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Generation of k-permutations in $O(1)$ time per permutation by reversing sublists

三河 賢治 (Kenji MIKAWA) 仙波 一郎 (Ichiro SEMBA)

Department of Computer Science, Ibaraki University
{mikawa,isemba}@cis.ibaraki.ac.jp

Abstract

We discuss the problem of generating all k-permutations of n objects. Several papers have introduced a technique to alternatingly reverse sublists of a listing for some combinatorial Gray codes in an efficient manner. Our approach is to apply the technique to a listing of all k-permutations of n objects constructed recursively by reversing sublists. We show that the list contains $n!/(n-k)!$ permutations so that each string differs from its predecessor by the transposition of two elements. It is easy to convert the construction to a recursive algorithm and then we develop the algorithm that produces successive permutations in a constant amortized time per permutation.

1 Introduction

Many algorithms have been published for generating all permutations of n objects and then there is a number of listings of successive permutations. One of the listings is the transposition order that is introduced independently by Johnson [3] and Trotter [11]. It is well-known that each permutation differs by the transposition of adjacent elements.

Recently several interesting papers have been achieved for generating some combinatorial Gray codes in a constant or constant amortized time per object [1, 9, 5, 6, 8, 10, 2]. However, it is not trivial to generate a listing of combinatorial Gray codes in a unique manner. Most of those papers managed to give a simple recurrence relation for combinatorial Gray codes. Ruskey generalized a close relationship between some combinatorial Gray codes constructed recursively by reversing sublists [9]. To reverse certain sublists seems to contribute a reduction of differences between successive objects.

A k-permutation of n objects is an arrangement of the first k objects out of n objects. First, we give a few modified definition for k-permutations which are extended into n length strings such that the set of all permutations of n objects contains the smaller set of the extended k-permutations. Our approach is to apply the reversing technique to such k-permutations. Then a listing of all k-permutations is obtained such that successive strings differ by the transposition of two elements. This paper presents a recursive algorithm for generating them in a constant amortized time per string. It is obtained directly from the recursively defined construction for k-permutations. Note that we do not count the time for printing permutations.

2 Definitions and properties

To begin with, we extend k-permutations of n distinct objects to strings of length n: a k-permutation of length n consists of n elements which the first k elements are arranged in its original order and the rests are arranged in a lexical order. For example, if a string 52 is a 2-permutation of the set $\{1, 2, 3, 4, 5\}$, then its extension is 52134. When it will not lead to confusion, we call them simply k-permutations.

The following useful notations are defined in [9]. If L is a list of strings and x is a symbol, then $x \cdot L$ denotes the list of strings obtained by appending an x to each string of L. For example, if $L = 12, 21$, then $3 \cdot L = 312, 321$. If L and L' are lists then $L \circ L'$ denotes the concatenation of the two lists. For example, if $L = 12, 21$ and $L' = 34, 43$, then $L \circ L' = 12, 21, 34, 43$.

For a list L, let *first* (L) denote the first element on the list and let *last* (L) denote the last element on the list. If L is a list $l_1, l_2, \cdots, l_n$, then $\overline{L}$ denotes the list obtained by listing the elements of L in reverse order; i.e., $\overline{L} = l_n, \cdots, l_2, l_1$. Note the obvious equations $\mathit{first}(\overline{L}) = \mathit{last}(L)$ and $\mathit{last}(\overline{L}) = \mathit{first}(L)$.

Let $\boldsymbol{T}_k(n)$ be a listing of all k-permutations of the set $\{p_1, p_2, \cdots, p_n\}$. The construction for the lists consists of two parts, one of which generates k length permutations in their original order and the other of which generates $n - k$ length permutations in a lexical order. The following construction is the case for the original part. The list involves n recursively defined sublists which are alternatingly reversed.

$$\boldsymbol{T}_k(n) = \begin{cases} \pi_1 \cdot \boldsymbol{T}_{k-1}(n-1) \circ \pi_2 \cdot \overline{\boldsymbol{T}_{k-1}(n-1)} \circ \cdots & \\ \qquad \cdots \circ \pi_{n-1} \cdot \overline{\boldsymbol{T}_{k-1}(n-1)} \circ \pi_n \cdot \boldsymbol{T}_{k-1}(n-1) & \text{if odd } n, \\ \pi_1 \cdot \boldsymbol{T}_{k-1}(n-1) \circ \pi_2 \cdot \overline{\boldsymbol{T}_{k-1}(n-1)} \circ \cdots & \\ \qquad \cdots \circ \pi_{n-1} \cdot \boldsymbol{T}_{k-1}(n-1) \circ \pi_n \cdot \overline{\boldsymbol{T}_{k-1}(n-1)} & \text{if even } n, \end{cases}$$

