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Nearest Common Ancestors: A Survey and a New Algorithm for a Distributed Environment

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Abstract. Several papers describe linear time algorithms to preprocess a tree, in order to answer subsequent nearest common ancestor queries in constant time. Here, we survey these algorithms and related results. Whereas previous algorithms produce a linear space data structure, in this paper we address the problem of distributing the data structure into short labels associated with the nodes. Localized data structures received much attention recently as they play an important role for distributed applications such as routing.

We conclude our survey with a new simple algorithm that labels in $O(n)$ time all the nodes of an n-node rooted tree such that from the labels of any two nodes alone one can compute in constant time the label of their nearest common ancestor. The labels assigned by our algorithm are of size $O(\log n)$ bits.

1. Introduction

Let T be a rooted tree. A node $x \in T$ is an *ancestor* of a node $y \in T$ if the path from the root of T to y goes through x. A node $v \in T$ is a *common ancestor* of x and y if it is an ancestor of both x and y. The *nearest common ancestor*, NCA, of two nodes x, y is the common ancestor of x and y whose distance to x (and to y) is smaller than the distance to x of any other common ancestor of x and y. We denote the NCA of x and y

by nca(x, y). The problem of efficiently computing NCAs has been studied extensively over the last three decades in an on-line and off-line setting, and in various models of computation (see, e.g., [48], [2], [3], [39], [61], [19], and [8]).

The NCA problem, also called the Least Common Ancestor or Lowest Common Ancestor (LCA) problem, has numerous applications. Solutions to this problem are routines of several optimization algorithms like algorithms for finding a maximum weighted matching in a graph [34], a minimum spanning tree in a graph [42], [22], and a dominator tree in a directed flow-graph [2]. It has also proved useful in several string algorithms [37], [26], for dynamic planarity testing [70], in network routing [66], for solving various geometric problems [15] including range searching [35], for finding evolutionary trees [27], and in bounded tree-width algorithms [16].

One of the most fundamental results on computing NCAs is that of Harel and Tarjan [39], [38]. Harel and Tarjan describe a linear time algorithm to preprocess a tree and build a data structure that allows subsequent NCA queries to be answered in constant time. Subsequent to this result of Harel and Tarjan several simpler algorithms with essentially the same properties but better constant factors have been proposed [54], [9], [35], [61], [12] (see also Section 2.2). These algorithms, including the one of Harel and Tarjan, use the observation that it is rather easy to solve the problem when the input tree is a complete binary tree.

To solve the problem when the input is a complete binary tree one can label the nodes by their index in an inorder traversal of the tree, starting with index 1. If the tree has n nodes each such number occupies $\ell = \lceil \log n \rceil$ bits.[1] We assume that the least significant bit is the rightmost and the index of this bit is 1. Let inorder(x) and inorder(y) be the inorder indices of x and y, respectively. Let i be the maximum among (1) the index of the leftmost bit in which inorder(x) and inorder(y) differ, (2) the index of the rightmost 1 in inorder(x), (3) the index of the rightmost 1 in inorder(y). It is easy to prove by induction that the inorder index of nca(x, y) consists of the leftmost $\ell - i$ bits of inorder(x) (or of inorder(y) if the maximum above was the index of the rightmost 1 in inorder(y)) followed to the right by a 1 and $i - 1$ zeros.

Note that this algorithm for complete binary trees is distributed in the sense that it constructs the inorder index of nca(x, y) from the inorder indices of x and y alone without accessing the original tree or any other global data structure. In case the application does not identify a node by its inorder index then tables converting identifiers to inorder indices and vice versa have to be constructed. In the common case where a node is identified by a pointer to a structure representing it, we can simply store the inorder index as an extra field in that structure. This will make it possible to get the inorder index of a node giving a pointer to its corresponding structure in constant time. In order to map the inorder index of the NCA back to a pointer to the corresponding node, a table of $O(2^{\ell}) = O(n)$ entries can easily be constructed.

The algorithms in [39], [54], [9], [35], [61], and [12] for general trees all work using some mapping of the tree to a completely balanced binary tree, thereby exploiting the fact that for completely balanced binary trees the problem is easier. Algorithms differ in the

[1] All the logarithms are in base 2.

way they do the mapping. Unfortunately, all algorithms, as a result of doing the mapping, have to use some precomputed auxiliary data structures in addition to the labels of the nodes, in order to compute NCAs. Thus, in contrast with the algorithm for completely balanced binary trees, the algorithms for general trees do not allow one to compute a unique identifier of $\mathrm{nca}(x, y)$ from short labels associated with x and y alone.

In this paper we show how to label the nodes of an arbitrary tree so that from the labels of x and y alone one can determine the label of $\mathrm{nca}(x, y)$. In particular we give an algorithm that proves the following theorem.

Theorem 1. *There is a linear time algorithm that labels the n nodes of a rooted tree T with distinct labels of length $O(\log n)$ bits such that from the labels of nodes $x, y \in T$ alone, one can compute the label of* $\mathrm{nca}(x, y)$ *in constant time.*

Our algorithm is as simple as most of the nondistributed algorithms mentioned above. In a scenario when nodes have to be identified by some fixed and predetermined identifiers one can use our algorithm together with a table converting labels to those predetermined identifiers and vice versa. Thus our algorithm provides an alternative to any of the algorithms mentioned above also in a nondistributed setting. Theorem 1 should be put in contrast with a recent lower bound of Peleg [53]. Peleg shows that one needs labels of $\Omega(\log^2 n)$ bits, if the query has to return a **predetermined identifier** of $\Omega(\log n)$ bits for $\mathrm{nca}(x, y)$ from the labels of x and y alone. So to obtain a theorem like Theorem 1 one has to exploit the freedom to choose the identifiers of the nodes. A distinguished feature in our algorithm is its use of alphabetic codes [36] to generalize the inorder approach for complete binary trees.

