

Succinct Encoding of Permutations and its Applications to Text Indexing (2003; Munro, Raman, Raman, Rao)

J r my Barbay (University of Waterloo), www.cs.uwaterloo.ca/~jbarbay
J. Ian Munro (University of Waterloo), www.cs.uwaterloo.ca/~imunro
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1 PROBLEM DEFINITION

A succinct data structure for a given data type is a representation of the underlying combinatorial object that uses an amount of space “close” to the information theoretic lower bound together with algorithms that supports operations of the data type “quickly”. A natural example is the representation of a binary tree [5]: an arbitrary binary tree on n nodes can be represented in $2n + o(n)$ bits while supporting a variety of operations on any node, which include finding its parent, its left or right child, and returning the size of its subtree, each in $O(1)$ time. As there are $\binom{2n}{n}/(n+1)$ binary trees on n nodes and the logarithm of this term¹ is $2n - o(n)$, the space used by this representation is optimal to within a lower order term.

In our applications, the principle concern is with indexes supporting search in strings and in XML-like documents (i.e. tree-structured objects with labels and “free text” at various nodes). As happens not only labeled trees but also arbitrary binary relations over finite domains are key building blocks for this. Preprocessing such data-structures so as to be able to perform searches is a complex process requiring a variety of subordinate structures.

A basic building block for this work is the representation of a permutation of the integers $\{0, \dots, n-1\}$, denoted by $[n]$. A permutation π is trivially representable in $n \lceil \lg n \rceil$ bits which is within $O(n)$ bits of the information theoretic bound of $\lg(n!)$. For our purposes, however, we require not only an arbitrary permutation but also its inverse. As a consequence, we discuss the issue of representing an arbitrary permutation π on $[n]$ in a succinct manner so that $\pi^k(i)$ (π iteratively applied k times starting at i , where k can be any integer so that π^{-1} is the inverse of π) can be evaluated quickly.

2 KEY RESULTS

Munro *et al.* [7] studied the problem of succinctly representing a permutation to support computing $\pi^k(i)$ quickly. They give two solutions: one supports the operations arbitrarily quickly, at the cost of extra space; the other uses essentially optimal space at the cost of slower evaluation.

Given an integer parameter t , the permutations π and π^{-1} can be supported by simply writing down π in an array of n words of $\lceil \lg n \rceil$ bits each, plus an auxiliary array S of at most n/t shortcuts or back pointers. In each cycle of length at least t , every t -th element has a pointer t steps back.

¹All logarithms are taken to the base 2. We denote the iterated logarithm by $\lg^{(i)} n$, hence $\lg \lg x$ is $\lg^{(3)} x$.

$\pi(i)$ is simply the i -th value in the primary structure, and $\pi^{-1}(i)$ is found by moving forward until a back pointer is found and then continuing to follow the cycle to the location that contains the value i . The trick is in the encoding of the locations of the back pointers: this is done with a simple bit vector B of length n , in which a 1 indicates that a back pointer is associated with a given location. B is augmented using $o(n)$ additional bits so that the number of 1's up to a given position and the position of the r -th 1 can be found in constant time (i.e. using the rank and select operations on binary strings [8]). This gives the location of the appropriate back pointer in the auxiliary array S .

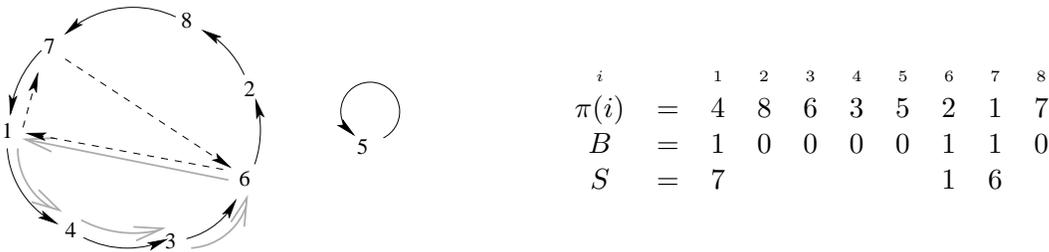


Figure 1: A permutation on $\{1, \dots, 8\}$, with 2 cycles and 3 back pointers. The full lines correspond to the permutation, the dashed lines to the back pointers, the grey lines to the edges traversed to compute $\pi^{-1}(3)$.

