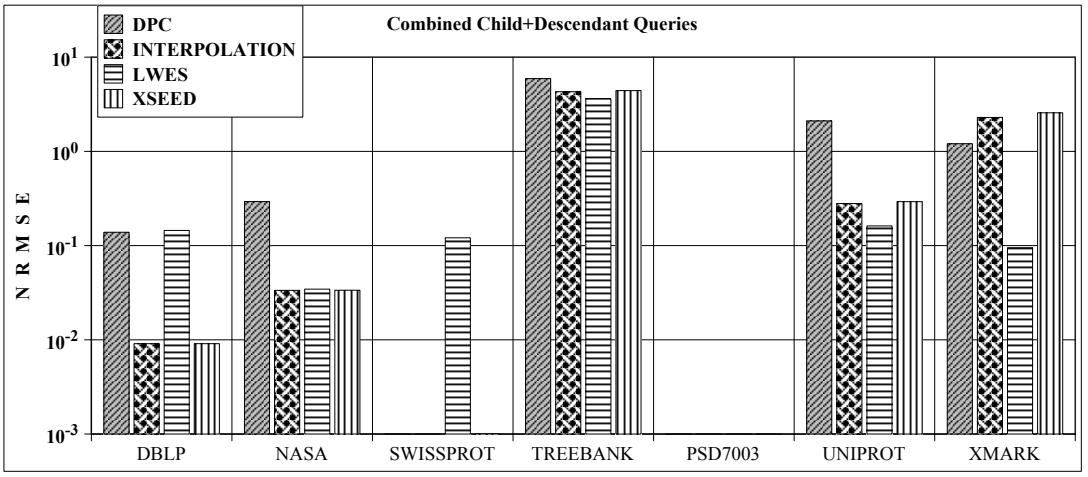


FIGURE 6.4: Comparative accuracy: combined child+descendant steps

TABLE 6.9: NRMSE error for queries with parent and ancestor steps

Document	Interpolation	LWES
dblp	0.089	91.475
nasa	0.000	0.333
swissprot	1.522	1.399
treebank	1.778	3.255
pds7003	0.000	0.000
uniprot	0.000	0.000
xmark	0.000	1.950

The main problem with path expressions containing existential (path) predicates is how to suitably estimate path predicates in a path expression, knowing that these predicates are also path expressions. Thus, a kind of syntactical (and semantic) recursion comes into play.

A path expression as $/a/b/c[./d]$ returns all c nodes having a d as its child. Hopefully, it is easy to estimate. However, when more than one predicate occurs or in the presence of an AND/OR connector, the estimation becomes difficult. For

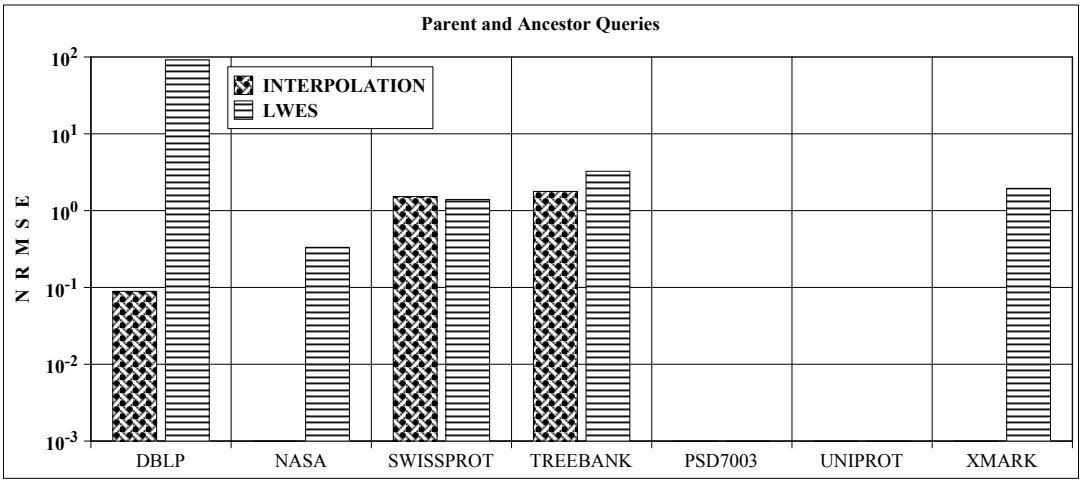


FIGURE 6.5: Comparative accuracy: parent/ancestor

TABLE 6.10: NRMSE error for queries with predicates

Document	DPC	Interpolation	XSeed
dblp	2.503	2.498	0.020
nasa	0.934	0.926	0.298
swissprot	1.495	1.520	1.078
treebank	2.750	2.636	0.714
pds7003	0.880	1.217	1.225
uniprot	0.980	0.981	0.387
xmark	2.959	3.708	3.708

example, an expression as $//b/c[./d]//e[.//f]/g$ can be considered complex to correctly estimate.