A labeling scheme to identify NCAs may be useful in routing messages on tree networks. When a message has to be sent from a node x to a node y in a tree it has to go through $\mathrm{nca}(x, y)$. Therefore the ability to compute the identifier of $\mathrm{nca}(x, y)$ from the identifiers of x and y may prove useful. Our particular NCA labeling scheme can also identify the first edge on the shortest path from x to y from the labels of x and y alone. In that sense it generalizes recent labeling schemes for routing on trees [28], [66] (see also Section 3). Another possible application of our algorithm arises in XML search engines. Such search engines typically maintain a reverse index. This index is a hash table mapping each word or a name of a tag to all XML documents containing it. The engine can exploit the fact that an XML document is essentially a tree and label each such tree using our algorithm. Then it can attach to each occurrence of a word in a document the label of the corresponding node. By doing that the engine can process sophisticated queries by accessing only the hash table rather than the documents themselves.

Outline of the Paper. In Section 2 we survey previous algorithms for computing NCAs, including related results and applications. In particular, we give a more direct relation between NCAs and range searching. Since our new algorithm makes it possible to identify the NCA from the two input nodes alone, its potential applications may avoid several lookups to perhaps expensive external memory. Further motivation for our new approach is given in Section 3. In Section 4 we prove Theorem 1.

2. NCA and Related Results

First we describe the relationship between NCAs and range searching, since most of the simple NCA algorithms are constructed using this relationship. Next we survey previous NCA algorithms for the RAM model of computation where the tree is static. Finally, we list results for finding NCAs in other models of computation and in cases where the topology of the tree can change. We also discuss a few closely related problems.

2.1. *NCA and Discrete Range Searching*

Gabow et al. [35] observed that the one-dimensional Discrete Range Searching (DRS) problem is equivalent to the NCA problem. The DRS problem is defined as follows. Given a sequence of real numbers $x_1, \ldots, x_n$, preprocess the sequence so that one can answer efficiently subsequent queries of the form "given a pair of indices (i, j), what is the index of a maximum element among $x_i, \ldots, x_j$?" We denote such a query by $\max[i, j]$. The DRS problem is a fundamental geometric searching problem and orthogonal range searching problems in two and higher dimensions are often reduced to DRS [35]. Gabow et al. (see also [44]) reduce the DRS problem to the NCA problem by constructing a Cartesian tree for the sequence $x_1, \ldots, x_n$, as defined by Vuillemin [68]. The *Cartesian tree* of the sequence $x_1, \ldots, x_n$ is a binary tree with n nodes, each containing a number x_i. Let $x_j = \max\{x_1, \ldots, x_n\}$. The root of the Cartesian tree for $x_1, \ldots, x_n$ contains x_j (and possibly also the index j). The left subtree of the root is a Cartesian tree for $x_1, \ldots, x_{j-1}$, and the right subtree of the root is a Cartesian tree for $x_{j+1}, \ldots, x_n$. Vuillemin shows how to construct the Cartesian tree of $x_1, \ldots, x_n$ in $O(n)$ time. It is easy to see that the maximum among $x_i, \ldots, x_j$ corresponds to the NCA of the node containing x_i and the node containing x_j.

Gabow et al. also show how to reduce the NCA problem to the DRS problem. Given a tree we first construct a sequence of its nodes by doing a depth first traversal [63]. Each time we visit a node we add it to the end of the sequence so that each node appears in the sequence as many times as its degree. Note that this sequence is a prefix of an Euler tour of the tree. Let $\text{depth}(x)$ be the depth of a node x. From the sequence of nodes we obtain a sequence of integers by replacing each occurrence of a node x by $-\text{depth}(x)$. To compute $\text{nca}(x, y)$ we arbitrarily pick two elements x_i, x_j in the sequence representing x and y, respectively, and compute the index of the maximum among $x_i, \ldots, x_j$. It is easy to see that the node corresponding to this maximum element is $\text{nca}(x, y)$.

Combining the equivalence between the NCA problem and the DRS problem with Theorem 1 we obtain the following corollary.

Corollary 2. *Let $x_1, \ldots, x_n$ be a sequence of real numbers. In linear time, one can associate a unique label of $O(\log n)$ bits to each element, such that the label of a maximum among $x_i, \ldots, x_j$ can be computed in constant time given the labels of x_i and x_j alone.*

If the value x_i is required rather than its label we need one lookup in a global table to map a label to a real number. We can implement this mapping either using sufficient space, using linear space and expected linear preprocessing time [32], or using linear space with $O(n \log n)$ deterministic preprocessing time [51].

2.2. *Previous Static Algorithms for Computing NCA*

As mentioned in Section 1, Harel and Tarjan [39] were the first who described how to preprocess a tree in linear time such that one can answer NCA queries in constant time per query. However they already point out in [39] that one could simplify some parts of their algorithm. Subsequently, Schieber and Vishkin [61] contracted some of the preprocessing steps of Harel and Tarjan into a single step and obtained a simpler algorithm which they could also parallelize. Powell [54] describes a simplification of the algorithm of Schieber and Vishkin.

