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A note on the Burrows-Wheeler transformation

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Abstract

We relate the Burrows-Wheeler transformation with a result in combinatorics on words known as the Gessel-Reutenauer transformation.

1 Introduction

The Burrows-Wheeler transformation is a popular method used for text compression [2]. The rough idea is to encode a text in two passes. In the first pass, the text w is replaced by a text $T(w)$ of the same length obtained as follows: list the cyclic shifts of w in alphabetic order as the rows w_1, w_2, \dots, w_n of an array. Then $T(w)$ is the last column of the array. In a second pass, a simple encoding allows to compress $T(w)$, using a simple method like run-length or move-to-front encoding. Indeed, adjacent rows will often begin by a long common prefix and $T(w)$ will therefore have long runs of identical symbols. For example, in a text in english, most rows beginning with ‘nd’ will end with ‘a’. We refer to [11] for a complete presentation of the algorithm and an analysis of its performances. It was remarked recently by S. Mantaci, A. Restivo and M. Sciortino [10] that this transformation was related with notions in combinatorics on words such as Sturmian words. Similar considerations were developed in [1] in a different context. The results presented here are also close to the ones of [4].

In this note, we study the transformation from the combinatorial point of view. We show that the Burrows-Wheeler transformation is a particular case of a bijection due to I.M. Gessel and C. Reutenauer which allows the enumeration of permutations by descents and cyclic type (see [9]).

The paper is organized as follows. In the first section, we describe the Burrows-Wheeler transformation. The next section describes the inverse of the transformation with some emphasis on the computational aspects. The last section is devoted to the link with the Gessel-Reutenauer correspondance.

2 The Burrows-Wheeler transformation

The principle of the method is very simple. We consider an ordered alphabet A . Let $w = a_1 a_2 \cdots a_n$ be a word of length n on the alphabet A . The *Parikh vector*

of a word w on the alphabet A is the integer vector $v = (n_1, n_2, \dots, n_k)$ where n_i is the number of occurrences of the i -th letter of A in w . We suppose w to be primitive, i.e. that w is not a power of another word. Let w_1, w_2, \dots, w_n be the sequence of conjugates of w in increasing alphabetic order. Let b_i denote the last letter of w_i , for $i = 1, \dots, n$. Then the Burrows-Wheeler transform of w is the word $T(w) = b_1 b_2 \cdots b_n$.

Example 1 Let $w = abracadabra$. The list of conjugates of w sorted in alphabetical order is represented below.

	1	2	3	4	5	6	7	8	9	10	11
1	a	a	b	r	a	c	a	d	a	b	r
2	a	b	r	a	a	b	r	a	c	a	d
3	a	b	r	a	c	a	d	a	b	r	a
4	a	c	a	d	a	b	r	a	a	b	r
5	a	d	a	b	r	a	a	b	r	a	c
6	b	r	a	a	b	r	a	c	a	d	a
7	b	r	a	c	a	d	a	b	r	a	a
8	c	a	d	a	b	r	a	a	b	r	a
9	d	a	b	r	a	a	b	r	a	c	a
10	r	a	a	b	r	a	c	a	d	a	b
11	r	a	c	a	d	a	b	r	a	a	b

The word $T(w)$ is the last column of the array. Thus $T(w) = rdarcaaabb$.

It is clear that $T(w)$ depends only on the conjugacy class of w . Therefore, in order to study the correspondance $w \mapsto T(w)$, we may suppose that w is a Lyndon word, i.e. that $w = w_1$. Let c_i denote the first letter of w_i . Thus the word $z = c_1 c_2 \cdots c_n$ is the nondecreasing rearrangement of w (and of $T(w)$).

Let σ be the permutation of the set $\{1, \dots, n\}$ such that $\sigma(i) = j$ iff $w_j = a_i a_{i+1} \cdots a_{i-1}$. In other terms, $\sigma(i)$ is the rank in the alphabetic order of the i -th circular shift of the word w .

Example 1 (continued)

We have

$$\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 \\ 1 & 3 & 7 & 11 & 4 & 8 & 5 & 9 & 2 & 6 & 10 \end{pmatrix}$$

By definition, we have for each index i with $1 \leq i \leq n$

$$a_i = c_{\sigma(i)}. \tag{1}$$

We also have the following formula expressing $T(w)$ using σ

$$b_i = a_{\sigma^{-1}(i)-1} \tag{2}$$

Indeed, $b_{\sigma(j)}$ is the last letter of $w_{\sigma(j)} = a_j a_{j+1} \cdots a_{j-1}$, whence $b_{\sigma(j)} = a_{j-1}$ which is equivalent to the above formula.