In the case of queries with (existential) predicates, we cannot always compute good estimation results. In this case, XSeed provides slightly better estimations than EXsum (see Table 6.10 and Figure 6.6), specially for *dblp*.

We have also made some tests concerning the text content summarization framework of EXsum, for which we only used data-centric documents. As stated in Section 6.2.3, we have generated a workload of queries with value predicates for each of four (out of seven) documents in our test document set, namely, *dblp*, *nasa*, *swissprot*, and *xmark*. The latter is a synthetic document, and the three former are real-life documents. With this workload, we present two graphs (Figures 6.7 and 6.8) concerning the estimation accuracy of such queries.

In the first graph (Figure 6.7), we evaluate only the accuracy of the predicate expression by applying three of our estimation procedures (*Interpolation*, *Prev.Step*, and *Total Freq.*). This means that given an expression as */a/b[text()='XML']*, we evaluate the estimated accuracy of the part *b[text()='XML']* with the three

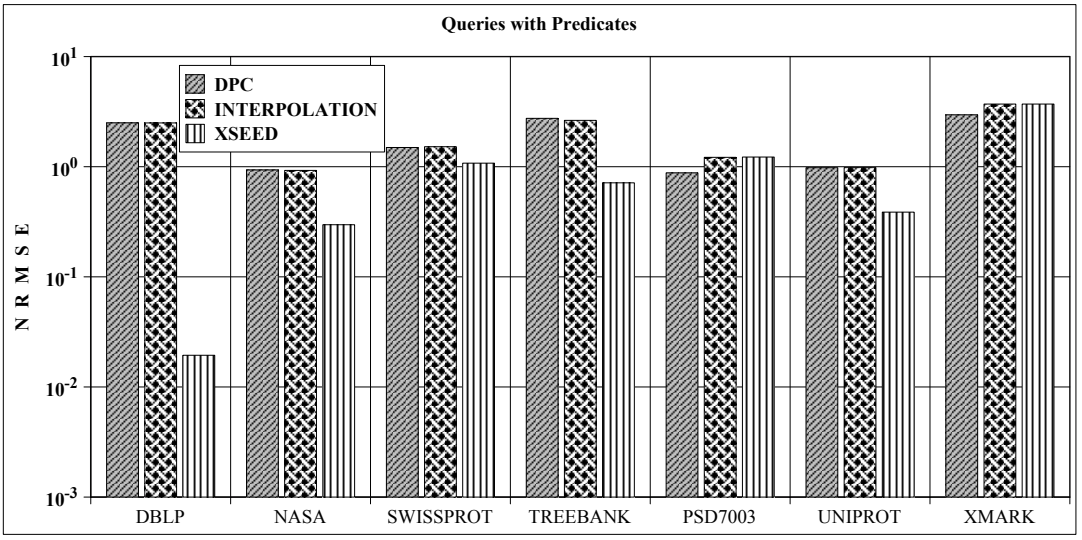


FIGURE 6.6: Comparative accuracy: predicates

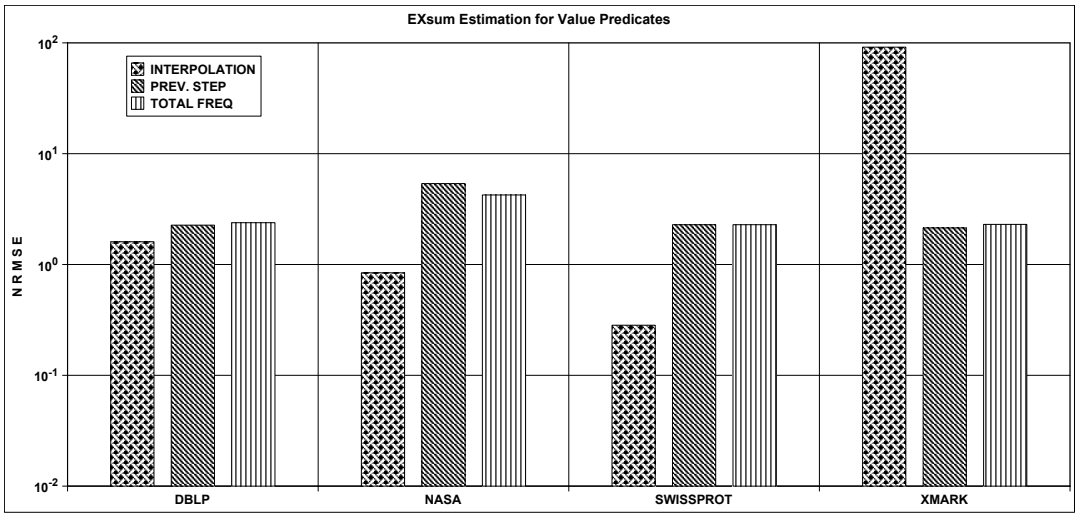


FIGURE 6.7: Accuracy of value predicates

different estimation procedures. Figure 6.7 shows us that, except for *xmark*, *Interpolation* yields the best results. However, the results of the *Prev.Step* and *Total Freq.* procedures can be considered acceptable, as they do not present a estimation quality much lower than that of *Interpolation*.