Berkman and Vishkin [12] describe a simpler algorithm which is based on the equivalence between the NCA problem and the DRS problem. Let $x_1, \ldots, x_n$ be the input to the DRS problem. We build a complete binary tree with leaves $x_1, \ldots, x_n$ from left to right. With each internal node we associate a *left value* which is the maximum among the values in its left subtree and a *right value* which is the maximum among the values in its right subtree. We also associate with each leaf l two tables, each with $\log n$ entries, denoted by right_l and left_l. For a leaf l the value $\text{right}_l(i)$ is the maximum right value of an ancestor z of l such that l belongs to the left subtree of z, and z is of distance no greater than i to l. The value of $\text{left}_l(i)$ is defined similarly. To answer a query of the form $\max[i, j]$ we find the depth d of $\text{nca}(x_i, x_j)$ using a simple NCA algorithm for complete binary trees. Then we return the maximum among $\text{right}_{x_i}(d-1)$ and $\text{left}_{x_j}(d-1)$. The drawback of this simple algorithm is that it requires $O(n \log n)$ preprocessing time and space.

To overcome this difficulty Berkman and Vishkin observed that the sequence of depths of nodes on an Euler tour of the tree (obtained by reducing the NCA problem to the DRS problem) consists of integers such that the absolute difference between consecutive integers is at most 1. Based on this observation they suggested a three-level algorithm for the DRS (and the NCA) problem which runs in linear time. In their scheme the sequence is partitioned into *blocks*, each of size $O(\log n)$, and each block is further partitioned into *microblocks*, each of size $O(\log \log n)$. They use the observation that $|x_i - x_{i+1}| = 1$, for $1 \le i \le n-1$, to precompute the answers to all possible queries inside all possible microblocks in one large table. Then they apply the nonlinear algorithm described above to each sequence of microblocks in a block, and to the sequence of blocks, representing each block or microblock by the maximum element in it. Since the number of microblocks in a block is $\log n / \log \log n$ and the number of blocks is $n / \log n$ the resulting structures are of linear size. We answer a maximum query in constant time using the algorithm above on the relevant blocks and two lookups in the table of precomputed answers to queries in microblocks. Bender and Farach-Colton [9] show that in fact one can precompute in linear time all answers to queries inside blocks if the size of the block is $\frac{1}{2} \log n$. Therefore the microblock level of [12] is not needed and a simpler two-level algorithm based on the same ideas exists.

The algorithm of Berkman and Vishkin implicitly reduces the NCA problem for general trees to the NCA problem for completely balanced binary trees. By solving the NCA problem for completely balanced binary trees they obtain an algorithm for DRS on inputs where $|x_i - x_{i+1}| = 1$, for $1 \le i \le n-1$. Then they reduce the general NCA problem to this special case of DRS. Using the reduction from DRS to NCA described in Section 1 this also implies a solution to DRS for general sequences.

Last, we observe that in fact one can solve the DRS problem for general sequences directly, without going through the long reduction sequence to the special case of DRS just described. The solution to DRS described above exploited the restriction that $|x_i - x_{i+1}| = 1$ only to solve small subproblems of size $\frac{1}{2}\log n$. Alternatively, we can solve a DRS problem $x_1, \ldots, x_m$ of size $m = \lfloor \log n \rfloor$ as follows. For each x_i we compute $g(x_i) = \max\{k \mid k < i \text{ and } x_k > x_i\} \cup \{-1\}$. It is not hard to see that one can compute $g(x_i)$ for every $1 \le i \le m$, in $O(m)$ time, by maintaining the largest elements in all the suffixes of the prefix of the sequence so far traversed in a stack. Based on the values of $g(x_i)$ we associate a label, $l(x_i)$, of m bits with x_i, for every $1 \le i \le m$. The jth bit of $l(x_i)$ corresponds to element x_j, $1 \le j \le m$, and it is set if and only if $j < i$, $x_j > x_i$, and for every x_k, $j < k < i$, $x_k < x_j$. We compute these labels recursively as follows. The label $l(x_1)$ is 0. For $i > 1$, $l(x_i)$ is the same as $l(x_{g(x_i)})$ but with bit $g(x_i)$ also set. Now for $i < j$, we find $\max[i, j]$ from $l(x_j)$ as follows. We clear all bits with an index smaller than i in $l(x_j)$, getting a word w. Then we return x_j if $w = 0$, and otherwise we return $x_{\mathrm{lsb}(w)}$, where $\mathrm{lsb}(w)$ is the index of the least significant bit[2] in w. Using this technique for the blocks we obtain simpler DRS and NCA algorithms.

None of these algorithms however implies Theorem 1 or Corollary 2. If we try to distribute the data structures of any of the algorithms described so far so that it is possible to answer queries from the labels of the corresponding nodes alone, then the best labeling schemes we can get may contain labels of length $\Omega(\log^2 n)$ bits.

A somewhat different and interesting approach for computing NCAs on trees of depth $O(\log n)$ has been suggested by King [43]. King's algorithm labels each edge of the tree by either 0 or 1 randomly by flipping a fair coin. Then we label each node v with the concatenation of the labels of the edges on the path from the root to v. To find $\mathrm{nca}(x, y)$ we first find the length, d, of the longest common prefix of the label of x and the label of y. Let $\mathrm{ancestor}(x, d)$ be the ancestor of depth d of x. If $\mathrm{ancestor}(x, d)$ is also an ancestor of y, then it is the NCA of x and y. Otherwise for $i = 1, 2, \ldots$ we check whether $\mathrm{ancestor}(x, d - i)$ is an ancestor of y until we find such a node which must also be the NCA of x and y. It is easy to see that we would have to perform k ancestor queries with probability at most $1/2^k$. Therefore, on average, we need to perform a constant number of ancestor queries that involve ancestors of x at a particular level. The drawback of this scheme is that it requires external data structures to compute the ancestor of a node with a specified depth and to answer ancestor queries (see, e.g., [56], [21], and [6]).

