BSBC: TOWARDS A SUCCINCT DATA FORMAT FOR XML STREAMS

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Abstract: XML data compression is an important feature in XML data exchange, particularly when the data size may cause bottlenecks or when bandwidth and energy consumption limitations require reducing the amount of the exchanged XML data. However, applications based on XML data streams also require efficient path query processing on the structure of compressed XML data streams. We present a succinct representation of XML data streams, called Bit-Stream-Based-Compression (BSBC) that fulfills these requirements and additionally provides a compression ratio that is significantly better than that of other queriable XML compression techniques, i.e. XGrind and DTD subtraction, and that of non-queriable compression techniques like gzip. Finally, we present an empirical evaluation comparing BSBC with these compression techniques and with XMill that demonstrates the benefits of BSBC.

1 INTRODUCTION

1.1 Motivation

XML is widely used in business applications and is the de facto standard for information exchange in fixed wired networks. Because of the verbose structure of XML, applications operating on continuous XML data streams or requiring very large amounts of XML data will likely benefit from XML compression techniques in platforms such as mobile networks where storage, bandwidth or energy are limited for the following reason. Applications save energy and processing time not only when loading compressed instead of uncompressed XML data, but also they can execute path queries directly on the compressed data format, i.e., without decompressing it. We propose an XML compression technique, called Bit-Stream-Based-Compression (BSBC), which supports path queries while achieving in our experiments a better compression ratio than other XML compression techniques for XML data streams which support path queries, i.e. XGrind and DTD subtraction. Furthermore, BSBC achieves an even better compression ratio than text compression tools like gzip, and it sometimes even beats XMill.

1.2 Contributions

This paper proposes a novel approach to XML compression, called Bit-Stream-Based-Compression (BSBC) that combines the following properties:

- It removes redundancies within the structure of the XML file by sharing identical sub-trees
- It separates an XML data stream into its constituent parts: its tree structure extended by pointers to common sub-trees, its names of elements and of attributes, and its values of text constants and of attributes.
- It compresses the tree structure to a bit stream and a sub-tree pointer stream, it collects bit stream positions of names of elements and attributes in inverted lists, and it groups structurally related text and attribute values into containers to improve the compression ratio.
- It stores compressed data into packages allowing thus shorter relative addresses in inverted lists and value containers.
- It combines a fast bit stream-based navigation technique along the child, descendant, following-sibling, and following axes with direct access to elements and attributes via inverted lists. As the navigation along these axes can be

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done on the bit stream alone, it needs a minimum of space and can be done very fast.

- Combined with a preliminary step, which rewrites queries containing backward axes into equivalent queries containing only on forward axes, BSBC allows fast navigation along all XML axes.

As a result, BSBC has the following advantages. In comparison to other approaches to path queries on XML streams (e.g. AFilter (Candan et al., 2006)) that support only some axes and that require decompression to process queries, BSBC supports the execution of path queries involving all XML axes, and it does not require decompression for the purpose of path query processing. Furthermore, our extensive evaluation demonstrates that the compression ratio achieved by BSBC outperforms that of other XML compression techniques (like XGrind and DTD subtraction) that support path queries. To the best of our knowledge, there is no other XML compression system that combines the advantages of BSBC.

1.3 Paper Organization

The remainder of this paper is organized as follows. Section 2 describes how a SAX stream is compressed by two compression steps each of which transforms an input data stream into two or three compressed output data streams, and it explains how the document structure is stored in a sub-tree pointer stream and in a bit stream and separated from the elements and attributes which are stored in inverted lists. Section 3 describes how to implement navigation along the XML axes and extended navigation on the bit stream, the sub-tree pointer stream, and the inverted lists. Section 4 compares the compression ratio of BSBC with that of other approaches. Section 5 compares BSBC to related work. Finally, Section 6 summarizes our contributions.

2 THE STREAMS – KEY OF OUR SOLUTION

BSBC views XML data as an input stream of SAX events that is transformed by two steps into four other streams (c.f. Figure 1).