Let $\pi = P(w)$ be the permutation defined by $\pi(i) = \sigma(\sigma^{-1}(i) + 1)$ where the addition is to be taken mod n . Actually, π is just the permutation obtained by writing σ as a word and interpreting it as an n -cycle. Thus, we have also $\sigma(i) = \pi^{i-1}(1)$ and

$$a_i = c_{\pi^{i-1}(1)} \quad (3)$$

Example 1 (continued)

We have, written as a cycle

$$\pi = (1 \ 3 \ 7 \ 11 \ 4 \ 8 \ 5 \ 9 \ 2 \ 6 \ 10)$$

and as an array $\pi = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 \\ 3 & 6 & 7 & 8 & 9 & 10 & 11 & 5 & 2 & 1 & 4 \end{pmatrix}$

Substituting in Formula (2) the value of a_i given by Formula (1), we obtain $b_i = c_{\sigma(\sigma^{-1}(i)-1)}$ which is equivalent to

$$c_i = b_{\pi(i)} \quad (4)$$

Thus the permutation π transforms the last column of the array of conjugates of w into the first one. Actually, it can be noted that π transforms any column of this array into the following one.

The computation of $T(w)$ from w can be done in linear time. Indeed, provided w is chosen as a Lyndon word, the order between the conjugates is the same as the order between the corresponding suffixes. The computation of the permutation σ results from the suffix array of w which can be computed in linear time [3] on a fixed alphabet. The corresponding result on the alphabet of integers is a more recent result. It has been proved independently by three groups of researchers, [7], [8] and [6].

3 Inverse transformation

We now show how w can be recovered from $T(w)$. For this, we introduce the following notation. The rank of i in the word $y = b_1b_2 \cdots b_n$, denoted $\text{rank}(i, y)$ is the number of occurrences of the letter b_i in $b_1b_2 \cdots b_i$.

We observe that for each index i , and for the aforementioned words $y = b_1b_2 \cdots b_n$ and $z = c_1c_2 \cdots c_n$

$$\text{rank}(i, z) = \text{rank}(\pi(i), y). \quad (5)$$

Indeed, we first note that for two words u, v of the same length and any letter a , one has $au < av \Leftrightarrow ua < va \quad (\Leftrightarrow u < v)$. Thus for all indices i, j

$$i < j \text{ and } c_i = c_j \Rightarrow \pi(i) < \pi(j). \quad (6)$$

Hence, the number of occurrences of c_i in $c_1c_2 \cdots c_n$ is equal to the number of occurrences of $b_{\pi(i)} = c_i$ in $b_1b_2 \cdots b_n$.

To obtain w from $T(w) = b_1b_2 \cdots b_n$, we first compute $z = c_1c_2 \cdots c_n$ by rearranging the letters b_i in nondecreasing order. Property (5) shows that $\pi(i)$ is the index j such that $c_i = b_j$ and $\text{rank}(j, y) = \text{rank}(i, z)$. This defines the permutation π , from which σ can be reconstructed. An algorithm computing π from $y = T(w)$ is represented below.

```

PERMUTATION( $b_1b_2 \cdots b_n$ )
1   $c \leftarrow \text{SORT}(b_1b_2 \cdots b_n)$ 
2  for  $i \leftarrow 1$  to  $n$  do
3      if  $i = 1$  or  $c_{i-1} \neq c_i$  then
4           $j \leftarrow 0$ 
5          do  $j \leftarrow j + 1$ 
6          while  $b_j \neq c_i$ 
7           $\pi(i) \leftarrow j$ 
8  return  $\pi$ 

```

This algorithm can be optimized to a linear-time algorithm by storing the first position of each symbol in the word z .

Finally w can be recovered from $z = c_1c_2 \cdots c_n$ and π by Formula (3). The algorithm allowing to recover w is represented below.

```

WORD( $z, \pi$ )
1   $j \leftarrow 1$ 
2   $a_1 \leftarrow c_1$ 
3  for  $i \leftarrow 2$  to  $n$  do
4       $j \leftarrow \pi(j)$ 
5       $a_j \leftarrow c_i$ 
6  return  $w$ 

```

The computation of w is not possible without the Parikh vector or equivalently the word z . One can however always compute the word w on the smallest possible alphabet associated with permutation π (this is the computation described in [1]).

4 Descents of permutations

A descent of a permutation π is an index i such that $\pi(i) > \pi(i+1)$. We denote by $\text{des}(\pi)$ the set of descents of the permutation π . It is clear by Property (6) that if i is a descent of $P(w)$, then $c_i \neq c_{i+1}$. Thus, the number of descents of π is at most equal to $k - 1$ where k is the number of symbols appearing in the word w .