2.3. *Dynamic NCA Problems and Different Models for Computation*

All algorithms mentioned above for the online NCA problem use random access to achieve constant query time. In contrast, on a pointer machine, Harel and Tarjan [39] proved a lower bound of $\Omega(\log \log n)$ on the query time. This matches a corresponding upper bound of van Leeuwen and Tsakalidis [65]. This lower bound stems from the need to answer a query by giving a pointer to the corresponding node.

[2] As previous NCA algorithms (e.g., [39] and [12]) we assume that bit operations, on words of size $\log n$, can be precomputed in $O(n)$ time if they are not supported to begin with.

The NCA problem is of interest also in an off-line setting where the list of, say m, queries is given in advance as input. Recently Buchsbaum et al. [14] gave an $O(m+n)$ time algorithm for the off-line NCA problem on a pointer machine, improving the previous best result by a factor of an inverse Ackermann's function [2], [64].

Returning to the on-line NCA problem, extensive research has also been done on how to allow update operations on the tree that are interspersed between NCA queries. Gabow [34] and Alstrup and Thorup [8] show how to add new leafs to the tree in amortized constant time while keeping the constant worst-case query time on a RAM, or the $O(\log\log n)$ worst-case query time on a pointer machine. Cole and Hariharan [19] gave an algorithm with *worst-case* constant update time for a RAM. The problem of computing NCAs in a forest of n nodes subject to dynamic updates has also been studied. Alstrup and Thorup [8] considered updates in which a root of one tree is made a child of a root of another tree. They gave a pointer machine algorithm with amortized constant update time and $O(\log\log n)$ worst-case query time. For a RAM, Harel and Tarjan [39] gave an algorithm which for m operations on a forest of n nodes uses time $O(n+m\alpha(m+n, n))$ time, where α denotes the inverse Ackermann function. If we allow roots to be linked the problem is at least as hard as the Union-Find problem [34]. Thus the amortized inverse Ackermann's lower bound in [33] is applicable.

A more general update operation on a forest would allow one to make any node in one tree a parent of a root of another tree. In [8] Alstrup and Thorup gave an algorithm for a pointer machine using $O(n+m\log\log n)$ time. This algorithm uses, in the worst case, $O(n)$ time both for queries and updates. For the RAM, an optimal algorithm which uses $O(i)$ worst-case time for queries and $O(a(i, n))$ amortized time for updates, where i is arbitrary and a is the row inverse Ackermann's function, is given in [34]. This tradeoff matches the lower bound given in [4]. If we also allow the deletion of edges, a pointer machine algorithm is given in [62] using $O(\log n)$ time per operation, where n is the size of the tree(s) involved in the operation. Other updates have also received some attention in connection with NCA, such as splitting an edge by inserting a new node on the edge [70], [19].

Let $level(x, i)$ return the ancestor to x whose depth is smaller by i than the depth of x. If we substitute NCA with *level* for the different dynamic settings the same bounds mentioned above hold for the RAM [21], [6], [13], [62]. For a pointer machine, however, we have a trivial lower bound on $\Omega(\log n)$ even for the static case, hence, for the pointer machine, Sleator and Tarjan's dynamic trees [62] give optimal results.

Research has also been done on parallel and distributed complexities [11], [55], [67], [46], [47], [60], [57], [58], [45], [18], [59], [69], [61] and on the I/O complexity [17] of several of the problems mentioned above. Some natural extensions of these problems to rooted directed trees [50] and Directed Acyclic Graphs [10], [24], [25] have also been studied.

3. Labeling Schemes for a Distributed Environment

Motivated by applications in the construction of XML search engines and network routing [1], [41], [52], labeling schemes that allow ancestor queries have recently been developed. Santoro and Khatib [56] have proposed labeling the leaves of the tree from left to right by consecutive integers, and then labeling each internal node by the pair of labels of its leftmost and rightmost leaf descendants. One can then answer ancestor queries by checking if the corresponding intervals are nested. Clearly, the maximum length of a label according to this scheme is $2 \log n$ bits. Recently, Alstrup and Rauhe [7] building upon the work of Abiteboul et al. [1] gave a more complicated recursive labeling scheme for ancestor queries that generates labels of length at most $\log n + O(\sqrt{\log n})$ bits. A lower bound showing that $\log n + \Omega(\log \log n)$ bits are needed is given in [5]. This lower bound also holds for NCA queries which are more general.

Labeling schemes for parent queries and other functions have also been studied [40], [41], [53]. Unfortunately neither of these labeling schemes can identify the nearest common ancestor of x and y, when x and y are unrelated. The labeling scheme that we describe in this paper does allow this extra functionality.

In [66] and [28] it is demonstrated how compact labelings of a tree can improve routing in trees and graphs. In the routing problem one assigns two labels to every node of the graph. The first label is the *address* of the node, whereas the second label is a data structure called the *local routing table*. The labels are assigned such that at every source node x, and for every destination node y, one can find the first edge (or an identifier of that edge) on a shortest path from x to y from the local routing table of x and the address of y. So the path from x to y is built in a distributed way by all intermediate nodes encountered along the way. The goal is to obtain such labeling with labels as small as possible.

