Lempel-Ziv Compression of Highly Structured Documents *†

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Abstract

We describe *LZCS*, a novel Lempel-Ziv approach suitable for compressing structured documents. LZCS takes advantage of repeated substructures that may appear in the documents, by replacing them with a backward reference to their previous occurrence. The result of the LZCS transformation is still a valid structured document which is human-readable and can be transmitted by ASCII channels. Moreover, LZCS transformed documents are easy to search, display, access at random, and navigate. In a second stage, the transformed documents can be further compressed using any semi-static technique, so that it is still possible to do all those operations efficiently; or with any adaptive technique to boost compression. LZCS is especially efficient to compress collections of highly structured data, such as XML forms, invoices, e-commerce and web-service exchange documents. The comparison with other structure-aware and standard compressors shows that LZCS is a competitive choice for this type of documents, while the others are not well-suited to support navigation or random access. When joined to an adaptive compressor, LZCS obtains by far the best compression ratios.

Keywords: Lempel-Ziv, XML Data, Structured Documents, Text Compression.

1 Introduction

The storage, exchange, and manipulation of structured text as a device to represent semistructured data is spreading across all kinds of applications, ranging from text databases and digital libraries to web-services and electronic commerce. Structured text, and in particular the XML format, is becoming a standard to encode data with simple or complex, fixed or varying structure. Although XML has been envisioned as a mechanism to describe structured data from some time ago, it has been the recent explosion of business-to-business applications that has shown its potential to describe all sorts of documents exchanged between and stored inside organizations. Examples are invoices, receipts, orders, payments, accounting, and other forms.

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Although the information stored by an organization is usually kept in relational databases and/or data warehouses, it is important to store digital sources, in XML format, of all the documents that have been exchanged and/or produced along time. A structured text retrieval engine should provide random access to those structured documents, so that they should be easily searched, visualized, and navigated. On the other hand, as usual, we would like this repository to take as little space as possible.

In this paper we focus on the compression of structured text. We aim specifically at compression of highly structured data, such as forms where there is little text in each field. Collections formed by those types of forms contain a lot of redundancy that is not captured well enough by classical compression methods. At the same time, we want the compressed collection to be easily accessed, visualized and navigated in compressed form. The most effective compression methods do not account for these capabilities: texts have to be uncompressed before they can be accessed.

It is usually argued that disk space is cheap and thus compression is not interesting. Compression, however, does not only save space, but it also saves disk and network transfer time, which are highly valuable resources. Hence the interest of compression by itself. Moreover, the types of texts we are focusing on in this paper are highly compressible: We will show that we can compress them up to 1% of their original size. With this compression ratio, it is likely that we can load the compressed text database in main memory, albeit we are unable to decompress it wholly into main memory. Hence the interest of manipulating and navigating the structure in compressed form, extracting only the documents we actually need.

We develop a compression method that we refer to as *Lempel-Ziv to Compress Structure (LZCS)*. The method is inspired by Lempel-Ziv compression, where repeated substructures are factored out. In the method, every time a repeated substructure is detected, it is replaced by a backward reference to its previous occurrence. The result of this *LZCS transformation* is a text that is still human-readable and well structured. Thus, it can be seamlessly transmitted over ASCII channels, handled by structured text management tools, and visualized in compressed form with conventional means. It is very fast and simple to decompress, in whole or in parts, and it can be accessed at random without need of decompressing the preceding text. With little additional effort, the compressed document can be browsed and navigated without decompressing it. As a plus, the LZCS transformed text can be searched for words or phrases using conventional algorithms directly in compressed form (and thus much faster than on the original text). This search, however, is limited: It tells whether the word or phrase appears in the text, but not the positions where it occurs.

Another rich source of highly structured documents is automatically generated structured text. In [SK04], the case of HTML-formatted documents generated from WYSIWYG interfaces is studied in detail, showing that they contain large amounts of redundancy. They apply HTML-specific techniques to obtain equivalent documents that are up to 1/3 of the original size.

LZCS provides an alternative solution to this problem. Instead of transforming a redundant document to a smaller, semantically similar one, we could compress it as-is, so that we could access and manipulate it in compressed form.

Compared to LZ77 [ZL77], which can factor out *any* repeated text substring, LZCS is restricted to consider only whole substructures. As a result, LZ77 compresses more than the LZCS transformation, yet the LZ77 compressed text lacks all of the LZCS features described above, except for the fast decompression. It is interesting that we build on an adaptive compressor (LZ77) that does

not permit local decompression, and obtain a compressor that does permit local decompression, navigation, and many other features.

To improve compression, the LZCS transformed text can be further compressed with a classical compressor. The use of a semi-static compressor retains fast decompression in whole or in parts, random access, and the possibility of direct searching, browsing and navigating the compressed document. In particular, we show that the use of a semi-static word-based Huffman method to compress the LZCS transformed text yields very competitive compression ratios, only beaten by adaptive schemes that do not permit any of the features we have described above. Adaptive schemes are suitable to compress an archival collection, but not a database that must frequently retrieve individual documents. On the other hand, it is possible to apply adaptive compression after the LZCS transformation, losing all the features retained by semi-static compression but boosting the compression ratio. In particular, we show that the combination of LZCS and an adaptive PPM compressor is unbeaten in compression ratio.

We show how the LZCS transformation can be carried out in linear expected time and in a single pass over the text. This means that we can start producing the transformed text shortly after starting reading the source text. This makes LZCS suitable for use over a communication network without introducing any delay in the transmission. For example, LZCS can be transparently used to transmit structured documents, even over a plain ASCII channel, in order to reduce communication time. The receiver needs very little computational power to decompress, and it can even navigate or display parts of the document without decompressing all of it.

The paper is organized as follows. In Section 2 we cover related work on compression, both for plain and structured text. In Section 3 we describe the LZCS transformation. In Section 4 we explain how the transformation can be carried out in linear expected time. In Section 5 we show empirical results comparing the compression ratio, as well as compression and decompression performance, of LZCS compared to other standard and structure-aware compressors. We conclude in Section 6 with future work directions.

2 Related Work

2.1 Standard Text Compression

In general, classic text compression methods [BCW90, MT02] do not take into account the structure of the documents they compress. Our aim is not to cover the whole area but just to focus on three families of compressors that are relevant for this paper.

Text compression is usually divided into two kinds. *Statistical* compression is based on estimating source symbol probabilities and assigning them codes according to the probabilities. *Dictionary* methods consist in replacing text substrings by identifiers, so as to exploit repetitions in the text. Statistical compression is conceptually divided into two tasks. *Modeling* regards the text as a sequence of *source symbols* and assigns probabilities to them, possibly depending on their surrounding symbols. *Zero-order* modeling assigns probabilities to the symbols regarding them in isolated form, while *k-th order* modeling assigns their probabilities as a function of the k symbols preceding them. *Coding* assigns to each source symbol a sequence of *target symbols* (its *code*), based on the probabilities given by the model. The output of the compressor is the sequence of target symbols given by the coder. Compression is *semi-static* when a single model is obtained for the whole text before coding

starts, so that all the occurrences of the same source symbol (in the same context) are assigned the same code. *Adaptive* compression interleaves the modeling and coding tasks, so that the model is built and updated as coding progresses. In adaptive compression, each new symbol is encoded using the current model and therefore different occurrences of the same source symbol may be assigned different codes.

Semi-static compression requires two passes over the text, as well as storing the model together with the compressed file. On the other hand, adaptive compression cannot start decompression at arbitrary file positions, because all the previous text must be processed so as to learn the model that permits decompressing the text that follows.

Lempel-Ziv. Lempel-Ziv compression is a dictionary method based on replacing text substrings by previous occurrences thereof. The two most famous algorithms of this family are called LZ77 [ZL77] and LZ78 [ZL78]. A well-known variant of the latter is called LZW [Wel84].

LZ77 maintains a window of the last N processed characters. In each step, it reads the longest possible string s from the input that also appears in the window. If s is of length ℓ, it is followed by character a in the input, and it was found at window position p (counting right to left), then the compressor outputs the triple (p, ℓ, a). Thus input string sa is replaced by the triple, and compression is obtained if the triple needs less bits than the string itself. Once this is done, the window is shifted forward by $\ell + 1$ positions and the algorithm resumes the scanning just past string sa.

In principle the use of a longer window improves compression because it makes more likely to find longer strings for replacement. However, the representation of position p requires $\log_2 N$ bits, which worsens as N grows. In practice the most convenient window size is not very long (for example, 64 kilobytes). This considers not only the achievable compression but also the time and space cost of searching the window for strings.

Decompression of LZ77 compressed files is extremely fast and simple. The compressed text is basically a sequence of triples (p, ℓ, a). For each such triple we must copy ℓ characters starting p positions behind the current output position, and then output a. Well-known representatives of LZ77 compression are Info-ZIP's *zip* and GNU's *gzip*.

Other variants, such as LZ78 and LZW, restrict somehow which previous strings can be referenced. This is done for efficiency reasons of different types, for example to improve compression time or to improve the compression ratio. However, the choice of strings that can be referenced does not take into account the meaning of those strings. A well-known representative of LZW is Unix's *compress*.

The Lempel-Ziv family is the most popular to compress text because it combines compression ratios around 35% on plain English text[1] with fast compression and decompression. However, Lempel-Ziv compressed text cannot be decompressed at random positions, because one must process all the text from the beginning in order to learn the window that is used to decompress the desired portion.

An interesting Ziv-Lempel variant [BM01] uses ideas somehow related to our approach. They give a way to name long repeated substrings using short pointers, to boost compression. They

[1] That is, the compressed text size is 35% of the uncompressed text size.

produce a plain text with embedded backward pointers, which can then be postprocessed by a bitwise compressor. Still, no attention is paid to the text structure.