Once the value predicate step is estimated, we need to estimate the rest of the expression. Figure 6.8 illustrates such results. As one can see, the estimation of value predicates follows the same pattern of that existential predicates, thus not providing quality estimations—although *Interpolation* presents the better results in the majority of the cases. For this finding, we can infer that the presence of predicates—whether existential or value predicates—impacts directly the estimation quality. Thus, the estimation of path expressions with predicates needs to be investigated further in order to find a more accurate method for such expressions.

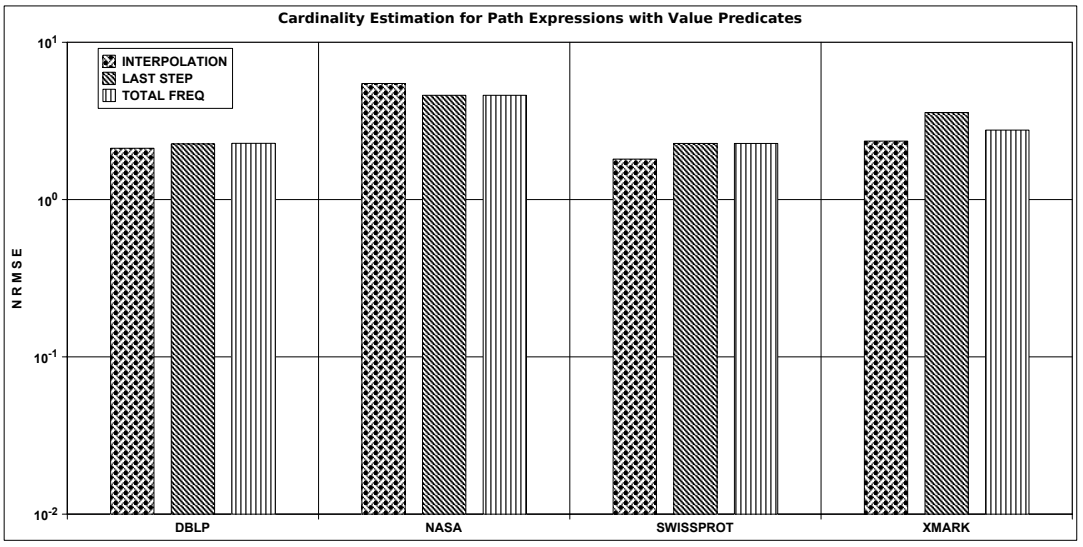


FIGURE 6.8: Accuracy of path expressions with value predicates

6.4 Discussion and Best-Effort Implementation of Competing Approaches

After having performed a substantial number of experiments, we want to discuss some important issues found during the experimental study. First of all, as explained in Section 6.3.3, we could not make an *NxM* comparison due to the restrictive support of XPath axes in most of the competing methods evaluated. However, this has not been the only problem.

Many methods were evaluated by experiments based on synthetic documents; in their original publications, however, detailed descriptions were missing regarding how these documents were generated. This deficiency has forced us to use a set of well-known documents in our experiments, where primarily the *dblp* document has been referenced in the majority of the original papers. Although available to everybody, the *dblp* version used in our experiments is different from those used in the original approaches. This is due to the publication dates in which *dblp* had different sizes (probably also shapes). We could not recover the "old" *dblp* files. Some approaches have only used a cut-out of some known documents (e.g., *treebank*) and presented their estimation quality results based on this cut-out (e.g., [ZÖAI06]). However, it is not clear from the original publications how these documents were cut.

