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Algorithms for finding the weight-constrained k longest paths in a tree and the length-constrained k maximum-sum segments of a sequence

Hsiao-Fei Liu[a], Kun-Mao Chao[a,b,c,*]

[a] Department of Computer Science and Information Engineering, National Taiwan University, Taipei 106, Taiwan

[b] Graduate Institute of Biomedical Electronics and Bioinformatics, National Taiwan University, Taipei 106, Taiwan

[c] Graduate Institute of Networking and Multimedia, National Taiwan University, Taipei 106, Taiwan

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ABSTRACT

In this work, we obtain the following new results:

- Given a tree $T = (V, E)$ with a length function $\ell : E \to \mathbb{R}$ and a weight function $w : E \to \mathbb{R}$, a positive integer k, and an interval $[L, U]$, the WEIGHT-CONSTRAINED k LONGEST PATHS problem is to find the k longest paths among all paths in T with weights in the interval $[L, U]$. We show that the WEIGHT-CONSTRAINED k LONGEST PATHS problem has a lower bound $\Omega(V \log V + k)$ in the algebraic computation tree model and give an $O(V \log V + k)$-time algorithm for it.
- Given a sequence $A = (a_1, a_2, \dots, a_n)$ of numbers and an interval $[L, U]$, we define the sum and length of a segment $A[i, j]$ to be $a_i + a_{i+1} + \cdots + a_j$ and $j - i + 1$, respectively. The LENGTH-CONSTRAINED k MAXIMUM-SUM SEGMENTS problem is to find the k maximum-sum segments among all segments of A with lengths in the interval $[L, U]$. We show that the LENGTH-CONSTRAINED k MAXIMUM-SUM SEGMENTS problem can be solved in $O(n+k)$ time.

1. Introduction

Optimization is one of the most basic types of algorithmic problems. In an optimization problem, the goal is to find the best feasible solution. However, it is often not satisfactory in practice to only find the best feasible solution, and we may be required to enumerate, for example, all the top ten or top twenty feasible solutions. We call a problem of such kind, where the goal is to find the top k best feasible solution for a given k, an enumeration problem. In this paper, we study some enumeration problems on trees and sequences.

We start by considering problems on trees. Let $T = (V, E)$ be a tree with a length function $\ell : E \to \mathbb{R}$ and a weight function $w : E \to \mathbb{R}$. Define the length and weight of a path $P = (v_1, v_2, \dots, v_n)$ in T to be $\sum_{1 \le i \le n-1} \ell(\overline{v_i v_{i+1}})$ and $\sum_{1 \le i \le n-1} w(\overline{v_i v_{i+1}})$, respectively. Given T, the TREE LONGEST PATH problem (also known as the TREE DIAMETER problem) is to find the longest path in T. The TREE LONGEST PATH problem is a fundamental problem in dealing with trees and solvable in $O(V)$ time [36]. In what follows, we introduce two generalizations of the TREE LONGEST PATH problem, which are closely related to our study in this paper.

One is the TREE k LONGEST PATHS problem. Given T and a positive integer k, the TREE k LONGEST PATHS problem is to find the k longest paths from all paths in T. Megiddo et al. [32] proposed an $O(V \log^2 V)$-time algorithm for finding the kth longest path. Later, Frederickson and Johnson [20] improved the time complexity to $O(V \log V)$. After finding the kth longest path,

[*] Corresponding address: Department of Computer Science and Information Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan. Tel.: +886 2 33664888; fax: +886 2 23628167.
E-mail address: kmchao@csie.ntu.edu.tw (K.-M. Chao).

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the k longest paths can be constructed with additional $O(k)$ time from the computed information. Hence, the Tree k Longest Paths problem is solvable in $O(V \log V + k)$ time.

The other is the Weight-Constrained Longest Path problem. Given T and interval $[L, U]$, the Weight-Constrained Longest Paths problem is to find the longest path among all paths in T with weights in the interval $[L, U]$. The Weight-Constrained Longest Path problem was formulated by Wu et al. [35] and motivated as follows. Given a tree network with length and weight on each edge, we want to maintain the network by choosing a path and renewing the old and shabby edges of this path. The length and weight on an edge measure the traffic load and update cost of this edge, respectively. Since we also have budget constraints which limit the weight of the path to be updated, the goal is to find the longest path subject to the weight constraints. Wu et al. [35] proposed an $O(V \log^2 V)$-time algorithm for the case where the edge weight lower bound is ineffective, i.e. $L = -\infty$. Kim [27] gave an $O(V \log V)$-time algorithm to cope with the case where the tree has a constant degree and a uniform edge weight and the edge weight lower bound is ineffective.

In this paper, we study the Weight-Constrained k Longest Paths problem, which is a combination of the Tree k Longest Paths problem and the Weight-Constrained Longest Path problem. Given T, a positive integer k, and interval $[L, U]$, the Weight-Constrained k Longest Paths problem is to find the k longest paths of T among all paths in T with weights in the interval $[L, U]$. We give an $O(V \log V + k)$-time algorithm for the Weight-Constrained k Longest Paths problem and prove that it has a lower bound of $\Omega(V \log V + k)$ in the algebraic computation tree model.