Huffman. Huffman coding [Huf52] is designed for statistical compression. It assigns a variable-length code to each source symbol, trying to give shorter codes to more probable symbols. Huffman algorithm guarantees that the code assignment minimizes the length of the compressed file under the probabilities given by the model.

A common usage of Huffman coding is to couple it with semi-static zero-order modeling, taking text characters as the source symbols and bits as the target symbols. That is, on a first pass over the text, character frequencies are collected, then Huffman codes (variable-length bit sequences) are assigned to the characters, and finally each character occurrence is replaced by its codeword in a second pass over the text. This combination, that we call "Huffman compression" for shortness, reaches the zero-order entropy of the text up to one extra bit per symbol. Being semi-static, Huffman compression permits easy decompression of the text starting at any position.

Huffman compression is not very popular on natural language text because it achieves poor compression ratios compared to other techniques. However, the situation changes drastically when one uses the text *words*, rather than the characters, as the source symbols [Mof89]. The distribution of words is much more skewed than that of symbols, and this permits obtaining much better compression ratios than character-based Huffman compressors. On English text, character-based Huffman obtains around 60% compression ratio, while word-based Huffman is around 25% [ZMNBY00]. Actually, similar compression ratios can be obtained by using Lempel-Ziv on words [BSTW86, HC92, DPS99].

Word-based Huffman compression has other advantages. Not only the text can be compressed and decompressed efficiently, as a whole or in parts, but it is also possible to search it without decompressing, *faster* than when searching the uncompressed text [ZMNBY00]. Also, this type of compression integrates very well with information retrieval systems, because the source alphabet is equivalent to the vocabulary of the inverted index [WMB99, NMN+00, MW01]. One of the best known systems in the public domain relying on word-based Huffman is the MG system [WMB99].

K-th order models. These models assign a probability to each source symbol as a function of the *context* of k source symbols that precede it. They are used to build very effective compressors such as Prediction by Partial Matching (PPM) and those based on the Burrows-Wheeler Transform (BWT).

PPM [CW84] is a statistical compressor that models the character frequencies according to the context given by the k characters preceding it in the text, and codes the characters according to those frequencies using arithmetic coding [WNC87]. PPM is adaptive, so the statistics are updated as compression progresses. The larger k, the more accurate is the statistical model and the better the compression, but more memory and time is necessary to compress and decompress.

More precisely, PPM uses $k+1$ models, of order 0 to k, in parallel. It usually compresses using the k-th order model, unless the character to compress has never been seen in that model. In this cases it switches to a lower-order model until the character is found.

The BWT [BW94] is a reversible permutation of the text that puts together characters having the same k-th order context (for any k). Local optimization over the permuted text obtain results

similar to k-th order compression (for example, by applying move-to-front followed by Huffman or arithmetic coding).

PPM and BWT usually achieve better compression ratios than other families (around 20% on English text), yet they are much slower to compress and decompress, and cannot decompress arbitrary portions of the text collection. Well known representatives of this family are Seward's *bzip2*, based on the BWT, and Shkarin/Cheney's *ppmdi* and Bloom/Tarhio's *ppmz*, two PPM-based techniques.

2.2 Structured Text Compression

There exist a few approaches specifically designed to compress structured text, taking advantage of its structure.

XMill [LS00]. Developed at AT&T Labs, *XMill* is an XML-specific compressor designed to exchange and store XML documents. Its compression approach is not intended for directly supporting querying or updating the compressed documents. *XMill* is based on the *zlib* library, which combines Lempel-Ziv compression with a variant of Huffman. Its main idea is to split the file into three components: elements and attributes, text, and structure. Each component is compressed separately. Another Lempel-Ziv based compressor, cutting the structure at some depth and using plain Lempel-Ziv compression for the subtrees, is commercial *XMLZip* (`http://www.xmls.com`).

XMLPPM [Che01]. This is a PPM-like compressor, where the context is given by the path from the root to the tree node that contains the current text. *XMLPPM* is an adaptive compressor that does not permit random access to individual documents. The idea is an evolution over *XMill*, as different compressors are used for each component, and the XML hierarchy information is used to improve compression.

XCQ [LW02] and Exalt [Tom04]. These are compression methods based on separating structure from data, and then using grammar-based compression for the structure. In *XCQ*, the tree shape is compressed using the DTD[2] information, while the text is compressed using a standard Lempel-Ziv software such as *gzip*. In *Exalt*, both elements are compressed using grammar-based methods. In particular, zero-order prediction depending on the structural context, plus arithmetic coding, is used for the tags. Other grammar-based techniques can be found in [Tar01], as well as in *XML-Xpress*, a commercial software (`http://www.ictcompress.com`) that compresses well when the DTD is known.

XGrind [TH02]. This compressor is interesting because it directly supports queries over the compressed files. An XML document compressed with *XGrind* retains the structure of the original document, permitting reuse of the standard XML techniques for processing the compressed document. Structure tags are represented in numeric form, while the text is compressed using character-oriented Huffman. A similar idea is explored in *XMillau* [GS00].

[2]Document Type Declaration, which describes the syntax of the XML document, see `www.w3.org/TR/REC-xml`, section 2.8.

SCMHuff [ANdlF03] and SCMPPM [AdlFN04]. SCM is a generic model used to compress semistructured documents, which takes advantage of the context information usually implicit in the structure of the text. The idea is to use a separate model to compress the text that lies inside each different structure type. *SCMHuff* uses a word-based Huffman compressor for each different tag, while *SCMPPM* uses a PPM compressor. The former permits random access to individual documents, while the latter cannot.

3 The LZCS Transformation

The LZCS transformation is a new technique to compress structured text, such as XML or HTML. The main idea is based on the Lempel-Ziv concept, so that repeating substructures and whole text blocks inside a structure or between two structural elements are replaced by a backward reference to their first occurrence in the processed document. The result is a valid structured text with additional backward reference tags that can be transmitted, handled or visualized in a conventional way, or further compressed using some classical compressor.

We start by formally describing the LZCS transformation, then present an example, and finally discuss its features.

3.1 Formal Definition

Definition 1 (Text Block) *A text block is any maximal consecutive character sequence not containing structure or backward reference tags.*

Definition 2 (Structural Element) *A structural element is any consecutive character sequence that begins with a start-tag and finalizes with its corresponding end-tag.*

Observe that structural elements not containing further internal structure make up a single text block. Also, all the inter-structural texts form text blocks. Let u be a structural element with children u_1 to u_k. Then the whole text between the start-tags of u and u_1, and between end-tags of u_k and u, make up text blocks, as well as the whole text between the end-tag of u_i and the start-tag of u_{i+1}, for each $1 \leq i < k$.

On the other hand, a structural element can contain one or more text blocks, one or more structural elements and/or (after the LZCS transformation) one or more backward reference tags. For simplicity, other types of valid tags (such as comment tags and self-contained tags in XML) will be treated as conventional text, and only start-tags and end-tags will be used to identify structural elements. Furthermore, tags will be treated as atomic elements. In particular, the XML attributes and values inside a tag are part of the tag name, and do not form text blocks.

The structure induces a hierarchy that can be represented as a tree. Text blocks will be represented by leaves, and structural elements by subtrees rooted at internal nodes.

Definition 3 (Node) *A* node *is either a text block or a structural element.*

The main point of LZCS is to replace some subtrees by references to equivalent subtrees seen before.

Definition 4 (Equivalent Nodes) *Let $\mathcal{N}_1$ and $\mathcal{N}_2$ be two nodes that appear in a collection. We will say that node $\mathcal{N}_1$ is equivalent to node $\mathcal{N}_2$ iff $\mathcal{N}_1$ is textually equal to $\mathcal{N}_2$.*

Definition 5 (Maximal Replaceable Nodes) *A node is maximal replaceable if (i) it is equivalent to a previous node and (ii) does not descend from another node satisfying (i) (that is, it is maximal among nodes satisfying (i)).*

We are ready to define the LZCS transformation.

Definition 6 (LZCS Transformation) *LZCS replaces each maximal replaceable node by a backward reference to its first occurrence in the transformed text. Other elements are left unchanged.*

A *backward reference* is represented by a special tag in the output. The special tag is constructed by means of the delimiters `"<@"` and `">"` that mark the beginning and end of the backward reference tag. The content of this tag will be formed by digits that express an unsigned integer indicating the absolute position in the transformed text where the referenced element begins. For space optimization, this number will be expressed in base 62, using `0..9`, `A..Z` and `a..z` as digits. This way, the transformed text is still ASCII and well-structured. The reference tag has been chosen to void tag name clashes in XML, but it can be changed.

It may happen that a referenced text block is smaller than the reference itself (for example, when the text block is formed only by character `'\n'`). In these circumstances, replacing it by a reference is not a good choice. Hence we do not replace text blocks that are shorter than a user-specified parameter l. The choice of l influences compression ratio, but not correctness.

3.2 Example

Assume that we are going to compress the collection of three documents represented in Figure 1 using LZCS. There exist three different structural elements represented by circles in the figure. The structural elements of type 1 (A, F, M) have their circle drawn with a solid line, those of type 2 (B, E, G, J, N) with a dashed line, and those of type 3 with a dotted line. Text blocks are represented by squares.

Letters and numbers in Figure 1 represent node identifiers. To illustrate the main steps of the LZCS algorithm let us assume that the text blocks numbered 1, 4, 7 and 9 in the figure are equivalent. Also assume that text blocks numbered 3 and 10 are equivalent, as well as those numbered 6 and 8. As a result, the documents share repeating parts, represented as equal subtrees. Figure 2 shows graphically these correspondences and Figure 3 shows the collection transformed with LZCS.