Step 1 transforms the SAX stream (a) into *constant containers* (b) and an intermediate binary *DAG stream* (c), which is in Step 2 transformed into a *sub-tree pointer stream* (d) representing the backward pointers to shared sub-trees within the DAG, a *bit stream* (e) capturing the tree structure of the XML data, and an *inverted list* (f), containing a mapping from element names to positions within the bit stream.

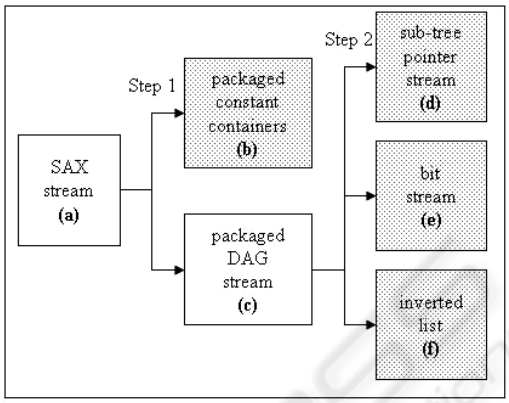


Figure 1: Compression Steps of the BSBC system.

2.1 Step 1: Separating XML into DAG Packages and Constant Containers

As we expect a significantly higher repetition ratio for element and attribute names than for constants, we first separate element and attribute names from constants, and we then use a different technique for the compression of element and attribute names than we use for the compression of constants.

Step 1 is done as follows (for an example see Figure 2). The input SAX stream (Figure 2(a)) is parsed and separated into a stream of two different kinds of packages: packages of constant containers (Figure 2(b)), which contain the *constants*, i.e., the text and attribute values of the SAX stream, and DAG packages which contain the XML structure. Figure 2(g) shows a graphical representation of the binary DAG of the SAX stream of Figure 2 (a), i.e., all text nodes have been replaced with "=T" and common binary sub-trees are shared, and Figure 2(c) shows the DAG package generated from the SAX stream.

The DAG packages are constructed by a DAG processor like e.g. the one presented in (Böttcher and Steinmetz, 2007) and consist of the following kinds of events: *startElement(id, label)* and *endElement(id, label)*, which are similar to the corresponding SAX events, but which contain an additional, unique node ID, and the additional event *commonSubtreeFound(id)* which represents a backward pointer to the sub-tree rooted by the node with ID id.

The structure-oriented SAX events, i.e., *startDocument*, *startElement*, *endElement*, and *endDocument*, are passed to the DAG compressor. Hereby the attributes are treated as follows: An attribute

definition of the form att="value" is passed as an event sequence *startElement("@att"), endElement("@att")*, which is sent to the DAG compressor, whereas the pair (@att, value) is passed to the constant containers and will be processed later.

Whenever a character-event is received, an event sequence *startElement("=T"), endElement("=T")* is sent to the DAG compressor, and the pair (element, value) is passed to the constant containers, where element is the label of the parent node of the text node.

However, if an event *startElement("E1")* is directly followed by an event *endElement("E1")* in the SAX stream, i.e., if an empty element tag is found, this is treated like a character-event receiving an empty text node. That is, an event sequence *startElement("=T"), endElement("=T")* is sent to the DAG compressor, and the pair (E1, "") is passed to the constant containers, where "" is the empty constant. This is done to ensure that all leaf nodes are either constants, which are represented by "=T", or attribute nodes, which are represented by a name starting with '@'.