Next, we consider problems on sequences. Let $A = (a_1, a_2, \ldots, a_n)$ be a sequence of numbers. Define the sum and length of a segment $A[i, j]$ to be $a_i + a_{i+1} + \cdots + a_j$ and $j - i + 1$, respectively. The Maximum-Sum Segment problem, given A, is to find a segment of A that maximizes the sum. The Maximum-Sum Segment problem was first presented by Grenader [22] and finds applications to pattern recognition [22,33], biological sequence analysis [1], and data mining [21]. The Maximum-Sum Segment problem is linear-time solvable using Kadane's algorithm [7]. A variety of generalizations of the Maximum-Sum Segment problem have been proposed to fulfill more requirements. In the following, let us introduce two of them, which are closely related to our study in this paper.

One is the k Maximum-Sum Segments problem. Given A and a positive integer k, the k Maximum-Sum Segments problem is to locate the k segments whose sums are the k largest among all possible sums. The k Maximum-Sum Segments problem was first presented by Bae and Takaoka [2]. Since then, this problem has drawn a lot of attention [3,6,9,12,30,31], and recently an optimal $O(n + k)$-time algorithm was given by Brodal and Jørgensen [9].

The other is the Length-Constrained Maximum-Sum Segment problem. Given A and two integers L, U with $1 \leq L \leq U \leq n$, the Length-Constrained Maximum-Sum Segment problem is to find the maximum-sum segment among all segments of A with lengths in the interval $[L, U]$ and is solvable in $O(n)$ time [16,30]. The Length-Constrained Maximum-Sum Segment problem was formulated by Huang [25] and motivated by its application to finding GC-rich segments of a DNA sequence. A DNA sequence is composed of four letters A, C, G, and T. Given a DNA sequence, biologists often need to identify the GC-rich segments satisfying some length constraints. By giving each of letters C and G a reward of $1 - p$ and each of letters A and T a penalty of $-p$, where p is a positive constant ratio, the problem is reformulated as finding the length-constrained maximum-sum segment.

In this paper, we study the Length-Constrained k Maximum-Sum Segments problem, which is a combination of the k Maximum-Sum Segments problem and the Length-Constrained Maximum-Sum Segment problem. Given A, a positive integer k and two integers L, U with $1 \leq L \leq U \leq n$, the Length-Constrained k Maximum-Sum Segments problem is to find the k maximum-sum segments among all segments of A with lengths in the interval $[L, U]$. Note that the Length-Constrained k Maximum-Sum Segments problem can also be considered as a specialization of the Weight-Constrained k Longest Paths problem if we treat the given sequence as a chain of edges whose lengths are given by the numbers in the sequence and weights are all equal to one. After giving an $O(V \log V + k)$-time algorithm to deal with the Weight-Constrained k Longest Paths problem, we give an $O(n + k)$-time algorithm for the Length-Constrained k Maximum-Sum Segments problem (or equivalently, an $O(V + k)$-time algorithm for a specialization of the Weight-Constrained k Longest Paths problem where the input tree is a chain of edges with a uniform weight). It should be noted that our basic approach for solving the Length-Constrained k Maximum-Sum Segments problem was discovered independently by Brodal and Jørgensen [9] in solving the k Maximum-Sum Segments problem. Both of us construct in $O(n)$ time a heap that implicitly stores all feasible solutions and then run Frederickson's [17] heap selection algorithm on this heap to find the k best feasible solutions in $O(k)$ time.

As a byproduct, we show that our algorithms can be used as a basis for delivering more efficient algorithms for some related enumeration problems such as finding the weight-constrained k largest elements of $X + Y$, finding the sum-constrained k longest segments, finding k length-constrained segments satisfying a density lower bound, and finding area-constrained k maximum-sum subarrays.

2. $O(V \log V + k)$-time algorithm for the weight-constrained k longest paths problem

In this section, we prove that the Weight-Constrained k Longest Paths problem can be solved in $O(V \log V + k)$ time.

2.1. Preliminaries

To achieve the time bound of $O(V \log V + k)$, we make use of Frederickson and Johnson's [20] representation of intervertex

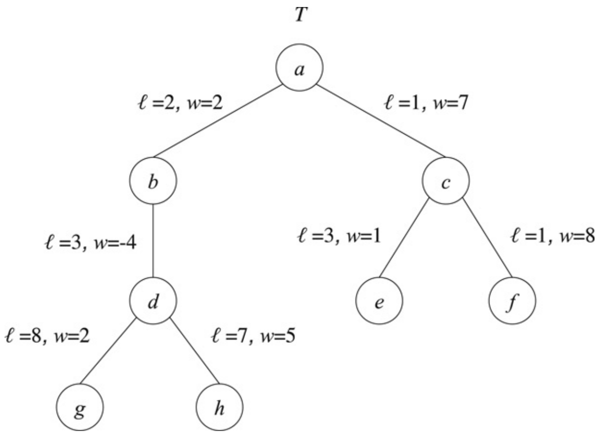

Fig. 1. A tree T associated with an edge length function ℓ and an edge weight function w.

distances of a tree, range maxima query (RMQ) [5,18,24], and Frederickson's [17] algorithm for finding the maximum k elements in a heap-ordered tree. In the following, we briefly review these data structures and algorithms.