In [20] Cowen shows how to construct a labeling for trees that uses $3 \log n$ bits for the addresses and $O(\min\{d \log n, \sqrt{n} \log n\})$ bits for the local routing table, where d is the degree of the node. In [23] Eilam et al. show that any labeling in which the length of the addresses is at most $\log n$ bits will require $\Omega(\sqrt{n})$ bits for the routing table in some trees. However, Gavoille and Fraigniaud [28], [29] showed that $c \log n$ bits, for a small constant c, are enough to encode both the address and the local routing table of each node of the tree. Thorup and Zwick [66] even show that both the address and the local routing table of each node can be encoded together using $\log n + O(\log n / \log \log n)$ bits (so $c = 1 + o(1)$ suffices). Thorup and Zwick also show how to use their tree labeling to construct labeling for general graphs based on tree covering.

The labeling schemes for routing mentioned above do not support NCAs without some extensions. The labeling scheme that we suggest in this paper, however, cannot only identify $\mathrm{nca}(x, y)$ from the labels of x and y but also identify the first edge on the shortest path from x to y. Therefore it is more general than the routing labeling schemes.

A particular routing context where a labeling scheme for NCA may prove useful is the design of routing labeling schemes for graphs that are close to a tree, say c-decomposable or graphs with tree-width $O(c)$ [30], [31] for $c = O(1)$. These graphs admit a tree-decomposition T where each node of T represents a separator of the graph of size at most c. So, one can use a compact labeling of T in order to determine the nearest separator S between the source x and the destination y. If x is contained in the component $X \in T$, and y is contained in the component $Y \in T$, then S is precisely the nearest common ancestor of X and Y. Since, any path from x to y has to cross some node of S, computing $\mathrm{nca}(X, Y)$ from the labels of x and y may simplify the local routing tables.

We also observe that a compact labeling scheme for routing queries may serve a labeling scheme for ancestor queries and vice versa. If the routing query of the first edge on the shortest path from x towards y, and the routing query of the first edge from y

towards x, both answer the edge from the corresponding node to its parent, then one knows that x and y are not related. Otherwise, either x or y is the ancestor of the other (and also $\mathrm{nca}(x, y) \in \{x, y\}$). On the other hand, if y is an ancestor of x or x and y are unrelated we know that the first edge on the shortest path from x to y is the edge from x to its parent. Otherwise, the first edge on the shortest path from x to y is an edge from x to one of its children.

4. An NCA Algorithm for a Distributed Environment

4.1. *Preliminaries*

We denote by $\langle y\rangle_k$ a sequence of objects $y_1, y_2, \ldots, y_k$ (such as integers or binary strings). For binary strings $a, b \in \{0,1\}^*$, $a <_{\mathrm{lex}} b$ if and only if a precedes b in the lexicographic order on binary strings. That is, a is prefix of b or the first bit in which a and b differ is 0 in a and 1 in b. An *alphabetic* sequence for $\langle y\rangle_k$ is a sequence of binary strings $\langle b\rangle_k$, $b_i \in \{0,1\}^*$, where $b_i <_{\mathrm{lex}} b_j$, for all $1 \le i < j \le k$. Let $|s|$ denote the length of a binary string $s \in \{0,1\}^*$. Observe that given machine words that contain a, b, $|a|$, and $|b|$, respectively, in their least significant bits, it is possible to determine whether $a <_{\mathrm{lex}} b$ in a constant number of operations. For instance, first align a and b by shifting the smallest string to the left, and then use standard integer comparison operators on the resulting words. If the two words are then equal, then we break the tie according to the length of a and b. When the strings $\langle b\rangle_k$ are also prefix-free (no string is a prefix of another) we call $\langle b\rangle_k$ an *alphabetic code*. The following lemma due to Gilbert and Moore [36] states the result which we need for alphabetic codes.

Lemma 3 [36]. *A sequence $\langle y\rangle_k$ of positive integers with $n = \sum_{i=1}^{k} y_i$ has an alphabetic code $\langle b\rangle_k$ where $|b_i| \le \log n - \log y_i + O(1)$ for all i.*

For our purposes it would suffice that $\langle b\rangle_k$ is alphabetic (strings can be prefixes of one another). We can construct in $O(k)$ time an alphabetic sequence satisfying the length bounds in Lemma 3 for a sequence $\langle y\rangle_k$ of non-null integers as follows. Let $s_i = \sum_{j=1}^{i} y_j$, $i = 1, \ldots, k-1$, and let $s_0 = 0$. Also let $I_i = [s_{i-1}, s_{i-1} + y_i)$ and $f_i = \lfloor \log y_i \rfloor$ for $i = 1, \ldots, k$. In the interval I_i of length $y_i \ge 2^{f_i}$ there must be an integer z_i such that $z_i \bmod 2^{f_i} = 0$, i.e., the f_i rightmost bits in its binary representation are 0. If $s_{i-1} \bmod 2^{f_i} = 0$, then $z_i = s_{i-1}$, otherwise $z_i = s_{i-1} - (s_{i-1} \bmod 2^{f_i}) + 2^{f_i}$. Hence, z_i can be represented in a word with $w = \lceil \log n \rceil$ bits, having the f_i less significant bits set to 0. Then we can let b_i be the bit string consisting of the $w - f_i$ most significant bit from z_i. Thus we get a sequence $\langle b\rangle_k$ where $|b_i| \le \lceil \log n \rceil - \lfloor \log y_i \rfloor$.

For instance, for a sequence $\langle y\rangle_5 = 3, 5, 3, 4, 1$ for which $n = 16$, we obtain $\langle f\rangle_5 = 1, 2, 1, 2, 0$, $\langle z\rangle_5 = 0, 4, 8, 12, 15$, and so its code is $\langle b\rangle_5 = 000, 01, 100, 11, 1111$. To assure that the sequence is alphabetic, one can interpret each string of $\langle b\rangle_k$ as the decimal part of a real number in $[0, 1)$ and observe that the numbers are in increasing order. In this example, these numbers are 0, 0.01, 0.1, 0.11, and 0.1111.