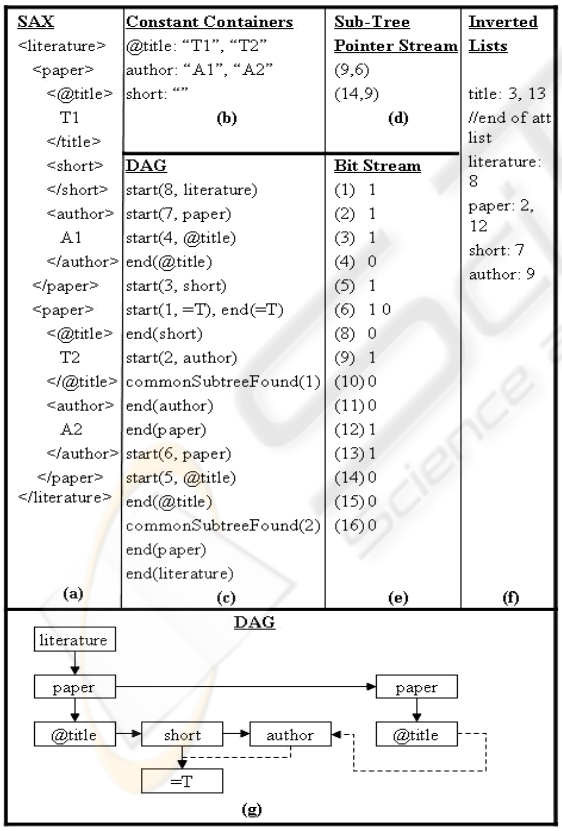


Figure 2: (a) SAX stream, (b) constant containers, (c) binary DAG stream, (d) sub-tree pointer stream, (e) bit stream, (f) inverted lists of our example, and (g) graph of the binary DAG.

For the storage of constants, we follow the idea presented in XMill (Liefke and Suciu, 2000) and sort the constants according to their parent element into separate data containers (i.e., the @title container, the author container, and the short container in Figure 2(b)). Each container for constants with a parent element Ei stores the text values included in Ei elements in the order in which they occur in the document. Each container is then compressed using BZip2 which implements Burrows-Wheeler Block-Sorting (Burrows and Wheeler, 1994) followed by Huffman-Encoding (Huffman, 1952).

In order to support (unbounded) XML streams, we divide both structures (DAG and constants) into packages: Whenever a certain number n of events was received, the DAG that was compressed so far, the path of non-compressed nodes (i.e., the nodes from root to the current node, the next-siblings of which were not yet inserted into the DAG), and the compressed constant containers are passed to the second step. This allows a pipelined approach that is capable to compress (unbounded) XML data streams.

2.2 Step 2: Transforming DAG Packages into Multiple Streams

During decompression or query processing, we have to correctly recombine element and attribute names with included constants, i.e., we have to know the correct relative positions of both kinds of data. For this purpose, we generate the so called bit stream during compression.

Within Step 2, we use the DAG stream for generating three new streams as follows. We separate element names from the structure of the DAG stream (Figure 2(c)), i.e., we transfer names to a separate stream, called *inverted lists* (Figure 2(f)) to hold the names of elements or their attributes. The remaining structure of the DAG stream is stored in the *bit stream* (Figure 2(e)) and the *sub-tree pointer stream* (Figure 2(d)). These three streams together enable the traversal of the XML document without requiring decompression.

2.2.1 The Bit Stream and the Sub-tree Pointer Stream

The *bit stream* simply contains a "1"-bit for each event *startElement* of the DAG stream, and a "0"-bit for each event *endElement* of the DAG stream.

In an intermediate table, a mapping from node IDs to positions of the corresponding '1'-bit within the bit stream is stored. Whenever a commonSub-

treeFound(id)-event is read, the position pID of the node with ID id is looked up, and the pair (currentPos, pID) representing the sub-tree pointer is written to the sub-tree pointer stream, where currentPos is the current position within the bit stream.

2.2.2 The Inverted Lists

In order to store the mapping of element names to positions within the bit stream, BSBC uses *inverted lists*, where each element name occurring in the package is associated with a list of relative addresses (N1,N2,…) where the elements with this element name occur.

Each element name is thus stored only once per package within the inverted list, regardless of how often it occurs in the XML data. As furthermore no additional pointers are needed, this succinct representation of elements and their positions can significantly save space.

While parsing the DAG stream, whenever receiving an event startElement(id, "E1"), a '1'-bit is inserted into the bit stream (as described above), but at the same time, the position P of the new '1'-bit within the bit stream is written to the inverted element list of the element E1.

This will be useful for the typical XPath location steps /E1 and //E1 as outlined in Section 3. In the rare case where the element name of an element at a specific position N, say N=10, is needed, it is still possible to search N in the sorted list of each element E until the position N is found or until a number >N indicates that N will not occur in the sorted list of positions of E elements.