and the case for the lexical part,

$$\boldsymbol{T}_k(n) = \pi_1 \cdot \boldsymbol{T}_{k-1}(n-1).$$

These are subject to the terminal condition that $\boldsymbol{T}_k(0) = \emptyset$. The construction appends π_i's $\in \{p_1, p_2, \cdots, p_n\}$ to sublists in a lexical order from left to right and each sublist is reconstructed with the set obtained by deleting a given element and renumbering the rests from π_1 to π_{n-1}. This constraint requires that permutations contain all distinct elements.

LEMMA 2.1 *The list $\boldsymbol{T}_k(n)$ satisfies the following properties:*

(1) *Successive k-permutations in $\boldsymbol{T}_k(n)$ differ in exactly two elements.*

(2) *first* $(\boldsymbol{T}_k(n)) = p_1 \, p_2 \, \cdots \, p_n$.

(3) *last* $(\boldsymbol{T}_k(n)) = \begin{cases} p_n \, p_{n-1} \, p_1 \, p_2 \, \cdots \, p_{n-2} & \text{if odd } n \text{ and } k \geq 2, \\ p_n \, p_1 \, p_2 \, \cdots \, p_{n-1} & \text{otherwise.} \end{cases}$

Proof. The proof is by induction on n. The list obviously has the stated properties for $1 \leq k \leq n \leq 2$. Suppose that the lemma is true for $n \geq 3$. We must show it to be correct for $n+1$. For convenience, we assume the ith element in a permutation to be placed in the position $n-i$, that is, the last element is placed in the position 0.

Obviously the list $\boldsymbol{T}_1(n+1)$ contains $n+1$ permutations in which the ith permutation is $p_i \, p_1 \, \cdots \, p_{i-1} \, p_{i+1} \, \cdots \, p_{n+1}$ and the permutation differs from its predecessor by two elements in positions n and $n-i$. Otherwise, for $k \geq 2$, the list contains $n+1$ sublists and we need to inspect the transposition of successive permutations at the interface between the ith sublist and the $(i+1)$st sublist. The transposition behaves in different ways according to the parities n and i.

The first case is for even i. The ith sublist is reverse and the $(i+1)$st sublist is natural. The contiguous permutations between the ith sublist and the $(i+1)$st sublist differ by two elements, since the last permutation of the ith sublist is the lexically first one, as shown below.

$$\begin{array}{rl} p_i \cdot \overline{\boldsymbol{T}_{k-1}(n)} & \left\{ \begin{array}{l} \vdots \\ \underline{p_i} \;\; p_1 \cdots p_{i-1} \;\; \underline{p_{i+1}} \;\; p_{i+2} \cdots p_{n+1} \end{array} \right. \\ p_{i+1} \cdot \boldsymbol{T}_{k-1}(n) & \left\{ \begin{array}{l} p_{i+1} \;\; p_1 \cdots p_{i-1} \;\; p_i \;\; p_{i+2} \cdots p_{n+1} \\ \vdots \end{array} \right. \end{array}$$

The underlined elements that are swapped appear in positions n and $n-i$. When odd $n+1$, this case occurs on the last interface. The third property holds, since the last permutation of $\boldsymbol{T}_k(n+1)$ is $p_{n+1} \cdot \mathit{last}(\boldsymbol{T}_{k-1}(n))$, that is, $p_{n+1}\, p_n\, p_1 \cdots p_{n-1}$.

The second case is for odd i. The ith sublist is natural and the $(i+1)$st sublist is reverse. (1) When odd $n+1$, the contiguous permutations between the ith sublist and the $(i+1)$st sublist are shown below.

$$p_i \cdot \boldsymbol{T}_{k-1}(n) = \begin{cases} p_i \;\; p_1 \cdots p_{i-1}\, p_{i+1} \cdots p_{n+1} \\ \vdots \\ \underline{p_i} \;\; p_{n+1}\, p_1 \cdots p_{i-1} \;\; \underline{p_{i+1}} \;\; p_{i+2} \cdots p_n \end{cases}$$

$$p_{i+1} \cdot \overline{\boldsymbol{T}_{k-1}(n)} = \begin{cases} p_{i+1} \;\; p_{n+1}\, p_1 \cdots p_{i-1} \;\; p_i \;\; p_{i+2} \cdots p_n \\ \vdots \\ p_{i+1} \;\; p_1 \cdots p_i\, p_{i+2} \cdots p_{n+1} \end{cases}$$