Another issue is the query workload used in the original papers. Most of them hide the characteristics of workloads. In addition, the results presented are normally condensed, in the sense that the publications do not show the result classified by

query type (e.g., child, descendant, etc.). An exception is [ZÖAI06]. Some methods (e.g., [AAN01, WJLY04]) allow the definition of a memory budget. Thus, the user can specify different budgets and get different estimation quality results. We have not shown this variation and used a specific budget (for MT). The implementation languages vary a lot, e.g., C, C++, Java, etc. are used. Moreover, it is not clear on which data engine the original experiments have been made (e.g., a native XML or relational engine) or whether they used direct access to files in a file system. To provide a common implementation base, we have implemented all evaluated approaches in Java and integrated them into XTC, a native XDBMS (see Section 6.2).

Additionally, the error metrics used vary a lot. For the sake of intelligibility, we have chosen a specific metric (NRMSE) that, by definition, better expresses the estimation quality, most important for the query optimization process. No concrete numbers concerning the absolute estimation time for different query types were reported in the evaluated publications. This comparison was at most limited to a ratio between estimation time and query running time [ZÖAI06]. However, this ratio is dependent on several factors (e.g., the underlying query processors, physical operators used, etc.) and should not be used as an indicator of access speed to the summary.

Nevertheless, some of our results can be verified by the original contributions. For example, we have reached the same conclusion concerning Markov Tables [AAN01] that the summary yields low estimation quality (errors above 50%) when a memory footprint below 10KB is used for the *dblp* document. Note, using this memory budget, [AAN01] only supports queries referring to child axes. Using XSeed [ZÖAI06], we reached similar results for *dblp*. We also could confirm the good-quality estimations of [ZÖAI06], which included queries containing predicates and referring to child/descendant axes. Furthermore, the building times reported coincide with our measurements in the case.

BH presents a worse estimation quality than MT in some cases for child queries (see Figure 6.2). This could apparently be a different finding from the original BH publication, but it is not the case. In fact, our graph confirms a characteristic of BH which, due to its probabilistic nature, increasing the number of buckets not necessarily implies better estimations (e.g., for *dblp*, 34 buckets were used). When it happens, more than one Bloom filter reports *true* in a BH lookup and BH averages bucket frequencies which may produce bad results if two (or more) buckets have strongly varying frequencies. Another problem happens when the false-positive rate of Bloom filters raises above 10^{-4}. In this case, because of the probabilistic nature of BH, the estimation results tend to present more variability

than that with low false-positive error rate. The balance between the number of buckets and the false-positive rate for looking up BH is, in our humble opinion, difficult to reach in practical scenarios.

Chapter 7

Conclusions and Outlook

No amount of experimentation can ever prove me right; a single experiment can prove me wrong.
Albert Einstein, German Physicist, 1879 – 1955

After having studied the XML summarization problems, having proposed three solutions, namely, LESS, LWES, and EXsum, and empirically compared them with some competitor approaches, we want to conclude our work.

XML summarization remains yet an open problem in its general concept. Compressing value and structure of an XML document to provide good estimates in the majority of the cases (or, at least, in the common cases) is neither a simple, nor an easy task. The most difficult issue to be tackled is the document order and, consequently, the possible axes derived, but it is not the only issue.

7.1 Main Results

The variability expected whether in structure or in values in an XML document is high. We should consider skewness as a rule, not as an exception. Taking only the structure into account, we have presented two factors which make it difficult to reach quality estimations: structural recursion and homonyms. However, we are aware that these factors may not be the only ones.

We have used, in LESS and LWES summaries, the well-known compression technique called histogram and studied the many types of histograms to be applied.

However, accuracy loses its power for a query optimization process if other important characteristics are not verified as well. With our initial insight on LESS and LWES, we wanted to find a new way to summarize XML documents.

This way is substantiated in the EXsum summary which brings, besides accuracy, positive and important features regarding its use for a query optimizer as scalability in its size. For example, the summary size do not have a strict relation to the document size, fast access, or low memory footprint. The EXsum summary provides a simple (and hopefully, intuitive) manner to approximate an XML document. Additionally, it is extensible enough to encompass value-and-structure summarizations.

We cannot obviously state that, considering all parameters involved in providing XML summaries for their use in the query optimization area, our proposals are the very champion among others published in the literature. However, we expect that at least EXsum, due to its nature, may have a place in a multi-user, full-fledged native XML database in the future.

7.2 Future Research

While the cost-based query optimizer of XTC is under development, we expect that our proposals can be integrated into it, thus, forming a complete XML cost-based query evaluation component. In fact, our design and implementation have been driven to this aim. It should be verified for the estimation of text predicates—using Information Retrieval assumptions—under varying scenarios of data-centric documents. Furthermore, to identify new problems, it could be extended towards longer text values ending up in document-centric characteristics.