Example 1 (continued) The descents of π appear in boldface.

$$\pi = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & \mathbf{7} & \mathbf{8} & \mathbf{9} & 10 & 11 \\ 3 & 6 & 7 & 8 & 9 & 10 & 11 & 5 & 2 & 1 & 4 \end{pmatrix}$$

Thus $\text{des}(\pi) = \{7, 8, 9\}$.

Let us fix an ordered alphabet A with k elements for the rest of the paper. Let w be a word and $v = (n_1, n_2, \dots, n_k)$ be the Parikh vector of w . We say that v is *positive* if $n_i > 0$ for $i = 1, 2, \dots, k$. We denote by $\rho(v)$ the set of integers $\rho(v) = \{n_1, n_1 + n_2, \dots, n_1 + \dots + n_{k-1}\}$. When v is positive, $\rho(v)$ has $k - 1$ elements. Let $\pi = P(w)$ and let v be the Parikh vector of w . It is clear by Formula 6 that we have the inclusion $\text{des}(\pi) \subset \rho(v)$.

Example 1 (continued) The Parikh vector of the word $w = \text{abracadabra}$ is $v = (5, 2, 1, 1, 2)$ and $\rho(v) = \{5, 7, 8, 9\}$.

The following statement results from the preceding considerations.

Theorem 1 For any positive vector $v = (n_1, n_2, \dots, n_k)$ with $n = n_1 + \dots + n_k$, the map $w \mapsto \pi = P(w)$ is one to one from the set of conjugacy classes of primitive words of length n on A with Parikh vector v onto the set of cyclic permutations on $\{1, 2, \dots, n\}$ such that $\rho(v)$ contains $\text{des}(\pi)$.

This result is actually a particular case of a result stated in [9] and essentially due to I. Gessel and C. Reutenauer [5]. The complete result ([9], Theorem 11.6.1 p. 378) establishes a bijection between words of type λ and pairs (π, E) where π is a permutation of type λ and E is a subset of $\{1, 2, \dots, n-1\}$ with at most $k-1$ elements containing $\text{des}(\pi)$. The type of a word w of length n is the partition of n realized by the length of the factors of its nonincreasing factorization in Lyndon words. The type of a permutation is the partition resulting of the length of its cycles. Thus, Theorem 1 corresponds to the case where w is a Lyndon word (i.e. λ has only one part) and π is circular.

We illustrate the general case of an arbitrary word with an example for the sake of clarity. For example, the word $w = \text{abaab}$ has the nonincreasing factorization in Lyndon words $w = (ab)(aab)$. Thus w has type $(3, 2)$. The corresponding permutation of type $(3, 2)$ is $\pi = (35)(124)$. Actually, the permutation π is obtained as follows. Its cycles correspond to the Lyndon factors of w . The letters are replaced by the rank in the lexicographic order of the cyclic iterates of the conjugates. In our example, we obtain

1	a	a	b	a	a	b	\dots
2	a	b	a	a	b	a	\dots
3	a	b	a	b	a	b	\dots
4	b	a	a	b	a	a	\dots
5	b	a	b	a	b	a	\dots

We have $\text{des}(\pi) = \{3\}$ which is actually included in $\rho(v) = \{3, 5\}$.

We may observe that when the alphabet is binary, i.e. when $k = 2$, Theorem 1 takes a simpler form: the map $w \mapsto P(w)$ is one-to-one from the set of primitive binary words of length n onto the set of circular permutations on $\{1, 2, \dots, n\}$ having one descent.

In the general case of an arbitrary alphabet, another possible formulation is the following. Let us say that a word $b_1 b_2 \dots b_n$ is *co-Lyndon* if the permutation

π built by Algorithm PERMUTATION is an n -cycle. It is clear that the map $w \mapsto T(w)$ is one-to-one from the set of Lyndon words of length n on A onto the set of co-Lyndon words of length n on A .

The properties of co-Lyndon words have never been studied and this might be an interesting direction of research.

Example 2 The following array shows the correspondance between Lyndon and co-Lyndon words of length 5 on $\{a, b\}$. The permutation π is shown on the right.

Lyndon	co-Lyndon	
<i>aaaab</i>	<i>baaaa</i>	(12345)
<i>aaabb</i>	<i>baaba</i>	(12354)
<i>aabab</i>	<i>bbaaa</i>	(13524)
<i>aabbb</i>	<i>babba</i>	(12543)
<i>ababb</i>	<i>bbbaa</i>	(14253)
<i>abbbb</i>	<i>bbbba</i>	(15432)

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