For example, the permutation $\pi = (4, 8, 6, 3, 5, 2, 1, 7)$ consists of two cycles, $(1, 4, 3, 6, 2, 8, 7)$ and (5) (see Figure 1). For $t = 3$, the back pointers are cycling backward between 1, 6 and 7 in the largest cycle (there are none in the other because it is smaller than t). To find $\pi^{-1}(3)$, follow π from 3 to 6, observe that 6 is a back pointer because marked by the second 1 in B , and follow the second value of S to 1, then follow π from 1 to 4 and then to 3: the predecessor of 3 has been found. As there are back-pointer every t elements in the cycle, finding the predecessor requires $O(t)$ memory accesses.

For arbitrary i and k , $\pi^k(i)$ is supported by writing the cycles of π together with a bit vector B marking the beginning of each cycle. Observe that the cycle representation itself is a permutation in “standard form”, call it σ . For example, the permutation $\pi = (6, 4, 3, 5, 2, 1)$ has three cycles $\{(1, 6), (3), (2, 5, 4)\}$ and is encoded by the permutation $\sigma = (1, 6, 3, 2, 5, 4)$ and the bit vector $B = (1, 0, 1, 1, 0, 0)$. The first task is to find i in the representation: it is in position $\sigma^{-1}(i)$. The rank and select operations on B now enable us to find the segment of the representation containing i . From this $\pi^k(i)$ is easily determined by taking k modulo the cycle length and moving that number of steps around the cycle starting at the position of i .

Other than the support of the inverse of σ , all operations are performed in constant time, hence the total time depends on the value chosen for t .

Theorem 1 (Munro et al. 2003). *There is a representation of an arbitrary permutation π on $[n]$ using at most $(1 + \varepsilon)n \lg n + O(n)$ bits that can support the operation $\pi^k()$ in time $O(1/\varepsilon)$, for any constant ε less than 1 and for any arbitrary value of k .*

It is not difficult to prove that this technique is optimal under a restricted model of pointer machine. So, for example, using $O(n)$ extra bits (i.e. $O(n/\lg n)$ extra words), $\Omega(\lg n)$ time is necessary to compute both π and π^{-1} . However, using another approach Munro *et al.* [7] demonstrate that the lower bound suggested does not hold in the RAM model. The approach is based on the Benes Network, a communication network composed of switches that can be used to implement permutations.

Theorem 2 (Munro et al. 2003). *There is a representation of an arbitrary permutation π on $[n]$ using at most $\lceil \lg(n!) \rceil + O(n)$ bits that can support the operation $\pi^k()$ in time $O(\lg n / \lg^{(2)} n)$.*

While this data-structure uses less space than the other, it requires more time for each operation. It is not known whether this time bound can be improved using only $O(n)$ “extra space”. As a consequence, the first data structure is used in all applications. Obviously, any other solution can be used, potentially with a better time/space trade-off.

3 APPLICATIONS

The results on permutations are particularly useful on two lines of research, first in the extension of the results on permutation to arbitrary integer functions; and second, and probably more importantly, in encoding and indexing text strings, which themselves are used to encode sparse binary relations and labeled trees. We summarize some of these results.

3.1 Functions

Munro and Rao [9] extended the results on permutations to arbitrary functions from $[n]$ to $[n]$. Again $f^k(i)$ indicates the function iterated k times starting at i . If k is nonnegative, this is straightforward. The case in which k is negative is more interesting as the image is a (possibly empty) multiset over $[n]$ (see Figure 2 for an example). Whereas π is a set of cycles, f can be viewed as a set of cycles in which each node is the root of a tree. Starting at any node (element of $[n]$), the evaluation moves one step toward the root of the tree or one step along a cycle (e.g. $f(8) = 7, f(10) = 11$). Moving k steps in a positive direction is straightforward, one moves up a tree and perhaps around a cycle (e.g. $f^5(9) = f^3(9) = 3$) When k is negative one must determine all nodes of distance k from the starting location, i , in the direction towards the leaves of the trees (e.g. $f^{-1}(13) = \{1, 11, 12\}$, $f^{-1}(3) = \{4, 5\}$). The key technical issue is to run across succinct tree representations picking off all nodes at the appropriate levels.