The algorithm runs in $O(k)$ time if machine operations to compute shifting, logical masks, and a discrete logarithm on $O(\log n)$ bit words are supported. In a machine that does not support such operations we can construct a table representing these functions using $O(n)$ preprocessing time and space. This will only increase the preprocessing time of our labeling algorithm which is described in Section 4.2 by a constant factor. Note that Mehlhorn [49] gives a somewhat more complicated algorithm which produces an *alphabetic code*, $\langle b\rangle_k$, for an arbitrary sequence $\langle y\rangle_k$ of positive real numbers with the same bound on the lengths, i.e., $|b_i| \le \log n - \log y_i + 2$. Mehlhorn's algorithm can be implemented to run in $O(k)$ time.

4.2. *Labeling for NCA Queries*

As in [39] we divide the tree into disjoint paths. For a tree T, let $|T|$ denote the number of nodes of T. Let T_v be the subtree rooted by v, and let $\text{size}(v) = |T_v|$. Let $\text{parent}(v)$ be the parent of v and let $\text{children}(v)$ be the set of children of v. We classify each node of T as either *heavy* or *light* as follows. The root is light. For each internal node v, we pick a child w of v, where $\text{size}(w) = \max\{\text{size}(z) \mid z \in \text{children}(v)\}$ and classify w as *heavy*. We classify each of the remaining children of v as *light*. We call an edge to a light child a *light edge*, and an edge to a heavy child a *heavy edge*. For a node v with a heavy child w, let $\text{lsize}(v) = \text{size}(v) - \text{size}(w)$. We define $\text{lsize}(v) = 1$ for when v is a leaf. The nearest ancestor of v which is light (possibly v itself if v is light) is denoted by $\text{apex}(v)$. By removing the light edges, T is partitioned into paths, which we call *heavy paths*. A node w belongs to the same heavy path as the nodes of the set $\text{HP}(w) = \{v \mid v \in T,\ \text{apex}(v) = \text{apex}(w)\}$. See Figure 1 for an example.

First we compute $\text{size}(v)$, $\text{lsize}(v)$, $\text{apex}(v)$, and the partition of T into heavy paths. It is easy to see that one can compute this information in linear time. Next we assign a heavy label, $\text{hlabel}(v)$, to each node $v \in T$, and a light label $\text{llabel}(v)$ to each light node v. These labels are defined as follows.

For the root r, $\text{llabel}(r)$ is the empty string. Then, for each light node $w \neq r$, $\text{llabel}(w)$ is a binary string such that

- Light label:
  $\text{llabel}(w) \not\in \{\text{llabel}(z) \mid z \neq w,\ z \in \text{children}(\text{parent}(w))\}$.

Let w be any node. Then $\text{hlabel}(w)$ is a binary string such that

- Heavy label:
  $\text{hlabel}(w) <_{\text{lex}} \min_{\text{lex}}\{\text{hlabel}(z) \mid z \neq w,\ z \in T_w \cap \text{HP}(w)\}$, where lex is the lexicographic order of two strings.

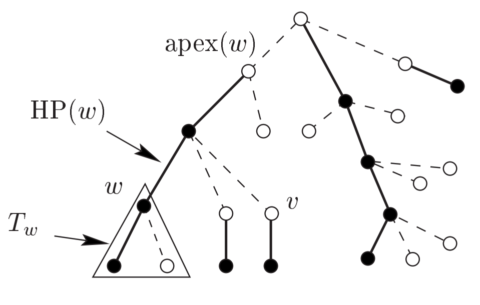

Fig. 1. Heavy nodes are black and light nodes are white. Heavy edges are solid and light edges are dashed. Heavy paths are subtrees composed of heavy edges only. In this example, $\text{apex}(v) = v$.

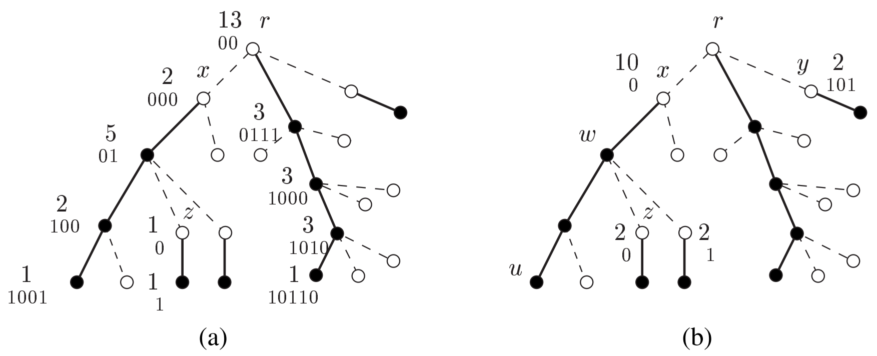

Fig. 2. Heavy (a) and light (b) label construction of some nodes.

In other words, the light children of a node must have distinct light labels, whereas the nodes of a same heavy path must have heavy labels lexicographically ordered according to their depth in T. We assign heavy and light labels using the algorithm described in Section 4.1, constructing alphabetic strings from an integer sequence (a concrete example is presented below).

More precisely, we associate heavy labels with the nodes on each heavy path separately. We associate the weight $\mathrm{lsize}(v)$ with each node v on a heavy path and we construct alphabetic strings for this sequence of weights. Each string is then associated with the corresponding node. Similarly, light labels are assigned to the light children of each node u separately. To do that we associate the weight $\mathrm{size}(v)$ with each light child of u, and construct alphabetic strings for this sequence of weights. Each string is then associated with the corresponding node. We remark that light labels have no alphabetic restriction imposed on them so in fact one can obtain even shorter light labels using a simpler algorithm.