In addition, we can realize at least three different areas to apply the concepts presented here. For example, one of the well-known flaws of a RDBMS query engine is how to correctly estimate a join operation. Nowadays, an independence assumption is made and a join predicate, between tables R and S, as $R.a = S.a$ is estimated assuming there is no correlation between $R.a$ and $S.a$. This is, in practice, not justified in all the cases, mostly when a join encompasses tables linked by a referential integrity constraint. In such case, there is really a correlation between the tables, and the actual estimation method may lead to an underestimation of the join result. The same applies to self-joins. Another problem comes with recursion provided by the *With Recursive* SQL clause. Only

linear recursion is permitted in SQL and, even though, the recursive clause is rewritten into a set of joins—sometimes correlated joins.

In such cases, LWES and EXsum structures can improve the estimation quality because they capture the correlation among values. EXsum, due to its capturing of binary relationships among values (see EXsum's construction principle in Section 5.3), is particularly suitable to be adapted for its use in an RDBMS join estimation process. Therefore, the use of EXsum in these cases might eliminate the independence assumption, and, hopefully, may yield better results.

In the Data Warehouse area, specifically in ROLAP (Relational On-Line Analytical Processing), the cube estimation, i.e., the estimated storage requirements for the cube size, is yet an area in which we can give some contributions. Most frequently, cubes in DW/ROLAP databases are a result of the so-called *star-queries*, i.e., queries with a pattern involving necessarily the fact table and two or more dimension tables. The resulting aggregation is a direct application of the *CUBE* and *ROLLUP* SQL clauses—in fact, subclauses of the *Group By*. Thus, the number of attributes in dimensions that intersect the measure group may be estimated and, consequently, the cube size, if we use EXsum by modeling each ASPE node as an attribute value and the spokes as the possible intersections.

Of course, we are aware that some heuristic-based star-query techniques may be, in addition, applied and also some compression techniques that may influence the estimation results.

Last but not least, cost-based query processing in sensor data management may benefit from our proposals. A sensor normally collects data as temperature, air pressure, humidity, etc. A sensor network has a (common) hierarchical topology, called routing tree overlay in sensor data management terminology, with a parent-child relationship among sensors (nodes). If a query is posed (and partially processed) in a base station—most probably a PC-based computer—we can estimate such a query by using, for example, LWES to model sensors in the routing tree overlay where each LWES node, corresponding to a sensor (or a set of sensors), might have the summarized data collected by the sensor.

Appendix A

Homonyms in XML documents

Document: dblp.xml					
		Frequency Study			
elem./attr. name	#repetit.	min.	max.	average	std.dev
mdate	8	7	531,130	109,594.88	190,516.40
key	8	7	531,130	109,594.88	190,516.40
title	8	7	531,130	109,594.88	190,516.40
booktitle	6	1	531,130	90,354.67	197,141.85
publisher	5	4	8,415	1,993.00	3,240.98
href	5	59	4,888	1,137.20	1,885.21
year	8	7	531,130	108,297.75	191,221.44
isbn	4	2	7,495	2,168.00	3,110.09
url	8	1	531,128	109,344.50	190,541.38
author	8	7	1,366,560	1263,213.63	478,548.19
cdrom	4	4	10,474	3,698.25	4,276.80
cite	5	212	120,822	34,480.20	46,700.49
label	5	65	55,718	14,551.40	21,188.29
ee	6	10	332,456	89,237.00	131,583.13
editor	5	8	17,415	3,544.80	6,935.76
sup	11	2	1,575	264.55	532.50
series	3	1	5,044	1,901.00	2,238.56
volume	3	620	322,060	109,202.67	150,523.14
crossref	4	13	408,603	102,522.50	176,716.28
month	5	1	2,474	496.00	989.00
sub	8	1	2,065	344.63	672.52
i	8	1	3,485	682.38	1,190.62