Theorem 3 (Munro and Rao 2004). *For any fixed ε , there is a representation of a function $f : [n] \rightarrow [n]$ that takes $(1 + \varepsilon)n \lg n + O(1)$ bits of space, and supports $f^k(i)$ in $O(1 + |f^k(i)|)$ time, for any integer k and for any $i \in [n]$.*

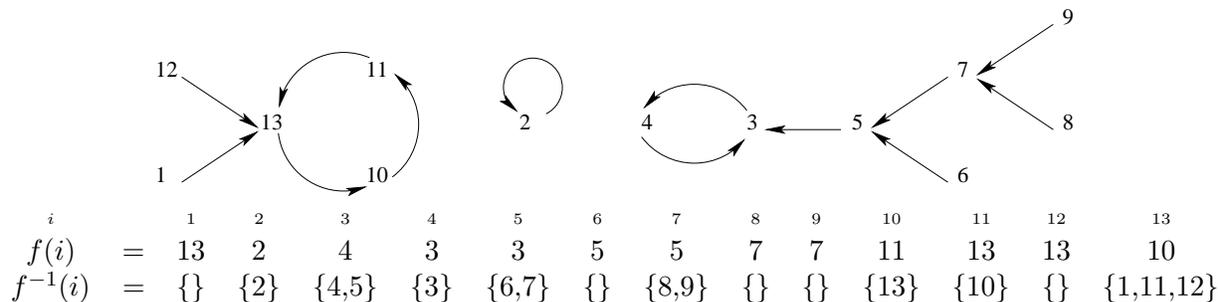


Figure 2: A function on $\{1, \dots, 13\}$, with 3 cycles and 2 nontrivial tree structures.

3.2 Text Strings

Indexing text strings to support the search for patterns is an important general issue. Barbay *et al.* [2] consider “negative” searches, along the following lines:

Definition 1. *Consider a string $S[1, n]$ over the alphabet $[l]$. A position $x \in [n]$ matches a literal $\alpha \in [l]$ if $S[x] = \alpha$. A position $x \in [n]$ matches a literal $\bar{\alpha}$ if $S[x] \neq \alpha$. The set $\{\bar{1}, \dots, \bar{l}\}$ is denoted by $[\bar{l}]$.*

Given a string S of length n over an alphabet of size l , for any position x in the string, any literal $\alpha \in [l] \cup [\bar{l}]$ and any integer r , we consider the following operators:

- **string_rank_s**(α, x): the number of occurrences of α in $S[1..x]$;
- **string_select_s**(α, r): the position of the r -th occurrence of α in S , or ∞ if none exists;
- **string_access_s**(x): the label $S[x]$;
- **string_pred_s**(α, x): the last occurrence of α in $S[1..x]$, or ∞ if none exists; and
- **string_succ_s**(α, r): the first occurrence of α in $S[x..]$, or ∞ if none exists.

Golynski *et al.* [4] observed that a string of length l on alphabet $[l]$ can be encoded and indexed by a permutation on $[l]$ (which for each label lists the positions of all its occurrences) together with a bit vector of length $2l$ (which signals the end of each sub-list of occurrences corresponding to a label). For instance, the string $ACCA$ on alphabet $\{A, B, C, D\}$ is encoded by the permutation $(1, 4, 2, 3)$ and the bit vector $(0, 0, 1, 1, 1, 0, 0, 1)$. Golynski *et al.* are then able to support the operators rank, select and access in time $O(\lg^{(2)} n)$, by using a value of $t = \lg^{(2)} n$ in the encoding of permutation of Theorem 1.

This encoding achieves fast support for the search operators defined above restricted to labels (not literals), with a small overhead in space, by integrating the encodings of the text and the indexing information. Barbay *et al.* [2] extended those operators to literals, and showed how to separate the *succinct encoding* of the string S , in a manner that assumes we can access a word of S in a fixed time bound, and a *succinct index* containing auxiliary information useful to support the search operators defined above.