To illustrate the construction of heavy and light labels we refer to Figure 2. The heavy labels of the nodes in $\mathrm{HP}(x)$ (see Figure 2(a)) are based on the light sizes of these nodes which are, starting from x and going down, 2, 5, 2, 1. The corresponding alphabetic strings are 000, 01, 100, 1001, so for instance $\mathrm{hlabel}(x) = 000$. The sequence of light sizes of the nodes of $\mathrm{HP}(r)$ is 13, 3, 3, 3, 1. That gives the alphabetic strings 00, 0111, 1000, 1010, 10110, so $\mathrm{hlabel}(r) = 00$. The sequence of light sizes of $\mathrm{HP}(z)$ is 1, 1 which gives 0, 1 for the heavy labels. The light labels of the children x, y of r (see Figure 2(b)) are based on their respective sizes, which are 10, 2. The alphabetic strings then imply that $\mathrm{llabel}(x) = 0$ and $\mathrm{llabel}(y) = 101$.

Next we assign a label $l(v)$ to each node $v \in T$ top-down as follows. We define $l(\mathrm{parent}(r))$ to be the empty string. Then for every node v (we use the $\cdot$ operator for concatenation of strings),

$$l(v) = l(\mathrm{parent}(\mathrm{apex}(v))) \cdot \mathrm{llabel}(\mathrm{apex}(v)) \cdot \mathrm{hlabel}(v).$$

See Figure 3 for an illustration. It follows from our definition that $l(r) = \mathrm{hlabel}(r)$ and that a label $l(v)$ consists of the concatenation of alternating light and heavy labels. Thus $l(v) = h_0 \cdot l_1 \cdot h_1 \cdots l_t \cdot h_t$, the first light label l_0 removed as being $\mathrm{llabel}(\mathrm{apex}(r))$, the empty string. We observe that $l(v) \neq l(w)$ for all distinct $v, w \in T$.

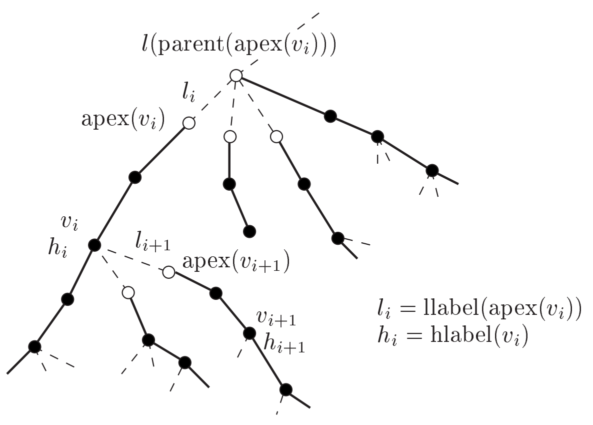
$l(\text{parent}(\text{apex}(v_i)))$
l_i
$\text{apex}(v_i)$
v_i
h_i
l_{i+1}
$\text{apex}(v_{i+1})$
v_{i+1}
h_{i+1}
$l_i = \text{llabel}(\text{apex}(v_i))$
$h_i = \text{hlabel}(v_i)$

Fig. 3. The construction of $l(v)$. Here $l(v_i) = l(\text{parent}(\text{apex}(v_i)))\cdot l_i \cdot h_i$.

For example, from Figure 2, we obtain $l(r) = 00$, $l(x) = l(r)\cdot\text{llabel}(x)\cdot\text{hlabel}(x) = 00\cdot 0\cdot 000$, $l(w) = l(r)\cdot\text{llabel}(x)\cdot\text{hlabel}(w) = 00\cdot 0\cdot 01$, $l(z) = l(w)\cdot\text{llabel}(z)\cdot\text{hlabel}(z) = 00\cdot 0\cdot 01\cdot 0\cdot 0$, and $l(u) = l(r)\cdot\text{llabel}(x)\cdot\text{hlabel}(u) = 00\cdot 0\cdot 1001$.

In addition to $l(v)$ we need a label $k(v)$ of the same length, where the ith bit of $k(v)$ is set if and only if the ith bit of $l(v)$ is the beginning of either a light or heavy label. The label $k(v)$ is well defined because $|\text{llabel}(v)|, |\text{hlabel}(v)| \geq 1$. The final label assigned to v, label(v), consists of the concatenation of $l(v)$ and $k(v)$. Once heavy and light labels of all the nodes have been computed, one can perform a depth first traversal [63] of the tree and compute $l(v)$ and $k(v)$ in linear time.

Before showing how to compute the NCA given two labels we bound the length of the labels. Using the alphabetic strings of Lemma 3, we have

- $|\text{llabel}(w)| \leq \log \text{lsize}(\text{parent}(w)) - \log \text{size}(w) + O(1)$, and
- $|\text{hlabel}(w)| \leq \log \sum_{v\in \text{HP}(w)} \text{lsize}(v) - \log \text{lsize}(w) + O(1)$.