Furthermore, it is possible to sort the inverted lists within each package such that the entries for all attribute names precede the entries for all elements. This makes unnecessary all the "@"-characters used as a prefix for each attribute name. Instead, all the "@"-characters can be replaced by a single pointer per package to the first inverted list of an element.

In order to reach a better compression result, we do not repeat each element name in each package. Instead, we define a symbol SE1 for an element name E1 the first time it occurs in the compressed data. And we replace each further occurrence of E1 in the following packages by its symbol SE1.

The inverted element list for the text nodes, i.e., the inverted element list for the element "=T" is not stored in the final compressed data, as each '1'-bit position that is not included in any inverted element list has to be a text node.

2.3 Optimizing Query Evaluation by Sparse Constant Pointers

Within the evaluation of path queries, we will have to find a constant T for a given position P within the bit stream that represents the placeholder "=T" for T. With the help of the element label "E1" of the parent of T, we can identify the correct constant container CE1, but in order to identify the correct position of T within CE1, we have to know, how many nodes with label "=T" and with a parent node with label "E1" exist up to the current context node.

Without any additional information, we would have to count these nodes from the start of the document, i.e., we would not be able to skip parts of the compressed document during query evaluation.

In order to avoid this disadvantage, we attach to every d-th bit D in the bit stream the information of how many nodes with label "=T" and with a parent node with label "E" exists up to D for each element label E that has occurred within the document so far.

3 NAVIGATION ON THE STREAMS

Each navigation step can start at the bit-stream position P_{start} of the start-element tag of an arbitrarily chosen current context node C. We first explain basic navigation steps, and then use them to compose more complex navigation steps on the compressed XML data.

3.1 Basic Navigation using the First-attribute, First-child and Next-sibling Axes

Given the bit-stream position P_{start} of the current context node C, many navigation steps, e.g., finding C's next–sibling, requires finding the bit-stream position P_{end} of C's end-element tag.

3.1.1 Finding the Position P_{end} of the End-tag

In order to proceed to the bit stream position P_{end} of the "0"-bit in the bit stream that represents the end-tag of the current context node, each start-tag has to be closed by exactly one end-tag, i.e., we search the corresponding "0"-bit for each "1"-bit on the bit stream as follows. The search counts "0"-bits and "1"-bits, starts at the bit stream position P_{start}, and continues counting bits of the bit-stream until the

number of "1"-bits is equal to the number of "0"-bits, i.e., each start-tag has been closed.

P_{end} may occur in a later package than P_{start}. Note that nevertheless, we can use relative addresses for P_{start} and P_{end} because the operation 'find position P_{end} of the corresponding end tag' operates on the bit streams only, i.e., searching for P_{end} in the bit stream of a later package does not disturb the use of small relative addresses.

3.1.2 Proceeding to the Next-sibling

In order to find the bit stream Position PNS_{start} of the bit that tells us whether or not the current context node has a next sibling, we first proceed to the position P_{end} of the "0"-bit in the bit stream that represents the end-tag of the current context node. The bit at position $P_{end}+1$, i.e., after the bit representing the end-tag, is a "1"-bit representing the next-sibling if a next-sibling exists, and a "0"-bit otherwise.

3.1.3 Distinguishing Elements and Attributes from Text Constants

The current context node represented by a "1"-bit at position P_{start} in the bit-stream is an element name if the node is an inner node, i.e., if the next bit stream position $P_{start}+1$ also contains a "1"-bit. However, if the next bit stream position $P_{start}+1$ contains a "0"-bit, the current context node represented by the "1"-bit at position P_{start} is a leaf node, i.e., it either is a constant, or it is an attribute name. It is a constant, if and only if P_{start} can not be found in any inverted list of an attribute name.

3.1.4 Determining Element Names and Attribute Names and Distinguishing Elements from Attributes

Which name the element or attribute of the current context node C has, can be distinguished by searching position P_{start} in the inverted lists. C is an attribute or an element, depending on in which kind of an inverted list P_{start} is found. Inverted lists for attributes are distinguished from inverted lists for elements by grouping inverted lists in each package and by providing a pointer to the first inverted list of an element for each package.