pages	3	2,510	506,175	270,452.67	206,878.74
number	4	3	301,104	75,292.25	130,372.48
note	3	2	189	69.33	84.84
tt	2	3	7	5.00	2.00
journal	2	4	322,534	161,269.00	161,265.00
school	2	7	85	46.00	39.00
Document: nasa.xml					
		Frequency Study			
elem./attr. name	#repetit.	min.	max.	average	std.dev
title	4	286	8,503	3,401.25	3,070.31
author	2	765	9,001	4,883.00	4,118.00
initial	2	1,171	13,341	7,256.00	6,085.00
lastName	4	765	9,001	3,252.25	3,383.66
suffix	2	16	39	27.50	11.50
name	6	286	606,630	11,948.00	21,852.64
date	4	286	2,435	1,483.75	944.46
year	4	286	2,435	1,483.75	944.46
bibcode	2	271	2,379	1,325.00	1,054.00
xlink:href	7	2	10,095	3,642.57	4,053.72
para	9	2	23,224	3,814.78	7,051.60
creator	2	833	2592	1,712.50	879.50
description	3	1,148	5690	2,733.00	2,092.72
footnote	3	2	13,122	4,380.00	6,181.53
type	2	362	7,305	3,833.50	3,471.50
Document: swissprot.xml					
		Frequency Study			
elem./attr. name	#repetit.	min.	max.	average	std.dev
prim_id	33	6	86,240	10,254.09	20,609.09
sec_id	31	6	86,240	10,891.61	21,105.17
status	4	1,203	47,878	24,055.50	22,656.90
Descr	33	1	69,008	10,448.91	15,259.19
from	35	22	46,559	8,339.51	10,634.26
to	35	22	46,559	8,339.51	10,634.26
Document: treebank.xml					
		Frequency Study			
elem./attr. name	#repetit.	min.	max.	average	std.dev

NP	49,901	1	30,434	8.73	214.40
NN	25,159	1	10,849	7.42	119.79
JJ	17,469	1	2,829	4.91	47.02
NNS	15,778	1	5,706	5.34	70.87
NNP	12,462	1	12,501	10.53	171.32
DT	19,068	1	8,847	6.08	99.01
PP	19,427	1	9,344	6.99	112.85
IN	22,162	1	7,216	6.33	93.63
CC	6,937	1	4,895	4.83	66.38
POS	3,304	1	1,112	3.75	26.99
CD	7,389	1	2,323	6.64	53.29
S	10,756	1	49,873	14.25	557.70
COMMA	5,140	1	17,853	13.44	282.84
VP	15,632	1	29,805	9.87	316.32
PNP	215	1	72	2.41	6.18
ADJP	7,807	1	1,794	4.53	41.05
JJS	1,188	1	188	2.31	7.90
NONE	12,350	1	4,154	4.38	55.05
VBG	5,329	1	1,820	3.90	35.66
VBN	5,808	1	4,224	4.88	71.89
QUOTES	2,069	1	2,329	4.94	62.56
BACKQUOTES	2,043	1	2,192	4.87	59.77
TO	6,985	1	2,347	4.50	48.96
RBS	376	1	25	1.63	2.28
RB	8,403	1	5,452	5.23	73.90
NNPS	1,097	1	332	2.96	13.50
PRP_DOLLAR_	3,827	1	417	3.06	15.43
VBD	3,432	1	11,657	12.60	254.40
VBZ	3,151	1	5,860	9.55	142.81
JJR	1,876	1	165	2.45	8.67
X	765	1	559	5.73	34.84
MD	1,784	1	2,382	7.65	88.37
DOLLAR	2,529	1	531	4.03	20.08
WHNP	2,731	1	572	3.41	19.02
WDT	2,055	1	341	2.96	13.81
VB	6,383	1	2,849	5.81	67.94

-PERIOD-	907	1	37,262	61.70	1301.73
-LRB-	775	1	107	2.51	7.40
SBAR	4,496	1	6,729	7.83	123.01
-RRB-	790	1	98	2.48	6.81
SBARQ	633	1	404	3.71	19.62
PRP	3,815	1	4,798	6.35	103.20
ADVP	1,784	1	933	4.51	36.72
VBP	2,487	1	2,746	7.03	85.72
WP	1,173	1	194	2.81	10.15
-COLON-	840	1	1,263	7.79	55.79
WHADVP	937	1	369	3.22	15.84
WRB	946	1	369	3.20	15.76
RBR	1,136	1	90	2.22	5.95
RP	961	1	219	2.52	10.36
FW	155	1	18	1.97	1.97
WP-DOLLAR-	138	1	32	1.82	3.14
PRT	182	1	37	2.07	4.31
PDT	282	1	37	1.75	3.16
ORD	93	1	9	1.38	1.28
EX	209	1	330	5.80	29.36
-NL-	280	1	58	1.81	4.49
PP-1	219	1	37	2.19	4.20
PP-2	92	1	14	1.74	2.26
SBAR-1	72	1	17	2.29	3.04
NP-1	125	1	17	1.94	2.59
INTJ	58	1	22	2.05	3.07
UH	71	1	22	1.92	2.83
POSS	72	1	9	1.47	1.34
WHPP	462	1	50	1.79	3.07
N	25	1	3	1.16	0.46
ADJ	25	1	2	1.04	0.20
-HASH-	116	1	13	1.64	1.50
-QUESTIONMARK-	103	1	6,157	67.92	603.44
SINV	89	1	2,164	32.80	231.04
SQ	101	1	143	4.91	17.47
SBAR-4	13	1	4	1.38	0.84