Finally, Figure 4 shows a textual version of the original and transformed documents. Note that the LZCS transformed text is a valid structured document, provided we accept `"<@...>"` as a valid self-contained tag.

3.3 Properties of the LZCS Transformed Text

As mentioned in the Introduction, the LZCS transformation has a number of attractive features, which we describe now more in depth.

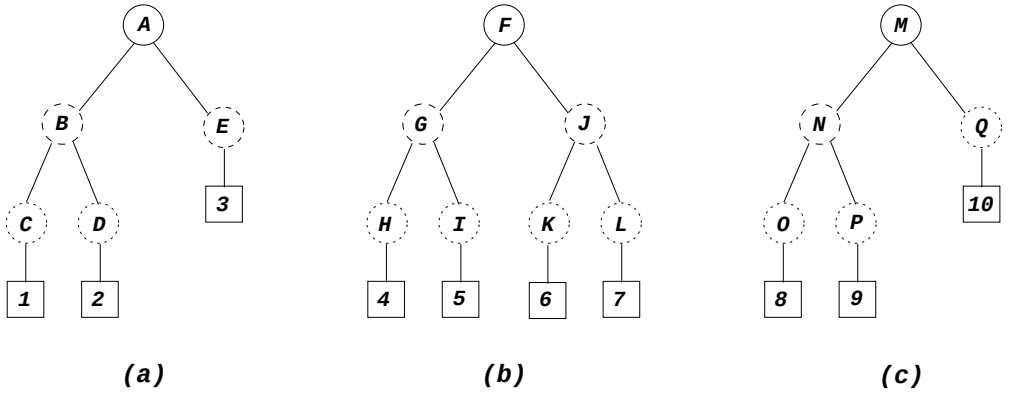


Figure 1: Three example documents.

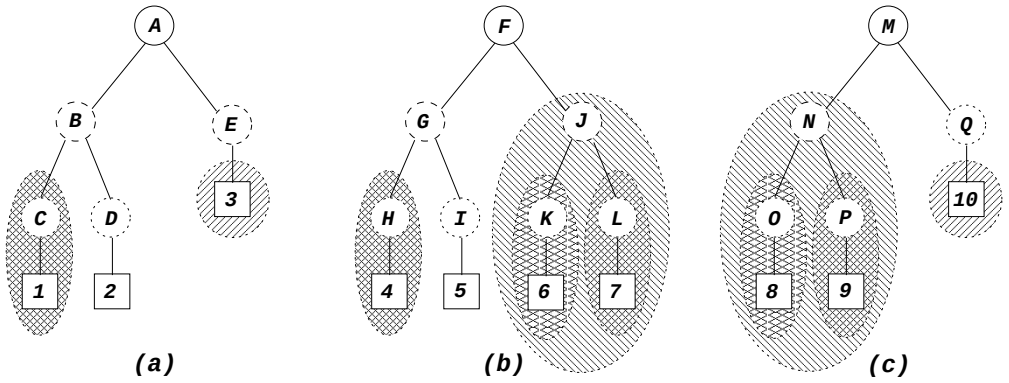


Figure 2: Equivalent subtrees of the documents.

Human readable: The output of the transformation is human-readable, as shown in the right column of Figure 4. This means that the transformed file can be read with any conventional text editor or terminal.

ASCII compliant: The only new characters introduced by LZCS are `'<'`, `'>'`, `'@'`, letters and digits. Therefore, an LZCS transformed document can be transmitted by any ASCII channel. For example it can be sent by email without any concern. Therefore, the LZCS could be transparently used by servers to transfer structured documents to clients, even over ASCII channels.

Well structured: The LZCS transformed text is a well formed structured document. As such, it can be handled with any tool that manages structured documents (in XML, for example). The only exception is that LZCS produces a special self-contained tag, `"<@...>"`, which must be dealt with as any other such tag. We could perfectly use instead a conventional self-contained tag to avoid any exception, such as `"<ref pos=.../>`, but we chose otherwise to avoid any

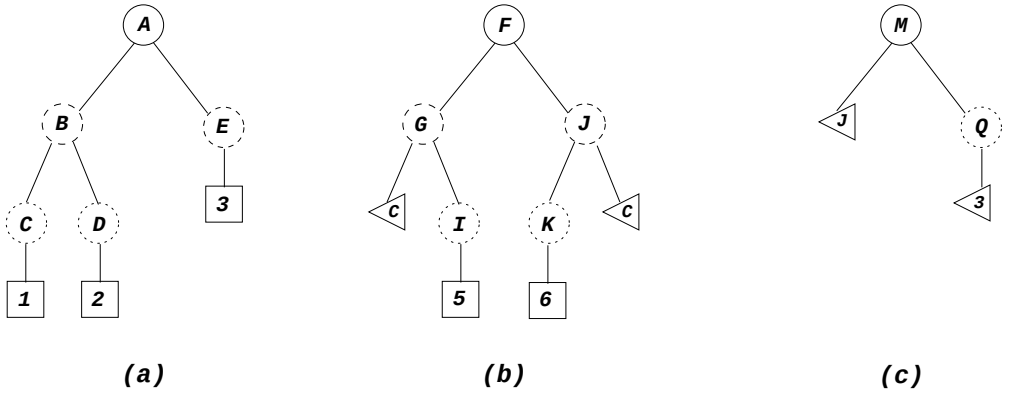


Figure 3: Example documents after applying the LZCS transformation. Backward references are represented by triangles.

possibility of clashing with the actual tags of the documents, and to have shorter references.

Directly searchable: The LZCS transformed text contains the same words and phrases of the original documents. A phrase cannot be split unless its words belong to different structural elements, in which case it is arguably not a phrase. Although the number of occurrences of words and phrases will change between the original and the transformed documents, a word or phrase is present in the original text if and only if it is present in the transformed text. Thus, the LZCS transformed text can be searched for words and phrases with any conventional string matching algorithm (such as GNU's *grep*) to determine whether the phrase appears or not. If the phrase appears, decompression is necessary to point out all the documents where it appears. Note in particular that the search on the LZCS transformed text will be *faster* than on the original text, as the original text is longer (in our experiments, 100 times longer).

Fast to decompress: Decompressing an LZCS transformed text is pretty much as decompressing LZ77, and therefore, very fast and simple. An important difference is that LZ77 uses pointers to the uncompressed file, so it can just copy the referenced uncompressed text to the output. LZCS, on the other hand, uses pointers to the compressed file, so it must recursively obtain the output text from the compressed file. This makes LZCS decompression somewhat slower, but in exchange LZCS allows navigating the compressed file and extracting individual documents without decompressing the whole text.

Easily navigable and visualizable: LZCS transformed documents can be navigated in the usual way (that is, going down and up in the hierarchy as with a tree). Instead of relying on any kind of parent pointer associated to nodes, we must use a stack to keep track of the current ancestors of the current node. Every time we have to go down to a child, it might be that the child is a backward reference or not. In the former case, we just move the current text position to the appropriate point back in the compressed file. All the rest is unchanged. When moving upwards, we pop the corresponding file position from the stack of ancestors.

```
A: <log>
B:    <entries>
C:       <event>
1:          Bug report
         </event>
D:       <event>
2:          Release announce
         </event>
      </entries>
E:    <entries>
3:       No further events
      </entries>
   </log>
F: <log>
G:    <entries>
H:       <event>
4:          Bug report
         </event>
I:       <event>
5:          New version
         </event>
      </entries>
J:    <entries>
K:       <event>
6:          Bug fix
         </event>
L:       <event>
7:          Bug report
         </event>
      </entries>
   </log>
M: <log>
N:    <entries>
O:       <event>
8:          Bug fix
         </event>
P:       <event>
9:          Bug report
         </event>
      </entries>
Q:    <event>
10:      No further events
      </event>
   </log>
```

```
A: <log>
B:    <entries>
C:       <event>
1:          Bug report
         </event>
D:       <event>
2:          Release announce
         </event>
      </entries>
E:    <entries>
3:       No further events
      </entries>
   </log>
F: <log>
G:    <entries>
H:       <@C>
I:       <event>
5:          New version
         </event>
      </entries>
J:    <entries>
K:       <event>
6:          Bug fix
         </event>
L:       <@C>
      </entries>
   </log>
M: <log>
N:    <@J>
Q:    <event>
10:      <@3>
      </event>
   </log>
```

Figure 4: The same example documents in textual form. The original document is on the left and the LZCS transformed document on the right. For readability we write references to line labels (uppercase letters and numbers) instead of character offsets. We remind that the references are offsets in the compressed text, not in the original text.

Accessible at random positions: With the algorithm above we can also produce the uncompressed text of any document, by simply starting decompression at its start-tag and following any reference as necessary.

Thus, LZCS can be integrated into a structured text retrieval system without loss (and in cases large gains) of efficiency in the search or visualization of results. As demonstrated in our experiments, the compression ratios are so good (1%) that it is feasible to maintain large collections compressed in main memory, even when there is not enough main memory to decompress all of it. LZCS is perfect for this scenario, as it can navigate, visualize and decompress individual documents without having to decompress the whole collection.

The LZCS transformed text can be further compressed with any conventional method. Since the documents generated by LZCS are navigable, a good idea is to further compress them using a semi-static compression method, like word-based Huffman. After this process, the documents cannot anymore be handled as plain text (a word-wise decompression is needed), but they are still navigable and accessible at random positions. Direct search over word-based Huffman is also possible and very efficient. On the other hand, we can use an adaptive compression to boost the compression ratio. LZCS can be seen as a preprocessing stage that factors out some types of redundancies, so that a further adaptive compressor takes much less time and can compress more than when applied over the original text (this could work or not, but we show experimentally that this is the case).