3.1.5 Proceeding to the First-attribute Node

Let P_{start} be the bit stream position of an element node C. C has a first-attribute if and only if bit stream position $P_{start}+1$ contains a "1"-bit and represents an attribute. In this case, $P_{start}+1$ represents C's first-attribute.

3.1.6 Proceeding to the First-child Node

In order to find the bit stream Position PFC_{start} of the bit that tells us whether the current context node has a first-child, we have to proceed similar as when searching for the first-attribute, except that whenever a "1"-bit represents an attribute instead of the first-child, we use the bit stream to proceed to the attribute's next-sibling.[1] The attribute's next-sibling is either the next attribute, in which case we continue to search for a next-sibling or it is the first-child or it does not exist, which means that there is no first-child.

3.2 Navigation using the other Forward Axes

Given a position P_{start} of the start-tag of the current context node, we first determine the position P_{end} of the end-tag of the current context node as explained before. The next step depends on the forward axis to be used.

3.2.1 Proceeding to Descendant-or-Self::E1

When a location step //E1 requires searching a descendant-or-self E1 element, the search is significantly easier than standard path search for a descendant-or-self E1. Only E1 elements with a bit stream position $PE1_{start}$ in the interval of $[P_{start}, P_{end})$ fulfill the descendant-or-self condition. Therefore, in the packages that match these addresses[2], we simply lookup the inverted lists for E1 in order to find the bit stream positions $PE1_{start}$ of E1 descendant nodes with $P_{start} \leq PE1_{start} < P_{end}$.

3.2.2 Proceeding to Child::E1 or to Attribute::A1

When we search a child::E1 or an attribute @A1 respectively, we use the inverted lists of E1 or @A1 in all relevant packages to look for positions $PE1_{start}$ with $P_{start} < PE1_{start} < P_{end}$, and we use the bit streams to check that the depth of $PE1_{start}$ is exactly one more

[1] This is where we find the first-child because further attributes of C are stored as siblings of the first-attribute and the first-child is stored as the 'next-sibling' of the last attribute in our simple element stream.

[2] We use $PE1_{start}<P_{end}$ as a shortcut for 'P_{end} belongs to a later package than $PE1_{start}$ or they belong to the same package and $PE1_{start}$ is less than P_{end}'.

than the depth of P_{start}, i.e., the number of "1"-bits is exactly one more than the number of "0"-bits in the bit stream interval from P_{start} to $PE1_{start}$. These positions $PE1_{start}$ represent the element start-tags for the child::E1 elements or the attributes @A1 that we are looking for.

3.2.3 Proceeding to Following-sibling::E1

When we search a following-sibling::E1, we additionally lookup the bit stream position PP_{end} of the end-tag of the parent of current context node. PP_{end} is the first bit stream position after P_{end} where the number of "0"-bits exceeds the number of "1"-bits by one.

Then, we use the inverted lists of E1 in all relevant packages to look for positions $PE1_{start}$ with $P_{end} < PE1_{start} < PP_{end}$, and we use the bit streams to check that the depth of $PE1_{start}$ is the same as the depth of P_{start}, i.e., the number of "1"-bits is equal to the number of "0"-bits in the bit stream interval from P_{start} to $PE1_{start}$. These positions $PE1_{start}$ represent the element start-tags for the following-sibling::E1 elements that we are looking for.

3.2.4 Proceeding to Following::E1

Finally, when we search a following::E1, we use the inverted lists of E1 to look for positions that are larger than P_{end} or occur in a later package.

3.2.5 Looking-up a Specific Constant

When searching a constant V for a given position X within the bit stream, we also regard the parent element – or parent attribute in the case of attribute values – E of V in the bit stream.

As described in Section 2.3, we have attached periodically sparse constant pointers to bit stream positions that define, how many text values V' for a given parent element or parent attribute E' have been parsed so far.