SBAR-3	29	1	4	1.17	0.59
PP-3	59	1	4	1.29	0.67
NEG	47	1	30	2.72	4.82
VP-2	41	1	6	1.76	1.57
SYM	12	1	2	1.25	0.43
VP-1	61	1	19	2.62	3.65
LS	21	1	11	3.52	2.97
VPPRT	13	1	3	1.38	0.74
NNS_OR_NN	8	1	2	1.13	0.33
NN_OR_NNS	11	1	2	1.09	0.29
X-2	29	1	7	1.55	1.33
VP-3	19	1	2	1.16	0.36
VBG_OR_NN	19	1	2	1.05	0.22
S-3	18	1	2	1.11	0.31
NN_OR_JJ	13	1	1	1.00	0.00
SBAR-2	59	1	8	1.59	1.50
RBR_OR_JJR	12	1	1	1.00	0.00
AUX	37	1	14	1.70	2.30
X-1	63	1	15	2.27	2.85
ADVP-2	18	1	4	1.44	0.83
NPS	20	1	2	1.05	0.22
S-2	32	1	12	2.00	2.28
NP-2	52	1	9	1.96	1.83
N-1	2	1	1	1.00	0.00
S-1	71	1	11	1.86	2.08
X-4	18	1	5	1.44	1.01
ADJP-5	2	1	1	1.00	0.00
NP-3	15	1	2	1.07	0.25
ADVP-4	7	1	2	1.14	0.35
PP-4	20	1	5	1.50	1.07
X-3	29	1	5	1.52	1.00
ADVP-1	29	1	9	1.76	1.65
ADJP-1	20	1	2	1.30	0.46
ADV	11	1	2	1.09	0.29
ADJP-3	7	1	2	1.29	0.45
CONJ-4	4	1	1	1.00	0.00

PP-5	14	1	1	1.00	0.00
CONJ	3	1	1	1.00	0.00
CONJ-1	6	1	1	1.00	0.00
ADJP-2	21	1	2	1.24	0.43
VBG_OR_JJ	16	1	1	1.00	0.00
VB_OR_NN	2	1	2	1.50	0.50
VP-4	16	1	1	1.00	0.00
RB_OR_RP	3	1	1	1.00	0.00
COMP	6	1	5	1.83	1.46
VBN_OR_JJ	15	1	2	1.07	0.25
SBARQ-1	12	1	3	1.33	0.75
NP-4	14	1	1	1.00	0.00
VP-7	4	1	1	1.00	0.00
NN_OR_DT	2	1	1	1.00	0.00
ADVP-5	2	1	1	1.00	0.00
S-4	8	1	1	1.00	0.00
earlier	2	1	1	1.00	0.00
PP-8	6	1	1	1.00	0.00
X-6	4	1	2	1.50	0.50
NP-7	2	1	1	1.00	0.00
ADVP-3	6	1	4	2.00	1.41
X-7	4	1	1	1.00	0.00
NP-8	2	1	1	1.00	0.00
CONJ-5	4	1	1	1.00	0.00
VP-6	6	1	1	1.00	0.00
V	6	1	1	1.00	0.00
NP-5	5	1	2	1.20	0.40
NNP_AMPERSAND_P	3	1	1	1.00	0.00
CONJ-3	4	1	1	1.00	0.00
ADVP-10	2	1	1	1.00	0.00
VP-5	5	1	2	1.20	0.40
IN_OR_RB	5	1	2	1.20	0.40
PP-6	4	1	1	1.00	0.00
JJ_OR_NN	4	1	1	1.00	0.00
JJR_OR_RBR	4	1	1	1.00	0.00
ADJP-4	6	1	1	1.00	0.00

RB_OR_JJ	3	1	2	1.33	0.47
SBARQ-5	2	1	1	1.00	0.00
SBAR-8	2	1	1	1.00	0.00
RBS_OR_JJS	2	1	1	1.00	0.00
SBAR-5	4	1	1	1.00	0.00
CONJ-2	2	1	1	1.00	0.00
WHADV	4	1	1	1.00	0.00
S-7	2	1	1	1.00	0.00
ADJP-6	2	1	1	1.00	0.00
PP_DOLLAR_	2	1	1	1.00	0.00
SBAR-6	4	1	1	1.00	0.00
SINV-1	3	1	1	1.00	0.00
WHADVP-1	2	1	1	1.00	0.00
JJ_OR_IN	2	1	1	1.00	0.00
VBN_OR_VBD	3	1	1	1.00	0.00
SINV-3	2	1	1	1.00	0.00
S-5	2	1	1	1.00	0.00
VP-8	2	1	1	1.00	0.00
PP-7	2	1	1	1.00	0.00
NN_OR_CD	2	1	1	1.00	0.00
LS_OR_NNS	2	1	1	1.00	0.00
Inc	2	1	2	1.50	0.50
LS_OR_NN	2	1	1	1.00	0.00
SBARQ-3	2	1	1	1.00	0.00
SBARQ-2	2	1	1	1.00	0.00
LS_OR_JJ	3	1	2	1.33	0.47
__	2	1	38	19.50	18.50