4 Efficient Implementation of the LZCS Transformation

A challenge with the LZCS transformation is how to implement it efficiently, as we must detect substructures that have appeared in the past. The simplest way to implement the LZCS transformation is by searching all previously processed text for each new structural element. This way, we have a complexity of $O(n^2)$, which is unacceptable.

We show now how to obtain $O(n)$ average time. The idea is to maintain a hash table with all the whole text blocks, as well as all the structural elements, seen in the past. While hashing text blocks is not new (see, e.g., [Wil91]), recognizing repeated structural elements in linear expected time requires more careful design.

When a text block is processed, we first obtain its digital signature (for example, using MD5 algorithm [Riv92][3]). If the text block is not equivalent to any previous text block (its signature does not coincide with previous ones), then the text block is copied verbatim to the output and its signature is added to the (hashed) set of signatures of original text blocks, together with the text position of the block (which is the first occurrence of this block in the output). Otherwise, if an equivalent text block appears (their digital signatures coincide) a backward reference to the first occurrence of the text block is written to the output. Since digital signature algorithms do not ensure that signatures are unique, texts are also directly compared when a coincidence arises. A similar approach is taken in [BM01].

In order to apply hashing to structure elements, a node signature is generated and stored, along with its start position in the output, for each new node that has not appeared before. Node signatures of parent nodes are produced after those of children nodes.

[3]Message Digest Algorithm 5, which computes a cryptographic signature of a message such that finding another message with the same signature is difficult.

Definition 7 (Node Signature) *A node signature is formed by concatenating its tag identifier and children identifiers. These are either their start text positions in the output if they are not references, or their referenced positions otherwise.*

As we show in Lemma 2, a node signature is unique within a collection. For each new structure element, its node signature is generated and searched for among the existing ones. If a coincidence is found then the current structure element is equivalent to a previous one, and it can be replaced.

Next lemma is useful to prove the correctness of this hashing scheme.

Lemma 1 *Let $\mathcal{N}$ and $\mathcal{N}'$ be two nodes that appear in a collection transformed with LZCS up to node $\mathcal{N}'$, $\mathcal{N}$ preceding $\mathcal{N}'$. Then, $\mathcal{N}$ is equivalent to $\mathcal{N}'$ iff $\mathcal{N}'$ is a backward reference to $\mathcal{N}$, or $\mathcal{N}$ and $\mathcal{N}'$ are equal backward references.*

Proof: We prove the equivalence in both directions.

1. If $\mathcal{N}$ is equivalent to $\mathcal{N}'$ then the LZCS transformation replaces $\mathcal{N}'$ by a backward reference to its first occurrence:

   (a) If $\mathcal{N}$ is the first occurrence then $\mathcal{N}'$ is replaced by a backward reference to $\mathcal{N}$.

   (b) Otherwise, let $\mathcal{N}_0$ be the first occurrence of $\mathcal{N}'$, then $\mathcal{N}'$ is replaced by a backward reference to $\mathcal{N}_0$, but also $\mathcal{N}$ was replaced by a backward reference to $\mathcal{N}_0$.

   Thus, it holds that either $\mathcal{N}'$ is a backward reference to $\mathcal{N}$, or $\mathcal{N}$ and $\mathcal{N}'$ are equal backward references.

2. If $\mathcal{N}'$ is a backward reference to $\mathcal{N}$, or $\mathcal{N}'$ and $\mathcal{N}$ are equal backward references, then $\mathcal{N}$ is equivalent to $\mathcal{N}'$, because in both cases it holds that $\mathcal{N}$ and $\mathcal{N}'$ contents are textually equal. □

Bearing in mind Lemma 1, we show next that the node signature is unique and works correctly.

Lemma 2 *Nodes $\mathcal{N}$ and $\mathcal{N}'$ are equivalent iff their node signature are equal.*

Proof: We observe that a node can repeat only if all its children repeat as well. Therefore, a node $\mathcal{N}$, parent of $\mathcal{N}_1 \ldots \mathcal{N}_k$, is textually equal to a later node $\mathcal{N}'$, parent of $\mathcal{N}'_1 \ldots \mathcal{N}'_k$, iff tag identifiers of $\mathcal{N}$ and $\mathcal{N}'$ are equal and $\forall i \in 1..k, \mathcal{N}'_i$ is equivalent to $\mathcal{N}_i$. By Lemma 1, the latter means that either $\mathcal{N}'_i$ points to $\mathcal{N}_i$, or $\mathcal{N}'_i$ points to some $\mathcal{N}_0$ and $\mathcal{N}_i$ points to $\mathcal{N}_0$. According to Def. 7, in the first case both children identifiers are $\mathcal{N}_i$, and in the second both are $\mathcal{N}_0$. These conditions are necessary and sufficient for the node signatures of $\mathcal{N}$ and $\mathcal{N}'$ being equal. □

We are now ready to explain the LZCS transformation algorithm. When an end-tag appears its corresponding node signature is obtained and searched for in the (hashed) set of node signatures. If the current node signature is present in the set, then it can be replaced by a backward reference. However, at this point we are not sure that the current node is maximal replaceable (Def. 5). Therefore the substitution is done only in memory, but nothing is yet written to the output. On

LZCS Transformation

```
NodeSigSet ← ∅
TextSigSet ← ∅
PreviousSubtree ← ⟨ ⟩
while there are more nodes do
        current_node ← get_node()    // in postorder
        if (current_node is a Text Block)
          then
                current_signature ← MD5(current_node)
                if (current_signature ∈ TextSigSet)
                  then
                        reference ← TextSigSet.reference(current_signature)
                        PreviousSubtree.add(reference)
                   else
                        current_position ← StartPosition(current_node)
                        TextSigSet.add(current_signature, current_position)
                        Write PreviousSubtree to the output
                        Write current_node to the output
                        PreviousSubtree ← ⟨ ⟩
                fi
           else
                current_signature ← NodeSignature(current_node)
                if (current_signature ∈ NodeSigSet)
                  then
                        reference ← NodeSigSet.reference(current_signature)
                        PreviousSubtree.erase_children(current_node)
                        PreviousSubtree.add(reference)
                   else
                        current_position ← StartPosition(current_node)
                        NodeSigSet.add(current_signature, current_position)
                        Write PreviousSubtree to the output
                        Write current_node to the output
                        PreviousSubtree ← ⟨ ⟩
                fi
        fi
od
Write PreviousSubtree to the output
```

Figure 5: LZCS transformation algorithm.

the other hand, if the current node signature is not present in the set, then the current subtree is not equivalent to any previous one and, therefore, non-written children and current node must be written to the output. Also, the current node signature is added to the set of node signatures.

Figure 5 describes the basic LZCS transformation. List *PreviousSubtree* contains the elements that have been converted to references but are not yet output because we do not know whether they are maximal. If we are currently processing some tree node, then *PreviousSubtree* may contain siblings to the left of the node and of ancestors of the node. By adding new nodes at the end of the set we know that, once we go back to the parent node, the latter elements of the set are all the children of that parent node. This permits implementing *PreviousSubtree.erase_ children* easily, just by knowing the arity of current node.

Also note that, if a subtree is not repeated, then no ancestor of it can be repeated. As all the elements in *PreviousSubtree* have not yet been sent to the output just because it might be that their parent (an ancestor of the current node) might be repeated, as soon as we know that the current node is not repeated we send all *PreviousSubtree* to the output. This is not strictly necessary (one could only send the children of the current node to the output, and previous elements would wait that their parent sends them) but it simplifies the algorithm, as the list to maintain is shorter and always composed of references.

Parameter l must be handled carefully. If we simply copy short blocks to the output without generating a signature for them, we will not be able to recognize any subtree containing short text blocks, because we require equal signatures. Instead, we process them fully, and only make a difference within *Write PreviousSubtree to the output*. At this point, when we are going to output a reference that points to a text block shorter than l, we instead output the text itself.

Decompression is very simple. It begins by writing the text to the output. When a backward reference tag is found, we recursively start decompression from the referenced position in the compressed text. If the text at that position begins with a start-tag, the recursive call will finish when the corresponding end-tag is written. Otherwise, it will finish when the first start-tag or end-tag appears. Upon returning from the recursive call, the main process resumes decompression from past the backward reference tag. Recursion is necessary because further backward references may appear when processing the text referenced by the first one.

Figure 6 gives the pseudocode for the LZCS inverse transformation. The pseudocode is simplified, for example it is implicit that matching the "corresponding end-tag" that finishes a reference involves keeping track of the current depth in the structure tree. Also, *end_word* being equal to "any structure tag" means that the process stops upon finding any start-tag or end-tag.

Note also that decompression could be faster and simpler if we stored pointers to references in the untransformed file, rather than in the transformed file. In this way, there would be no recursion because the referenced text would be already untransformed. We recall that this, however, prevents navigating in the transformed file without decompressing it.