In order to search the text value for a given position X, we have to go back within the bit stream to the last constant pointer, i.e., to the last bit stream position C that contains the text container offset and lookup the offset O for the parent element – or parent attribute – E. Afterwards, we start there to count the number N of text nodes that have the parent element – or parent attribute – E. This has to be done in consideration of the sub-tree pointers as described in Section 3.3. As some of the elements might contain mixed mode, we have to consider, that one element may not only contain a single text node as child, but as well two or more.

The text value that we are looking for, can then be found as the O+Nth text value within the constant container of the element – or attribute – E.

3.3 Sub-tree Pointers

So far, we did not handle the sub-tree pointers stored within the sub-tree pointer stream. Whenever we reach a position p within the bit stream for which an entry (p, pID) exists within the sub-tree pointer stream, we store the position p on a stack and continue to parse the bit stream at position pID. When the end of the sub-tree started at pID is reached, i.e., when we have read as many '1'-bits as '0'-bits, we jump back to the position which is given on top of the stack and remove this position from stack.

3.4 Backward Axes

We do not explicitly consider backward axes here, as it is possible to rewrite each XPath query using backward axes into an equivalent XPath query using forward axes only. An approach on how to rewrite backward axes is presented in (Olteanu et al., 2002).

4 EVALUATION OF THE COMPRESSION

We have implemented BSBC using Java 1.5 and a SAX parser for parsing XML documents. We have evaluated BSBC on the following datasets:

1. XMark(XM) – an XML document that models auctions (Schmidt et al., 2002)
2. hamlet(H) – an XML version of the famous Shakespeare play
3. catalog-01(C1), catalog-02(C2), dictionary-01 (D1), dictionary-02(D2) – XML documents that were generated by the XBench benchmark (Yao and Özsu, 2002)
4. dblp(DB) – a bibliographic collection of publications

As can be seen in Table 1, the sizes of the documents reach from a few hundred kilobytes to more than 300 Megabytes.

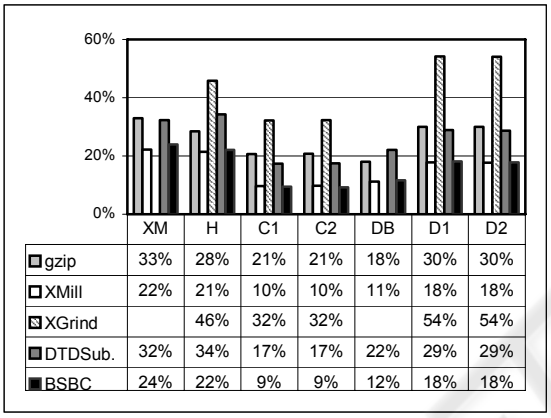
Table 1: Sizes of documents of our dataset.

document	XM	H	C1	C2	DB	D1	D2
Uncompressed size in MB	5.3	0.3	10.6	105.3	308.2	10.8	106.4

We compared BSBC with four other approaches:

- XGrind (Tolani and Hartisa, 2002) – a queryable XML compressor
- gzip – a widely used text compressor
- XMill (Liefke and Suciu, 2000) – an XML compressor using BZip2 for the compression of constant values
- DTD subtraction (Böttcher, Steinmetz, and Klein, 2007) – a DTD-conscious XML compressor using gzip for the compression of constant values that allows query evaluation and partial decompression

During our experiments, we have chosen d=100, i.e., each 100th bit contains direct pointers into the constant containers.



	XM	H	C1	C2	DB	D1	D2
gzip	33%	28%	21%	21%	18%	30%	30%
XMill	22%	21%	10%	10%	11%	18%	18%
XGrind		46%	32%	32%		54%	54%
DTDSub.	32%	34%	17%	17%	22%	29%	29%
BSBC	24%	22%	9%	9%	12%	18%	18%

Figure 3: Compression ratio of the whole XML document.