The underlined elements that are swapped appear in positions n and $n-i-1$. (2) When even $n+1$, we can give some formulae for detecting the transposition of successive permutations at each interface. The successive permutations at the last interface differ by the elements in positions n and $n-1$, as shown below.

$$p_n \cdot \boldsymbol{T}_{k-1}(n) \begin{cases} p_n \;\; p_1 \cdots p_{n-1}\, p_{n+1} \\ \vdots \\ \underline{p_n} \;\; \underline{p_{n+1}} \;\; p_1 \cdots p_{n-1} \end{cases}$$

$$p_{n+1} \cdot \overline{\boldsymbol{T}_{k-1}(n)} \begin{cases} p_{n+1} \;\; p_n \;\; p_1 \cdots p_{n-1} \\ \vdots \\ p_{n+1} \;\; p_1 \cdots p_{n-1}\, p_n \end{cases}$$

The last property holds in this case. Otherwise, for $i < n$, the transposition behaves in two different ways depending upon the value of k. When $k = 2$, the elements of permutations that appear in positions greater than 2 are arranged in a lexical order. The contiguous permutations between the ith sublist and the $(i+1)$st sublist are identical in arrangements as the ones for the case (1), that is, the elements that are swapped appear in positions n and $n-i-1$. When $k > 2$, they are shown below.

$$p_i \cdot \boldsymbol{T}_{k-1}(n) \begin{cases} p_i \;\; p_1 \cdots p_{i-1}\, p_{i+1} \cdots p_{n+1} \\ \vdots \\ \underline{p_i} \;\; p_{n+1}\, p_n\, p_1 \cdots p_{i-1} \;\; \underline{p_{i+1}} \;\; p_{i+2} \cdots p_{n-1} \end{cases}$$

$$p_{i+1} \cdot \overline{\boldsymbol{T}_{k-1}(n)} \begin{cases} p_{i+1} \;\; p_{n+1}\, p_n\, p_1 \cdots p_{i-1} \;\; p_i \;\; p_{i+2} \cdots p_{n-1} \\ \vdots \\ p_{i+1} \;\; p_1 \cdots p_i\, p_{i+2} \cdots p_{n+1} \end{cases}$$

The elements that are swapped appear in positions n and $n-i-2$. The list $\boldsymbol{T}_k(n+1)$ has the stated properties. The proof is complete. ∎

```
procedure interchange(n,k,i:integer);
begin
  if (k=1) or not(odd(i)) then swap(n-1,n-i-1)
  else if odd(n) then swap(n-1,n-i-2)
    else if i=n-1 then swap(n-1,n-2)
      else if k=2 then swap(n-1,n-i-2) else swap(n-1,n-i-3);
end {of procedure};
```

Figure 1: The procedure `interchange(n,k,i)`.

```
procedure gen(n,k:integer);
var i:integer;
begin
  if k>0 then
    for i:=1 to n do begin
      if odd(i) then gen(n-1,k-1) else neg(n-1,k-1);
      if i<n then interchange(n,k,i);
    end
end {of procedure};
```

Figure 2: The recursive procedure `gen(n,k)`.

3 Implementation and analysis

To begin with, we summarize the transposition of successive permutations between the ith sublist and the $(i+1)$st sublist and show it in a Pascal procedure, in Figure 1. The procedure `swap(i,j)` swaps the elements in positions i and j. The definition of the list $\boldsymbol{T}_k(n)$ leads directly to a recursive algorithm for generating all k-permutations of n objects. The Pascal procedure `gen(n,k)` generates the list $\boldsymbol{T}_k(n)$, shown in Figure 2 and the procedure `neg(n,k)` is a symmetric procedure of `gen(n,k)` which generates the reversed list $\overline{\boldsymbol{T}_k(n)}$.

Let us analyze the running time of `gen(n,k)`. The procedure **gen** does n recursive calls to either **gen** or **neg** in the while statement. We also know that it calls `interchange` once per loop and the interchange operation takes a constant time to find the two elements that are swapped. Thus the total amount of computations is proportional to the number of recursive calls, which is $O(n!\,/\,(n-k)!)$. To summarize above, the procedure **gen** generates all k-permutations in an amortized constant time to go from one string to the next.

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