About memory usage, both the compression and decompression algorithm work better if they maintain all the compressed text in main memory (although they could work with the text on disk). In addition, the compressor needs to maintain the hash tables for text block and node signatures. Note that items are inserted into those tables only when they do not become references but pass to the output, so the space required for those tables is also proportional to the size of the compressed text. The size of *PreviousSubtree* and stacks is negligible. Just like other compressors, LZCS can

LZCS Inverse Transformation

```
word ← get_word()
while not end of transformed text do
        if (word is a reference tag)
           then position ← get_position(word)
                SolveReference(position)
            else write word to the output
        fi
        word ← get_word()
od


procedure SolveReference(position)
do
    go to position in input file
    word ← get_word()
    if (word is a start-structure tag)
       then end_word ← corresponding end-structure tag
        else end_word ← any structure tag
    fi
    while word ≠ end_word do
            if (word is a reference tag)
               then position ← get_position(word)
                    SolveReference(position)
                else write word to the output
            fi
            word ← get_word()
    od
od
```

Figure 6: LZCS inverse transformation algorithm.

clean up all its structures and start afresh when the memory consumption exceeds some predefined limit. This would only affect compression ratio, but not correctness.

4.1 Example

Let us go back to the documents shown in the example of Section 3.2. The documents will be processed left to right, as they appear in Figure 1. In the first document (Figure 1(a)) no substitution is carried out, since there are no equivalent nodes in the document. At this moment, the output will contain an exact copy of the first document. Then the second document (Figure 1(b)) is processed. Since text block 4 is equivalent to 1, it is replaced by a backward reference, represented by triangles in Figure 7(a). As the structural elements that contain blocks 4 and 1 also coincide (nodes are equivalent), the previous backward reference is replaced again with another that contains the structural element, as shown in Figure 7(b). The same happens to text block 7, as shown in Figures 7(c) and 7(d).

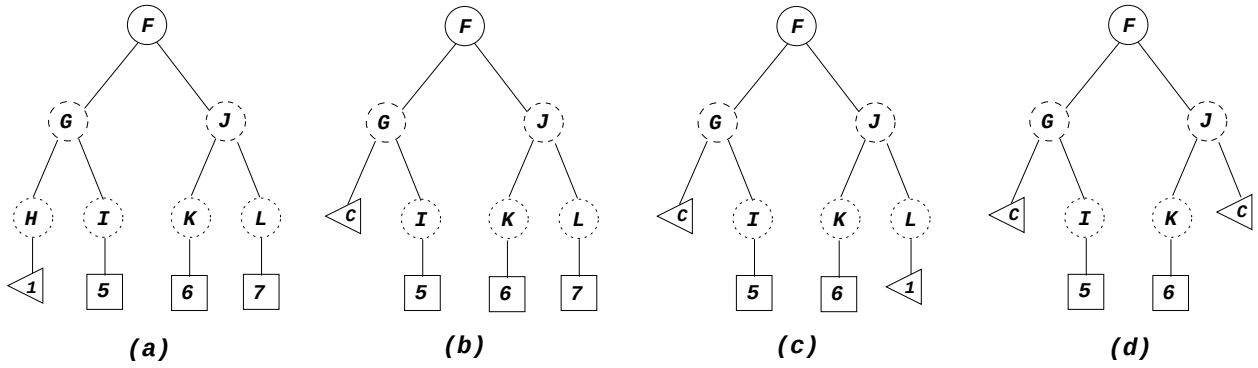


Figure 7: Substitutions performed in the second document.

Finally, the third document is processed. First, the substitutions of text blocks 8 and 9 are carried out, as well as those for their corresponding structural elements, see Figures 8(a) to 8(d) (actually the order they are processed is 8, O, 9, P). When structural element N has just been processed, it is verified that it can be completely replaced by a backward reference to J, because they are equivalent elements: They have the same number of children and the children are equivalent one by one left to right (Figure 8(e)). Finally, text block 10 is replaced by a backward reference since it is equivalent to text block 3, see Figure 8(f). In this case, structural element Q is not substituted because it is not equivalent to E.

The crux of Lemma 2 is illustrated at this point. Note that we detect that the subtree rooted at N in Figure 8(d) is a repetition of the subtree rooted at J in Figure 7(d). The left subtree of node J is not a backward reference, so its signature is the very same position of K in the compressed text (let us call it k). The left subtree of node N is a backward reference pointing precisely to k. The right subtrees of J and N are both a backward reference equal to c, the position of node C in the compressed text. According to Definition 7, both signatures are equal to (type-1:k:c) and thus the equivalence is detected.

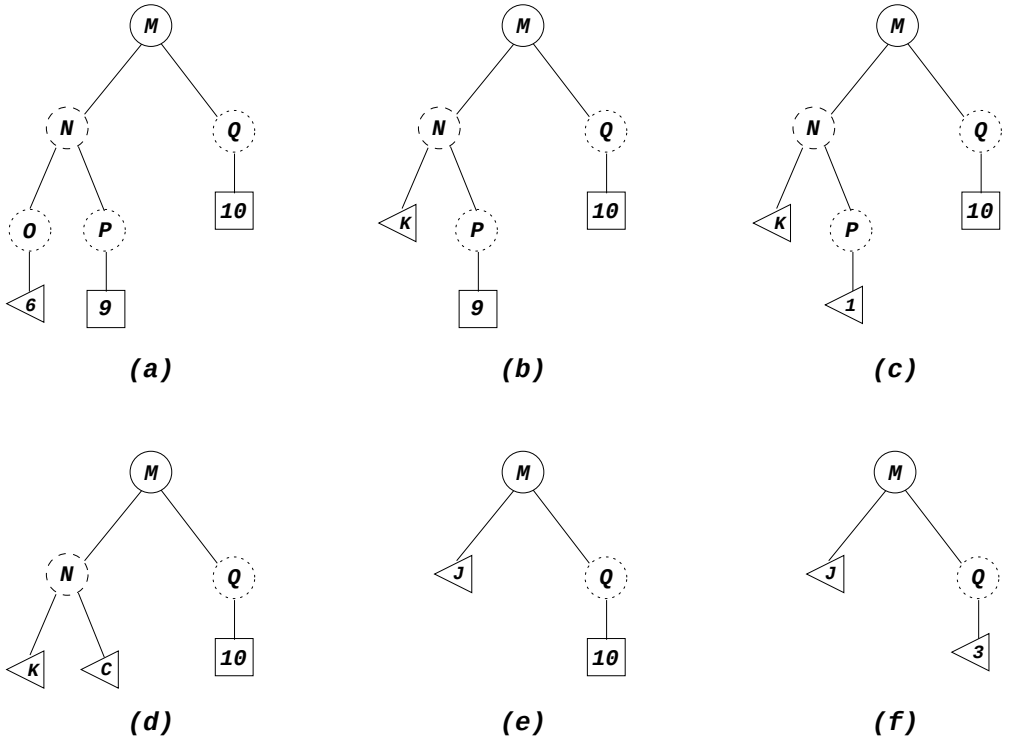


Figure 8: Substitutions carried out in the third document.

5 Experimental Evaluation

LZCS compression was tested using different XForms collections, which correspond to real documents in use in small and medium Chilean companies. XForms (`http://www.w3.org/MarkUp/Forms`), an XML dialect, is a W3C Candidate Recommendation for a specification of Web forms that clearly separate semantic from presentation aspects. In particular, XForms is becoming quite common in the representation and exchange of information and transactions between companies.

For privacy reasons we cannot use actual XForms databases, but we can get rather close. We have obtained five different types of forms (e.g., invoices). Each such form has several fields, and each field has a controlled vocabulary (e.g., names of parts) we have access to. Hence, we have generated actual forms by randomly choosing the contents of each field from their controlled vocabulary. We remark that this is pessimistic, since actual data may contain more regularities than randomly generated data.

A brief description of the five types of forms used follows.

- XForms type 1 (40.21 MB): Centralization of Remunerations. It represents the accounting of the monthly remunerations, both for total quantities and with itemization. This is a frequently used document.

- XForms type 2 (46.00 MB): Sales Invoice. It is a legal Chilean document.

- XForms type 3 (42.25 MB): Purchase Invoice. It is a legal Chilean document, similar to the previous one.
- XForms type 4 (7.19 MB): Work Order. It is the document used in companies that install heating systems, to register the account detail of contracted work.
- XForms type 5 (5.78 MB): Work Budget. It is the document used in companies that build signs and publicity by request, to determine the parts and costs of works to carry out. Construction companies use a similar document.

Figure 9 shows a couple of excerpts from the collections, so as to appreciate their amount of redundancy. In the first (XForms 4), tags `<ciudad>`, `<comunaobra>` and `<ciudadobra>` are essentially city names, with very limited vocabulary. Also, every work order from the same client will repeat fields `<rut>`, `<nomcliente>`, `<direccion>` and `<ciudad>`. Every order for the same project will share all the fields finishing with `"obra"` and some others. In the second example (XForms 2), items such as `<medida>`, `<familia>`, `<origen>` and `<M>` have even more limited vocabulary, with just one option in many cases. Moreover, every time the same item is sold again, contents under tags `<codigo>`, `<descripcion>` and `<costo>` repeat as well.[4] These examples are representative of what is actually found in real XForms documents.

For the experiments we selected different size sub-collections of XForms types 1, 2, and 3. Collections of XForms types 4 and 5 were smaller so we used them as a whole.

5.1 Optimizing the Choice of l

We tested LZCS with different l values (recall the end of Section 3.1), where value $l = 0$ means that all possible substitutions are made, whereas $l = \infty$ means that no text block is replaced, just structural elements.

Figure 10 shows how compression ratios evolve when different values for l are used, for XForms type 3. Other XForms collections give similar results. We remind that "compression ratio" is the size of the compressed text as a percentage of the size of the uncompressed text. We do not yet apply further compression after the LZCS transformation.

As it can be seen, the worst compression has been obtained in all cases for $l = 0$, this is, when all possible text blocks are replaced. Compression for $l = \infty$ has obtained intermediate results, obtaining on large collections size reductions of 28% compared to the option $l = 0$. However, choice $l = \infty$ is still much worse than intermediate choices. Different intermediate values for l yield similar compression, with very small variations. Their compression improves upon $l = \infty$ by 18% and upon $l = 0$ by 42% for large collection sizes. This shows that most reasonable intermediate values of l are almost optimal and thus fine-tuning of l is not an issue.