Theorem 4 (Barbay *et al.* 2007). *Given access to a label in the raw encoding of a string $S \in [l]^n$ in time $f(n, l)$, there is a succinct index using $n(1 + o(\lg l))$ bits that supports the operators **string_rank_s**, **string_pred_s** and **string_succ_s** for any literal $\alpha \in [l] \cup [\bar{l}]$ in $O(\lg^{(2)} l \cdot \lg^{(3)} l \cdot (f(n, l) + \lg^{(2)} l))$ time; and the operator **string_select_s** for any label $\alpha \in [l]$ in $O(\lg^{(3)} l \cdot (f(n, l) + \lg^{(2)} l))$ time.*

The separation between the encoding of the string or an XML-like document and its index has two main advantages:

- The string can now be compressed and searched at the same time, provided that the compressed encoding of the string supports the access in reasonable time, as does the one described by Ferragina and Venturini [3].
- The operators can be supported for several orderings of the string, for instance induced by distinct traversals of a labeled tree, with only a small cost in space. It is important for instance when those orders correspond to various traversals of a labeled structure, such as the depth-first and DFUDS traversals of a labeled tree [2].

3.3 Binary Relations

Given two ordered sets of sizes l and n , denoted by $[l]$ and $[n]$, a binary relation R between these sets is a subset of their Cartesian product, i.e. $R \subset [l] \times [n]$. It is used, for instance, to represent the relation between a set of labels $[l]$ and a set of objects $[n]$.

Although a string can be seen as a particular case of a binary relation, where the objects are positions and exactly one label is associated to each position, the search operations on binary relations are diverse, including operators on both the labels and the objects. For any literal α , object x , and integer r , we consider the following operators:

- `label_rankR(α, x)`: the number of objects labeled α preceding or equal to x ;
- `label_selectR(α, r)`: the position of the r -th object labeled α if any, or ∞ otherwise;
- `label_nbR(α)`, the number of objects with label α ;
- `object_rankR(x, α)`: the number of labels associated with object x preceding or equal to label α ;
- `object_selectR(x, r)`: the r -th label associated with object x , if any, or ∞ otherwise;
- `object_nbR(x)`: the number of labels associated with object x ; and
- `table_accessR(x, α)`: checks whether object x is associated with label α .

Barbay *et al.* [1] observed that such a binary relation, consisting of t pairs from $[n] \times [l]$, can be encoded as a text string S listing the t labels, and a binary string B indicating how many labels are associated with each object. So search operations on the objects associated with a fixed label are reduced to a combination of operators on text and binary strings. Using a more direct reduction to the encoding of permutations, the index of the binary relation can be separated from its encoding, and even more operators can be supported [2]:

Theorem 5 (Barbay *et al.* 2007). *Given support for `object_accessR` in $f(n, l, t)$ time on a binary relation formed by t pairs from an object set $[n]$ and a label set $[l]$, there is a succinct index using $t(1 + o(\lg l))$ bits that supports `label_rankR` for any literal $\alpha \in [l] \cup [\bar{l}]$ and `label_accessR` for any label $\alpha \in [l]$ in $O(\lg^{(2)} l \cdot \lg^{(3)} l \cdot (f(n, l, t) + \lg^{(2)} l))$ time, and `label_selectR` for any label $\alpha \in [l]$ in $O(\lg^{(3)} l \cdot (f(n, l, t) + \lg^{(2)} l))$ time.*

We conclude this entry by mentioning that a labeled tree T can be represented by an ordinal tree coding its structure [6] and a string S listing the labels of the nodes. If the labels are listed in preorder (resp. in DFUDS order) the operator `string_succS` enumerates all the descendants (resp. children) of a node matching some literal α . Using succinct indexes, a single encoding of the labels and the support of a permutation between orders is sufficient to implement both enumerations, and other search operators on the labels. These issues, along with strings and labeled trees compression techniques which achieve the entropy of the indexed data, are covered in more details in other entries cited in the Cross References section.

4 OPEN PROBLEMS

None is reported.

5 EXPERIMENTAL RESULTS

None is reported.

6 DATA SETS

None is reported.

7 URL to CODE

None is reported.

8 CROSS REFERENCES

Compressed Text Indexing; Compressed Suffix Array; Rank and Select over Binary Strings; Text Indexing, Tree Compression and Indexing.

9 RECOMMENDED READING

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