Document: psd7003.xml					
		Frequency Study			
elem./attr. name	#repetit.	min.	max.	average	std.dev
id	2	1	26,2525	131,263.00	131,262.00
uid	5	14250	1,199,979	389,883.20	415,798.65
accession	2	312,506	323,043	317,774.50	5,268.50
xrefs	3	8,396	281,246	174,456.33	119,014.12
xref	3	14,250	1,199,979	497,877.33	508,125.04
db	4	14,250	1,199,979	382,831.75	483,062.89

note	5	2,124	34,640	13,359.80	11,212.35
label	4	383	312,467	99,404.00	127,583.68
description	3	7,683	129,114	56,676.67	52,272.21
seq-spec	2	132,377	312,467	222,422.00	90,045.00
status	3	501	353,838	145,163.67	151,183.95
link	2	114	863	488.50	374.50
type	2	76,886	262,525	169,705.50	92,819.50

Document: uniprot.xml					
		Frequency Study			
elem./attr. name	#repetit.	min.	max.	average	std.dev
name	14	1,507	1,0490,886	890,360.71	2,668,529.62
ref	5	1,086	90,028	384,11.40	390,92.59
type	15	7,994	3,937,497	791,989.60	1,133,994.60
key	7	16,840	2,833,362	678,179.14	930,590.56
dbReference	4	16,840	2,833,362	1,012,795.75	1,109,378.38
id	8	11,114	2,833,362	694,221.00	910,510.44
person	2	1,507	1,0490,886	5,246,196.50	5,244,689.50
note	2	4,076	6,282	5,179.00	1,103.00
status	7	13	660,912	134,294.57	233,004.00
position	8	2,207	1,136,443	421,659.63	46,8457.35
sequence	3	90	228,669	84,859.33	102,229.84
text	3	23	889,886	296,661.00	419,473.42
location	2	4,829	1,683,314	844,071.50	839,242.50
begin	2	2,338	1,137,858	570,098.00	567,760.00
end	2	2,338	1,137,858	570,098.00	567,760.00
mass	2	2,325	228,669	115,497.00	113,172.00
modified	2	228,669	228,670	228,669.50	0.50
version	2	228,669	228,670	228,669.50	0.50

Document: xmark.xml					
		Frequency Study			
elem./attr. name	#repetit.	min.	max.	average	std.dev
bold	99	11	5,787	725.82	1,315.59
emph	99	4	5,798	702.91	1,280.63
keyword	99	4	5,933	706.76	1,279.09
parlist	18	119	3,619	1,156.28	1,088.60
listitem	18	342	10,533	3,360.06	3,157.86

text	33	342	9,663	3,185.27	2,870.41
item	8	550	12,000	5,437.50	4,310.94
id	9	550	25,500	6,694.44	7,731.98
location	6	550	10,000	3,625.00	3,349.10
quantity	8	550	12,000	5,437.50	4,310.94
name	8	550	25,500	6,031.25	7,956.01
payment	6	550	10,000	3,625.00	3,349.10
description	9	550	12,000	4,944.44	4,296.99
shipping	6	550	10,000	3,625.00	3,349.10
incategory	6	2,061	37,843	1,3691.83	1,2677.72
category	8	1,000	37,843	1,5105.00	1,4514.29
mailbox	6	550	10,000	3,625.00	3,349.10
mail	6	544	9,663	3,491.00	3,235.68
from	7	544	9,663	3,135.14	3,119.90
to	7	544	9,663	3,135.14	3,119.90
date	8	544	59,486	11,272.75	18,550.57
featured	6	54	997	368.33	333.41
open_auction	2	12,000	50,269	31,134.50	19,134.50
person	7	9,750	59,486	19,748.00	17,038.35
seller	2	9,750	12,000	10,875.00	1,125.00
itemref	2	9,750	12,000	10,875.00	1,125.00
type	2	9,750	12,000	10,875.00	1,125.00
annotation	2	9,750	12,000	10,875.00	1,125.00
author	2	9,750	12,000	10,875.00	1,125.00
happiness	2	9,750	12,000	10,875.00	1,125.00

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