We note that our XForms collections are highly compressible, as expected from this densely structured data.

[4] Note that this is the same kind of redundancy usually removed through normalization in relational databases, yet in this context we wish to keep the documents as independent entities for several reasons.

```
<ordendetrabajo>
   <rut>970040005</rut>
   <nomcliente>BANCO DE CHILE</nomcliente>
   <direccion>AHUMADA N251 </direccion>
   <ciudad>SANTIAGO</ciudad>
   <nrolistaprecio>4</nrolistaprecio>
   <codobra>501658-03</codobra>
   <valorcontrato>27104</valorcontrato>
   <descripcionobra>ALIMENTACION ELECTRICA PENDON</descripcionobra>
   <direccionobra>ANIBAL PINTO N398</direccionobra>
   <lugarobra>CC 10  SUCURSAL CONCEPCION</lugarobra>
   <comunaobra>CONCEPCION</comunaobra>
   <ciudadobra>CONCEPCION</ciudadobra>
   <solicitante>JOVANA ARRIAGADA</solicitante>
   <valoruf>18050</valoruf>
   <totalcosto>270276</totalcosto>
</ordendetrabajo>
```

```
<filaItem>
   <codigo>05555-14</codigo>
   <descripcion>CABLE A TIERRA</descripcion>
   <medida>Unidad</medida>
   <familia>Familia Especial</familia>
   <origen>1</origen>
   <M>PESO</M>
   <cambio>5454</cambio>
   <costo>2</costo>
   <venta>89</venta>
   <cantidad>5550</cantidad>
   <total>5550</total>
</filaItem>
```

Figure 9: Excerpts of two different XForms files.

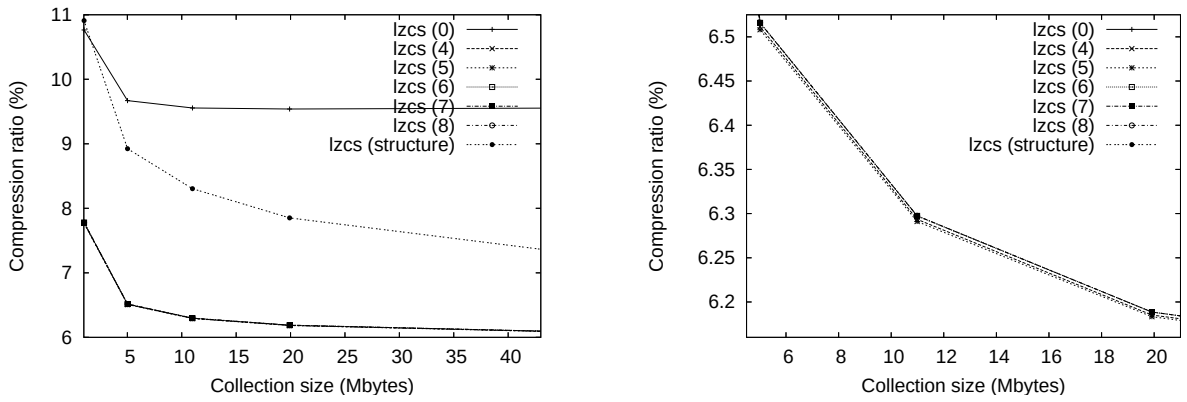


Figure 10: Compression ratios using different values for l, for XForms type 3. On the right we show a zoom of the left plot. By "lzcs(structure)" we refer to the setting $l = \infty$.

5.2 Comparison against Classical Compressors

We first compared LZCS against the basic word-based Huffman method [Mof89] (*Word Huffman*, from the *MG* system, `http://www.cs.mu.oz.au/mg`). We separate this comparison from the rest because word-based Huffman is one of the methods we use for the second step after the LZCS transformation, and because word-based Huffman compression still permits random access to the compressed text. For LZCS, we use the best l value for each collection.

Table 1 shows the compression ratio obtained for each method and for each document type. Column "LZCS" indicates the compression obtained when the LZCS transformation is applied alone, while column "LZCS+Huff" indicates the compression obtained after applying word-based Huffman to the output of the first stage.

Collection / Method	Word Huffman	LZCS	LZCS+Huff
XForms 1	9.6935%	0.1760%	0.05867%
XForms 2	12.646%	4.3111%	0.92209%
XForms 3	11.550%	6.0872%	1.32940%
XForms 4	13.994%	4.8861%	0.89281%
XForms 5	12.441%	3.6245%	0.83933%

Table 1: Compression ratios for LZCS versus *Word Huffman*.

In all cases the compression obtained by LZCS transformation alone is remarkably good. Let us remind that the output obtained by the transformation is still a plain text document, and this already halves the space needed by *Word Huffman*, at the very least. When word-based Huffman coding is applied over the LZCS transformed text the compression is still better, reducing the LZCS transformed text to 20%–25% of its size.

We now compare LZCS against other classical compression systems that allow neither navigation nor random access in the compressed file: (1) *gzip* v.1.3.5 (`http://www.gnu.org`), which uses LZ77

plus a variant of Huffman algorithm (we also tried *zip* with almost identical results); (2) *UNIX's compress* v.4.2.4, which implements the LZW algorithm; (3)*bzip2* v.1.0.2 (`http://www.bzip. org`), which uses the Burrows-Wheeler block sorting text compression algorithm, plus Huffman coding; (4)*ppmdi* (extracted from *XMLPPM 0.98.2*, `http://sourgeforge.net/projects/xmlppm`) and *ppmz* v.9.1 (Linux port, `http://www.cs.hut.fi/~tarhio/ppmz`), two PPM compressors. We used standard options for all (yet, letting them use much more memory did not significantly affect the results).

For LZCS we consider three variants: LZCS+Huff, LZCS+ppmdi, and LZCS+ppmz. These consist in applying, respectively, word-based Huffman, PPMDI, and PPMZ compression to the LZCS transformed text. Note that the LZCS+PPM combinations does not permit navigation nor random access to the compressed text. We use $l = 5$ in all the following experiments.

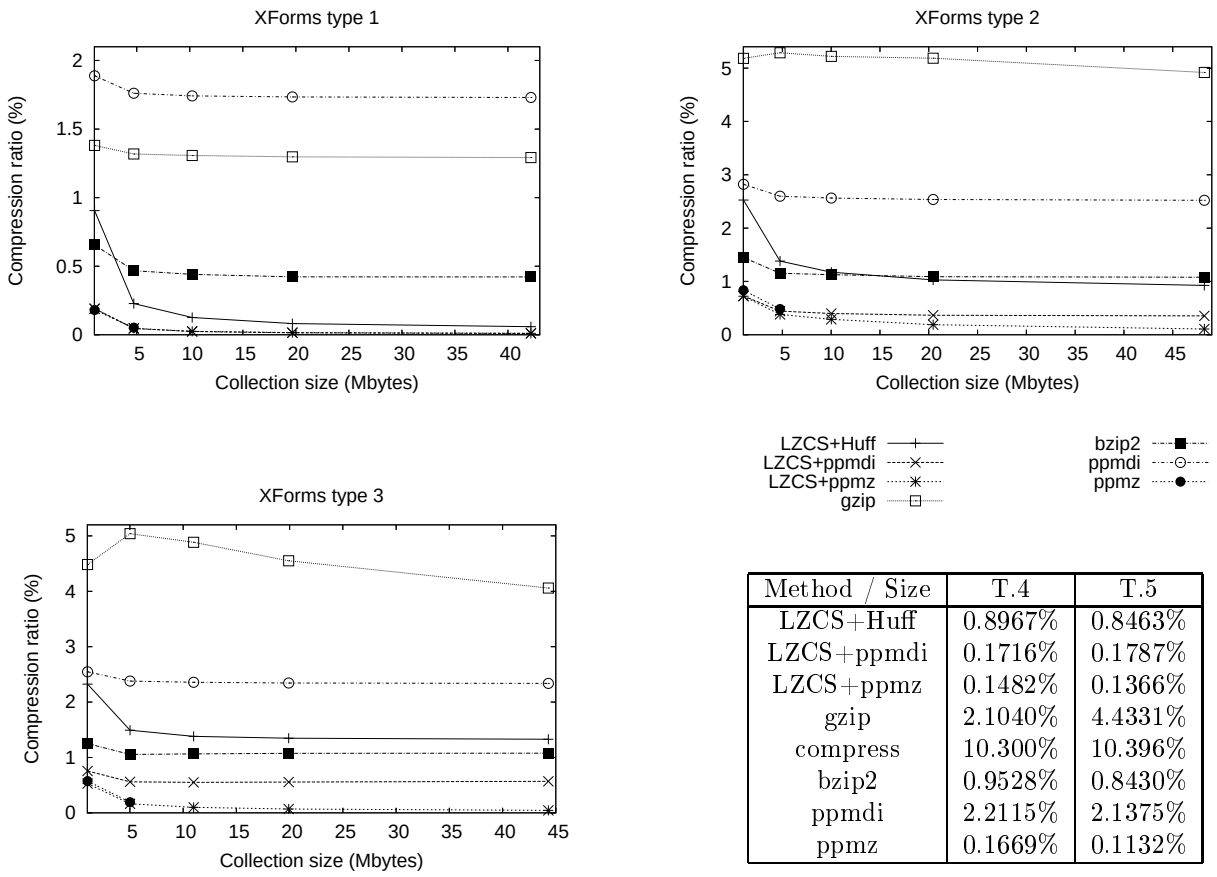
Compression ratios are shown in Figure 11. *Ppmz* compresses much better than *ppmdi*, but it is much slower. For example, it took from 4.5 to 10 hours to compress 5 megabytes of text with *ppmz*. For this reason, we show *ppmz* compression only for the first 5 megabytes of XForms 1, 2, and 3, and for the whole XForms 4 and 5. On the other hand, LZCS+ppmz is much faster because *ppmz* is applied over the already transformed text, which is much smaller. As we see in the results, LZCS+ppmz obtains the best compression ratios. It even outperforms *ppmz* alone in many cases, at least for short texts. For longer texts, *ppmz* is simply not a choice. This shows that LZCS serves as a preprocessing stage that maintains (and even improves) the performance of *ppmz*, at the same time dramatically reducing the time needed for compression, at the point of making it a viable alternative for text sizes where *ppmz* alone is not.