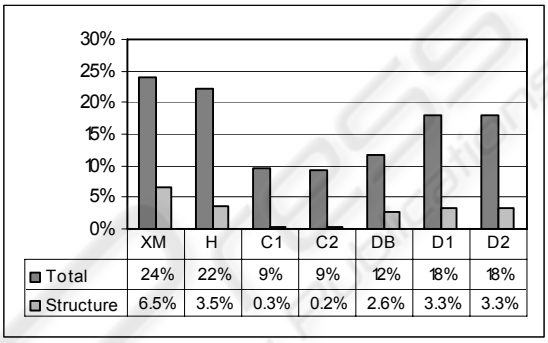
The results of our experiments are shown in Figure 3. Using these datasets, XMill performs better for XM, H, DB, D1 and D2 achieving compression ratios that are up to 2% lower than those of BSBC, whereas BSBC performs better for C1 and C2 achieving compression ratios that are up to 1% lower than those of XMill. However, in contrast to XMill, BSBC allows to evaluate queries on the compressed data and to decompress data only partially.

Our approach, BSBC, performs significantly better than gzip, and has the additional advantage over gzip that query processing can be performed efficiently directly on the compressed data. The improvements in compression ratios over gzip range from 6% to 12%.

Compared to XGrind – an approach that allows efficient query evaluation and partially decompression – our approach, BSBC, achieves a higher compression ratio[3]. The difference of the compression ratios (XGrind minus BSBC) range from 24% to 36%.

Compared to DTDsubtraction, BSBC achieves a higher compression ratio. The differences of the compression ratios (DTDsubtraction minus BSBC) range from 8% to 11%.

In a second series of measurements, we have measured the size of the structure compression, i.e., the constant containers were removed from the compressed data. The results of these experiments are shown in Figure 4.



	XM	H	C1	C2	DB	D1	D2
Total	24%	22%	9%	9%	12%	18%	18%
Structure	6.5%	3.5%	0.3%	0.2%	2.6%	3.3%	3.3%

Figure 4: Structure compression compared to total compression.

Our experiments have shown that especially the structure compression of BSBC is extremely high. While the total compression reaches a ratio of 9% to 24%, the structure compression ranges from 0.2% to 6.5%. The structure compression is up to 40 times stronger than the total compression for C1, in general it is at about 5 times stronger than total compression.

5 RELATED WORK

There exist several XML compression approaches, which can be mainly divided into three categories. First, approaches that avoid redundancies within the string values (of element and attribute names as well as of constants) by using dictionaries and tokenization. Second, approaches that avoid redundancies within the structure, i.e., that avoid multiple occurrences of complete sub-trees within the XML document tree. Finally, approaches that avoid redundancies that occur when schema information is known. All these approaches differ in their features, particularly in whether the compressed data structures can be decompressed partially, whether the compressed data structures are queriable, and whether they support unbounded XML data streams.

[3] Note that on our test computer, we got access violations when running XGrind on XM and DB and therefore the compression ratios for these two documents are missing.

The last category (avoiding external redundancies given by schema information) includes such approaches as XCQ (Ng et al., 2006) and DTD subtraction (Böttcher, Steinmetz, and Klein, 2007). They both separate the structural information from the textual information and then subtract the given schema information from the structural information. Instead of a complete XML structure stream or tree, they only generate and output information not already contained in the schema information (e.g., the chosen alternative for a choice-operator or the number of repetitions for a *-operator within the DTD). Both approaches, XCQ and DTD subtraction, are queriable and applicable to XML streams, but they can only be used if schema information is available.

XQzip (Cheng and Ng, 2004) and the approach presented in (Buneman, Grohe, and Koch, 2003) belong to the second category (avoiding structural redundancies). They compress the data structure of an XML document bottom-up by combining identical sub-trees. Afterwards, the data nodes are attached to the leaf nodes, i.e., one leaf node may point to several data nodes. The data is compressed by an arbitrary compression approach. These approaches allow querying compressed data, but they are not directly applicable to infinite data streams.

An extension of (Buneman, Grohe, and Koch, 2003) and (Cheng and Ng, 2004) is the BPLEX algorithm (Busatti, Lohrey, and Maneth, 2005). This approach does not only combine identical sub-trees, but recognizes patterns within the XML tree that may span several levels, and therefore allows a higher degree of compression. In comparison to BSBC, this approach does not explicitly define how to compress text constants and attribute values contained in XML data and how to distinguish both in the compressed XML format.