Lemma 4. *For any node $v \in T$, $|\text{label}(v)| = O(\log n)$.*

Proof. First, note that $|\text{label}(w)| = |l(w)| + |k(w)| = 2|l(w)|$. The number of heavy and light labels in $l(w)$ is at most $\log n$, since there is at most $\log n$ light edges on a path from a leaf to the root. Hence, the additive $O(1)$ terms in the light and heavy labels of $l(w)$ sum to $O(\log n)$. So, in the remaining analysis we disregard the additive constant term. We prove by induction on the depth of w that $|l(w)| \leq \log n - \log \text{lsize}(w)$. For a node w, where $\text{apex}(w) = r$, in a tree with root r, $|l(w)| = |\text{hlabel}(w)| \leq \log n - \log \text{lsize}(w)$ so the statement holds. For another node w, where $\text{apex}(w) \neq r$, $l(w) = l(\text{parent}(\text{apex}(w)))\cdot \text{llabel}(\text{apex}(w)) \cdot \text{hlabel}(w)$. Now, by induction, $|l(\text{parent}(\text{apex}(w)))| \leq \log n - \log \text{lsize}(\text{parent}(\text{apex}(w)))$, and also by the definitions of the heavy labels and the light labels we have $|\text{llabel}(\text{apex}(w))| \leq \log \text{lsize}(\text{parent}(\text{apex}(w))) - \log \text{size}(\text{apex}(w))$, and $|\text{hlabel}(w)| \leq \log \sum_{v\in\text{HP}(w)} \text{lsize}(v) - \log \text{lsize}(w)$. By summing up the last three bounds and using the fact that $\sum_{v\in\text{HP}(w)} \text{lsize}(v) \leq \text{size}(\text{apex}(w))$ we complete the proof. □

The next lemma indicates how to answer NCA queries.

Lemma 5. *Let x and y be two nodes of T:*

1. *If $l(x) = h_0{\cdot}l_1{\cdot}h_1 \cdots h_{i-1}{\cdot}l_i{\cdot}u$ and $l(y) = h_0{\cdot}l_1{\cdot}h_1 \cdots h_{i-1}{\cdot}l'_i{\cdot}u'$ with $u, u' \in \{0,1\}^*$, where $l_i \neq l'_i$ or $l_i{\cdot}u$ is empty or $l'_i{\cdot}u'$ is empty, then $l(\mathrm{nca}(x,y)) = h_0{\cdot}l_1{\cdot}h_1 \cdots l_{i-1}{\cdot}h_{i-1}$.*
2. *If $l(x) = h_0{\cdot}l_1{\cdot}h_1 \cdots l_i{\cdot}h_i \cdots$ and $l(y) = h_0{\cdot}l_1{\cdot}h_1 \cdots l_i{\cdot}h'_i \cdots$, where $h_i \neq h'_i$, then $l(\mathrm{nca}(x,y)) = h_0{\cdot}l_1{\cdot}h_1 \cdots l_i{\cdot}\min_{\mathrm{lex}}\{h_i, h'_i\}$.*

Proof. Let $z = \mathrm{nca}(x,y)$. By definition $l(\mathrm{parent}(\mathrm{apex}(z)))$ is a prefix of both $l(x)$ and $l(y)$. Let w be the heavy child of z. If $x \in T_a$, $y \in T_b$, $a, b \in \mathrm{children}(z)\backslash\{w\}$, or x is an ancestor of y or y is an ancestor of x, then case 1 occurs; otherwise case 2 occurs. □

For instance, in the example of Figure 2, we have seen that $l(u) = 00{\cdot}0{\cdot}1001$, $l(w) = 00{\cdot}0{\cdot}01$, and $l(z) = 00{\cdot}0{\cdot}01{\cdot}0{\cdot}0$. Case 1 of Lemma 5 applies while computing $\mathrm{nca}(w,z)$. We obtain $l(\mathrm{nca}(w,z)) = 00{\cdot}0{\cdot}01$ which is the label of w. Case 2 occurs for $\mathrm{nca}(u,z)$, and we obtain $l(\mathrm{nca}(u,z)) = 00{\cdot}0{\cdot}01$ which is the label of w.

To implement the calculation of $\mathrm{nca}(x,y)$ described in Lemma 5 we need to be able to identify the maximum i such that both $l(x)$ and $l(y)$ have $h_0{\cdot}l_1{\cdot}h_1 \cdots l_i{\cdot}h_i$ as a prefix. To that end we calculate the length j_1 of the maximum common prefix of $l(x)$ and $l(y)$, and the length j_2 of the maximum common prefix of $k(x)$ and $k(y)$. Then we take $j = \min\{j_1, j_2\}$ and calculate whether this bit (jth from the left) is part of a light label or a heavy label. To determine easily whether bit j occurs within a light label or a heavy label we can for example add to the label of v a mask containing a 1 in every bit that belongs to a light label or alternatively use a table that counts the parity of the number of bits set to 1 in a word. Once we identify whether j occurs within a light or heavy label we can extract the label of $\mathrm{nca}(x,y)$ using straightforward bit manipulations.

5. Concluding Remarks

(1) In case we want to solve the unrestricted DRS problem using a Cartesian tree, we can let all the light labels be an empty string, since a Cartesian tree is binary. This will improve the constant factor for the length of the labels.

(2) If we use an alphabetic code for the heavy labels (no heavy label on a path is a prefix of another) and any prefix code for the light labels, then $l(v)$ uniquely identifies v, and there is no need to look at $k(v)$ in order to ascertain the maximum i such that $h_0{\cdot}l_1{\cdot}h_1 \cdots l_i{\cdot}h_i$ is a prefix of both $l(x)$ and $l(y)$.

(3) Optimizing the label length is an interesting problem. We wonder whether NCA labels of length at most $c \log n$ bits, with some constant $c < 2$, is possible or not. The current lower bound is only $\log n + \Omega(\log\log n)$ using a reduction from labeling for ancestor queries in trees [5].

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