The worst performing compressor is *compress*, with compression ratios around 10% in all the texts. This is similar to *Word Huffman* (which in exchange permits random access) and not competitive in this experiment. *Compress* is excluded from the plots of XForms types 1, 2, and 3 for readability. It is followed by *gzip* and *ppmdi*, with significant differences among them depending on the collection, and then by LZCS+Huff and *bzip2*. These have similar compression ratio, although there are again significant differences depending on the collection. Recall, however, that LZCS+Huff is the only method in the group permitting random access and navigation in the collection. Finally, the best compression ratios are achieved by LZCS+ppmdi, LZCS+ppmz and *ppmz*, which are very close. LZCS+ppmdi usually loses to the others and *ppmz* usually loses to LZCS+ppmz. Moreover, *ppmz* is so slow that it cannot be applied except in small collections. These results show that taking advantage of the structure yields significant gains in compression.

5.3 Comparison against Structure-Aware Methods

We now compare LZCS against structure-aware methods: (1)*XMill* v.0.8 (`http://sourceforge.net/projects/xmill`), (2)*XMLPPM* v.0.98.2 (`http://sourceforge.net/projects/xmlppm`), (3) *SCMHuff* (`http://www.infor.uva.es/~jadiego`), and (4)*SCMPPM* (same page).

XGrind, (`http://cvs.sourceforge.net/viewcvs.py/xmill/xmill/XGrind`) was excluded from this comparison because we could not make it work properly on our dataset. To be sure that this exclusion was not important, we altered our collection (in a statistically insignificant way) until producing 1 megabyte of text where *XGrind* finally worked. The resulting compression ratio was 32.63%, which is not competitive at all in this experiment. *XCQ* was also excluded because we could not find the code, yet results reported in [LWL03] indicate that the compression ratios achieved are



Method / Size	T.4	T.5
LZCS+Huff	0.8967%	0.8463%
LZCS+ppmdi	0.1716%	0.1787%
LZCS+ppmz	0.1482%	0.1366%
gzip	2.1040%	4.4331%
compress	10.300%	10.396%
bzip2	0.9528%	0.8430%
ppmdi	2.2115%	2.1375%
ppmz	0.1669%	0.1132%

Figure 11: Comparison between LZCS and classical compressors.

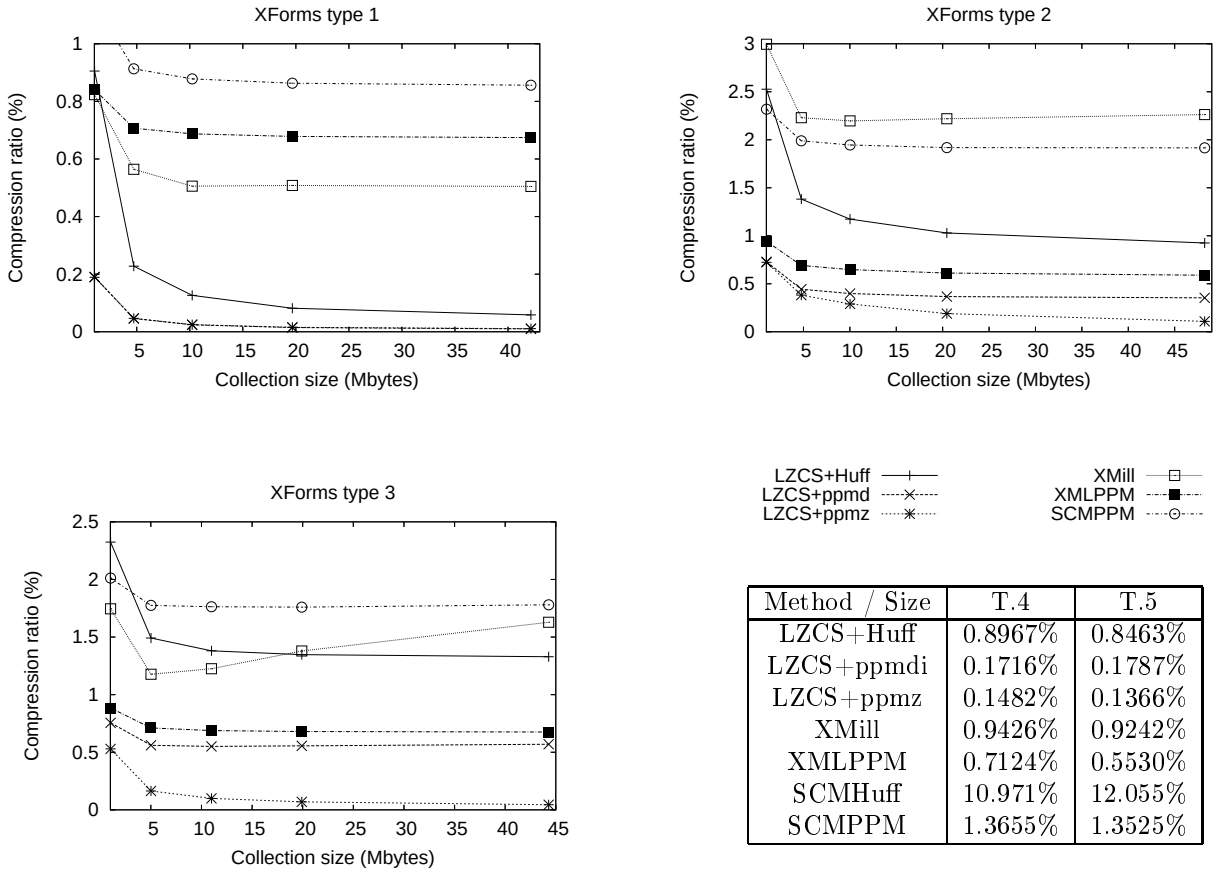
similar to those of *XMill*, which we show to be not competitive in our experiments either. The same happens with *Exalt*, according to the results in [Tom04].

Compression ratios are shown in Figure 12. We used default settings for all (yet, letting them use much more memory did not affect the results).

SCMHuff is, apart from LZCS+Huff, the only method permitting navigation and random access. *SCMHuff* compression, however, is not competitive, being only slightly superior to *Word Huffman*. We omitted the results of *SCMHuff* for XForms 1, 2, and 3 for readability, where its compression ratio was within 7%-12%. *SCMPPM* is within bounds but still not competitive in most cases.

With few exceptions, LZCS+Huff is significantly better than *XMill* and *SCMPPM* in all sufficiently large collections, producing compressed texts from just 5% smaller to as much as 25 times smaller than *XMill*. *XMLPPM*, on the other hand, obtains clearly better compression than LZCS+Huff in most cases, except for the notable exception of XForms type 1, where all the LZCS family is by far unbeaten. However, *XMLPPM* uses adaptive compression, and hence it is not suitable for navigation or random access on the compressed text.

If we consider the LZCS variants that do not permit navigation and random access, then LZCS+ppmdi and LZCS+ppmz come into play, beating by far all other competitors.



Method / Size	T.4	T.5
LZCS+Huff	0.8967%	0.8463%
LZCS+ppmdi	0.1716%	0.1787%
LZCS+ppmz	0.1482%	0.1366%
XMill	0.9426%	0.9242%
XMLPPM	0.7124%	0.5530%
SCMHuff	10.971%	12.055%
SCMPPM	1.3655%	1.3525%

Figure 12: Comparison between LZCS and other structure-aware methods.

We note the interesting fact that, since it produces structured documents, LZCS can in principle be composed with structure-aware methods, such as SCMPPM, instead of plain text compressors. We have tried some combinations, but the results were no better than those already obtained with the basic PPM compressors.

5.4 Compression and Decompression Performance

All the tests in this section were carried out on the SuSE Linux 9.1 operating system, running on a computer with a Pentium IV processor at 1.2 GHz and 384 megabytes of RAM.

Figure 13 shows the time required to apply the LZCS transformation over XForms types 1, 2, and 3. As expected, the results display a clear linear-time behavior. The reason behind the better performance on XForms 1 is their higher compressibility, which implies less insertions of new text blocks and structures into the hash tables.

Table 2 shows compression and decompression speed for all the softwares involved. The speeds are averaged over all the collections. For the reasons explained, *ppmz* speed is measured only over the first 5 megabytes of the larger collections. By "LZCS" we mean just the LZCS transformation.

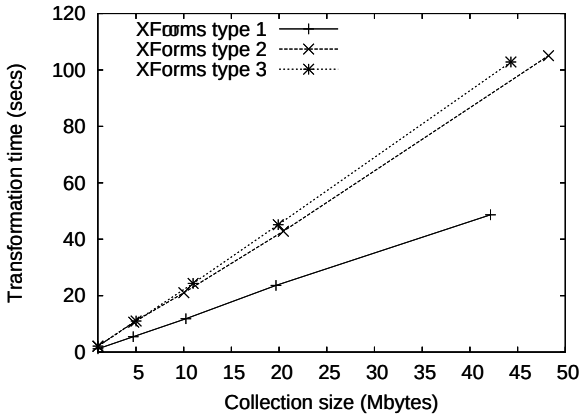


Figure 13: Time required to carry out the LZCS transformation on incremental subsets of different text collections.