The first category (avoiding textual redundancies by tokenization) allows for a much faster compression approach than the second one, as only local data has to be considered in the compression as opposed to considering different sub-trees as in the second category.

The XMill algorithm (Liefke and Suciu, 2000) is an example of the first category. It compresses the structural information separately from the data. Data is grouped according to its enclosing element and collected into several containers, and each container is compressed afterwards. The structure is compressed, by assigning each tag name a unique and short ID. Each end-tag is encoded by the symbol '/'. This approach does not allow querying the compressed data.

XGrind (Tolani and Hartisa, 2002), XPRESS (Min, Park, and Chung, 2003) and XQueC (Arion et al., n.d.) are extensions of the XMill-approach. Each of these approaches compresses the tag information using dictionaries and Huffman-encoding (Hufman, 1952) and replaces the end-tags by either a '/'-symbol or by parentheses. All three approaches allow querying the compressed data, and, although not explicitly mentioned, they all seem to be applicable to data streams.

Approaches (Bayardo et al., 2004), (Cheney, 2001), and (Girardot and Sunderesan, 2000) are based on tokenization. (Cheney, 2001) replaces each attribute and element name by a token, where each token is defined the first time it is used. (Bayardo et al., 2004) and (Girardot and Sunderesan, 2000) use tokenization as well, but they enrich the data by additional information that allows for a fast navigation (e.g., number of children, pointer to next-sibling, existence of content and attributes). All three of them use a reserved byte to encode the end-tag of an element. They are all applicable to data streams and allow querying the compressed data.

The approach in (Ferragina et al., 2006) does not belong to any of the three categories. It is based on Burrows-Wheeler Block-Sorting (Burrows and Wheeler, 1994), i.e., the XML data is rearranged in such a way that compression techniques such as gzip achieve higher compression ratios. This approach is not applicable to data streams, but allows querying the compressed data if it is enriched with additional index information.

The approach in (Zhang, Kacholia, and Özsu, 2004) is another succinct representation of XML. It does not separate the raw data structure that describes the document tree from the tokens representing the elements. Therefore, one byte is required to represent an end-tag, whereas our approach, BSBC, only needs one bit. Furthermore, our separation of structural data from element names does not only allow for a better compression as shown in the evaluation; it also enables a more efficient evaluation of path queries because raw bit data can be compared more efficiently than tokens. A second difference is our use of inverted element lists instead of token-dictionaries, which additionally increases the speed of path query evaluation significantly because the number of possible path hits can be reduced quite fast with a simple lookup within the inverted list.

To the best of our knowledge, the separation of an XML stream into different compressed streams linked by a bit stream that is also used to evaluate path queries is unique to our compression technique,

and there is no other XML compression system that combines the advantages of our approach.

6 SUMMARY AND CONCLUSIONS

We have presented Bit-Stream-Based-Compression (BSBC), a two-step XML compression approach that is based on DAG compression and supports the compression of XML streams and path queries on compressed data by combining the following advantages. First, both transformation steps can be executed in a pipelined fashion, which avoids storing intermediate data or streams. Second, an XML data stream is separated into its constituent parts: the DAG structure, represented as a bit stream and a sub-tree pointer stream; the sequence of elements and attributes, stored in inverted lists together with their corresponding bit stream positions; and finally, the constants, stored in different containers depending on the element or the attribute embedding the value. This separation allows adapting the compression technique to the node type, i.e., to compress elements and attributes different from constants. Third, the bit stream and the sub-tree pointer stream support fast navigation along all the forward axes. Forth, inverted lists not only provide a better compression of elements and attributes, but, in combination with the bit stream, they also support efficient path queries. Fifth, constants are grouped together according to their embedding element or attribute to achieve better compression.

Our comparative evaluation with other available XML compression approaches shows that BSBC achieves a better compression ratio within our experiments than the other approaches that support path queries, i.e. XGrind and DTD substraction, that BSBC beats gzip, and that BSBC even sometimes beats XMill.. BSBC is thus a very useful technique for applications that require the exchange and querying of large XML data sets or XML streams on platforms with limited bandwidth or energy, as e.g. mobile networks.

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