The fastest at compression/decompression are *gzip* and *XMill* (both based on LZ77), followed by *compress* (based on LZ78). This is expected as this family of compressors is fast, especially at decompression. Shortly after in decompression performance is the LZCS family (also based on Lempel-Ziv), except LZCS+ppmz for obvious reasons. Compression is much slower with the LZCS family, yet not slower than *bzip2*, for example. All other compressors are several times slower to decompress. Other fast options to compress are *ppmdi* and *XMLPPM*.

At compression time, LZCS is not very fast because it has to parse the structure and use the linear time, yet complex, compression algorithm we have explained in Section 4. However, we have managed to make it competitive against start-of-the art compressors. At decompression, LZCS is much faster, benefiting from its Lempel-Ziv nature. Yet, to allow navigability, recursive decompression is necessary, and this slows it down compared to other Lempel-Ziv methods. When combined with other compressors, their overhead must be added to that of LZCS. Yet, this is not as significant as it could because the other compressors act over the much smaller LZCS transformed text. We note that none of the compressors that significantly outperform LZCS in time get even close to it in compression ratios achieved.

Figure 14 shows all the competing schemes in a two-dimensional area where they are ranked by compression/decompression performance and compression ratio. Word Huffman and *SCMHuff* are excluded as their compression ratio is too poor in this experiment. A compressor is completely superseded by others when it is, in both plots, on top and to the left of (that is, slower and compressing less than) some other compressor. In this sense, we can see that *ppmz*, *bzip2*, *ppmdi*, and *SCMPPM* are completely superseded for this type of text collections. LZCS (the transformation alone) is also completely superseded, yet it has the special feature of using a plain ASCII representation. The remaining compressors are relevant in this speed/ratio tradeoff: LZCS+Huffman, LZCS+ppmdi, LZCS+ppmz, *XMLPPM*, *XMill* and *gzip* (the latter basically for its speed).

Another possible concern besides time is how much memory we need to compress. The idea, as with most other compressors, is that large texts are handled by cutting them into chunks that will be compressed individually. Therefore, one needs memory just to compress one chunk.

The question is: How long should a chunk be so that compression ratios remain good? Or

Program	Compression	Decompression
LZCS	0.385	30.262
LZCS+Huff	0.376	21.634
LZCS+ppmdi	0.387	19.200
LZCS+ppmz	0.154	0.779
Word Huffman	0.388	5.438
gzip	17.858	112.212
compress	4.400	43.368
bzip2	0.351	3.746
ppmdi	5.073	4.990
ppmz	0.0002	0.0002
XMill	12.751	103.038
XMLPPM	4.943	3.855
SCMHuff	0.187	4.169
SCMPPM	0.964	1.310

Table 2: Compression and decompression speeds, in megabytes per second.

alternatively, how much main memory is necessary to achieve good compression ratios?

We observe that, in our experiments, compression ratios of LZCS stabilize after processing 10–20 megabytes of text, so we can process texts in chunks of that size without significantly affecting compression ratio. In practice, the amount of memory we need to compress is 35–45 times the size of the compressed text (this is 1–3 times the size of the original text). In our collections, we need about 25 megabytes of main memory to obtain the same compression performance we have shown, by means of partitioning the text. Even when this is rather reasonable, we note that our implementation is not optimized in this aspect, and it could be significantly improved.

6 Conclusions and Future Work

We have presented LZCS, a compression scheme based on Lempel-Ziv aimed at compressing highly structured data. The main idea of LZCS is to replace whole substructures by previous occurrences thereof. The main advantages of LZCS are (1) very good compression ratios, outperforming most classical and structure-aware methods; (2) easy random access, visualization and navigation of compressed collections; (3) fast and one-pass compression and decompression. Only PPM-based methods compressed better than LZCS in our experiments, but random access to a particular document is impossible with PPM, since it is adaptive and needs to decompress first all the documents that precede the desired one. This is adequate for archival purposes but unsuitable for use in a compressed text database scenario. On the other hand, if we combine LZCS with PPM compression we obtain the best compression ratio among all the PPM-related compressors.

One of the most challenging problems faced was the efficiency problem of the LZCS compression stage, which is quadratic if implemented naively. We overcame this problem by designing a linear average-time compression algorithm, by using an ad-hoc hashing scheme. The algorithm turns out

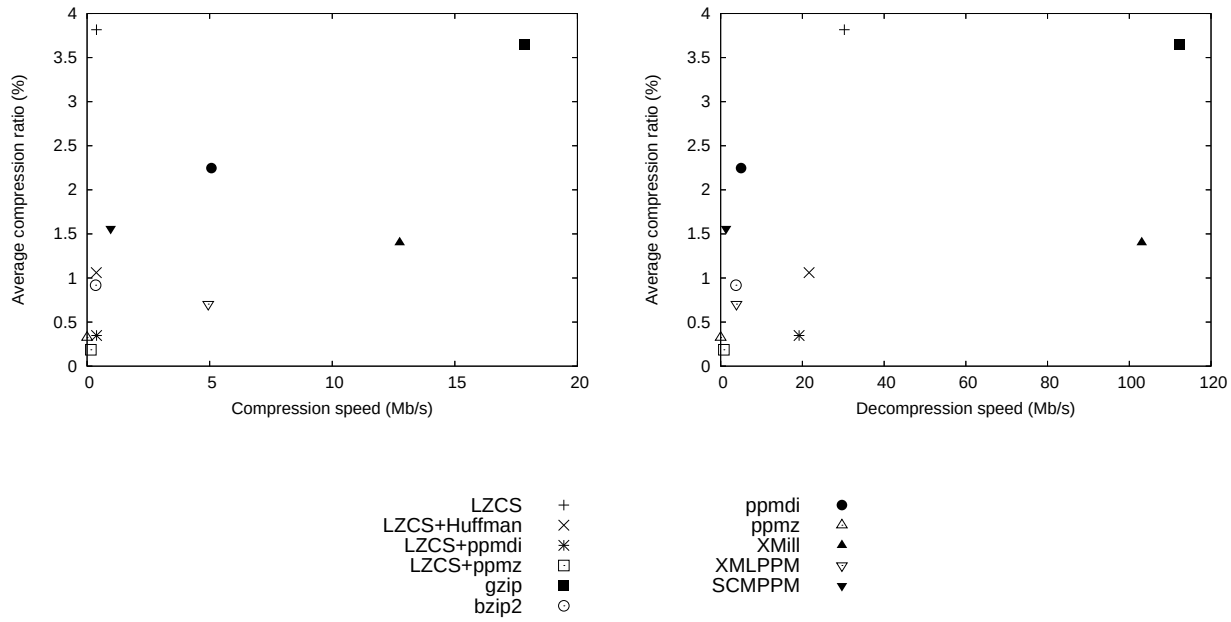


Figure 14: Tradeoff between compression ratio and compression (left) or decompression (right) time of the different compressors.

to be competitive in practice.

We have considered compression of static collections in this paper. In many scenarios, new documents are added to the document collection, but these are never deleted or modified. This is the case, for example, when XML forms are used to keep track of all the transactions made by a company along time (even modifications to previous transactions are expressed by means of a compensating transaction, but the past cannot be changed). LZCS can easily cope with insertion of new documents, as it is a matter of resuming the compression at the point it was left when processing of the previous collection finished. It is a trade-off decision how much of the data in the hash tables can be maintained to improve compression of future additions to the collection, but this does not affect correctness.

In other cases, for example descriptions of stock, documents may also be updated and deleted. More research is needed in order to accommodate such operations in a text collection compressed with LZCS. The main problem is, of course, that the documents we wish to delete could be referenced elsewhere. One possibility is to maintain a reference count per structure indicating how many references point to it, so the structure can be physically deleted when this counter becomes zero. An update would consist of inserting the new value and changing the old one by a *forward* pointer to the new one, so that the old one could be deleted or not depending on its reference count. Periodical removal of unused text areas and remapping of pointers would be necessary to avoid the presence of too many gaps due to eliminated documents. Several other alternatives are possible.

The most important future work is to permit searching the compressed structured text. We have seen that the existence of words and phrases in the compressed document can be easily established as their first occurrence cannot appear in compressed form. Yet, this is the most elementary search

problem.

A more challenging problem is to answer structural queries, for example XPath queries, on the LZCS compressed collection. One can use the navigation approach to essentially ignore that the text has repeated substructures, and apply any sequential XPath search algorithm. Yet, much more interesting is being able of reusing the results of the search over repeated substructures to avoid working on them again. The final goal is to search in time proportional to the size of the compressed text, rather than the original text, as would be the case if we ignored the compression. Some approaches to this problem are briefly presented in [LWL03]. A very recent development on Burrows-Wheeler-based tree compression permitting limited XPath queries is [FLMM05].

Another interesting problem is indexed searching. On very large collections, sequential searching is unacceptable. Index data structures largely improve the sequential search time, at a cost in extra space. For example, a sort of inverted index storing positions of words and structural elements has shown to be useful to solve combined textual and structural queries [NBY97, BYN02]. Although we could, again, build the indexes over the uncompressed text, it would be much better to design indexes that reduce their size when the text is compressible, so that we exploit repetitions in the text to factor out the corresponding repetitions in the indexes.

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