Definition 1. Let $T = (V, E)$ be a tree. A node $v \in V$ is said to be the *centroid* of T if and only if after removing v from T, each resulting connected component contains at most $|V|/2$ nodes.

Definition 2. Let $T = (V, E)$ be a tree. A triplet $(c, T_1 = (V_1, E_1), T_2 = (V_2, E_2))$ is called a *centroid decomposition* of T if it satisfies the following properties: (1) c is a centroid of T; (2) T_1 and T_2 are two subtrees of T such that $V_1 \cap V_2 = c$, $\frac{|V|+2}{3} \leq |V_1| \leq \frac{2|V|+1}{3}$, and $E_1 \cup E_2 = E$.

Notation 1. Let $T = (V, E)$ be a tree with a length function $\ell : E \to \mathbb{R}$ and a weight function $w : E \to \mathbb{R}$. We slightly overload the notation by letting $\ell(u, v)$ and $w(u, v)$ also denote the length and weight of the path from u to v if there is no edge from u to v.

Definition 3. Let $T = (V, E)$ be a tree with a length function $\ell : E \to \mathbb{R}$ and a weight function $w : E \to \mathbb{R}$. A rooted ordered binary tree $T' = (V', E', r)$ in which each node contains fields *cent*, *list*$_1$ and *list*$_2$ is called a *centroid decomposition tree* of T rooted at r if it satisfies the following recursive properties: (1) If $|V| = 1$, then $|V'| = 1$, $r.cent$ is the only vertex in V, and $r.list_1 = r.list_2 =$ NIL; (2) if $|V| = 2$, then $|V'| = 1$, $r.cent$ is one of the vertex in V, $r.list_1 = ((v, \ell(r.cent, v), w(r.cent, v))$, and $r.list_2 = ((r.cent, 0, 0))$, where $v \in V \backslash \{r.cent\}$; (3) if $|V| > 2$, then $\exists$ centroid decomposition $(c, T_1 = (V_1, E_1), T_2 = (V_2, E_2))$ of T such that the left subtree and right subtree of r are centroid decomposition trees of T_1 and T_2, respectively, $r.cent = c$, and $r.list_j, j \in \{1, 2\}$, is a list of triplets $((v_i, \ell(c, v_i), w(c, v_i)) : v_i \in V_j - \{c\})$ sorted on $w(c, v_i)$.

As an illustration, a tree T and its centroid decomposition tree T' are shown in Figs. 1 and 2, respectively.

Theorem 1 (*Frederickson and Johnson [20]*). *Given a tree $T(V, E)$ with a length function $\ell : E \to \mathbb{R}$ and a weight function $w : E \to \mathbb{R}$, we can construct a centroid decomposition tree of T in $O(V \log V)$ time.*

Now we describe the Range Maxima Query (RMQ) problem. In the RMQ problem, a list $A = (a_1, a_2, \ldots, a_n)$ of n real numbers is given to be preprocessed such that any range maxima query can be answered quickly. A range maxima query specifies an interval $[i, j]$ and the goal is to find the index k with $i \leq k \leq j$ such that a_k achieves maximum.

We first describe a simple algorithm for solving the RMQ problem in $O(n \log n)$ preprocessing time and $O(1)$ time per query. For each $1 \leq i \leq n$ and each $1 \leq j \leq \lfloor \log n \rfloor$, we pre-compute $M[i][j] = \arg\max_{k=i,\ldots,i+2^j-1}\{a_k\}$, i.e. the index of the maximum element in $A[i, i + 2^j - 1]$. This can be done in $O(n \log n)$ time by using dynamic programming because

$$M[i][j] = \begin{cases} M[i][j-1] & \text{if } A[M[i][j-1]] \geq A[M[i+2^{j-1}-1][j-1]]; \\ M[i+2^{j-1}-1][j-1] & \text{otherwise.} \end{cases}$$

Given a query interval $[i, j]$, let $k = \lfloor \log(j - i) \rfloor$. Because both $[i, i + 2^k - 1]$ and $[j - 2^k + 1, j]$ are subintervals of $[i, j]$ and $[i, i + 2^k - 1] \cup [j - 2^k + 1, j] = [i, j]$, the index of the maximum element in $A[i, j]$ is $\arg\max_{k \in \{M[i][i+2^k-1], M[j-2^k+1][j]\}}\{A[k]\}$.

We now sketch an algorithm for solving the RMQ problem in $O(n)$ preprocessing time and $O(1)$ time per query. This algorithm was given by Bender and Farach-Coltongiven [5], and they showed that the RMQ problem is linearly equivalent to the RMQ ± 1 problem which is the same as the RMQ problem except that the adjacent elements of the input list differ by exactly one. Thus, in the following we focus on the RMQ ± 1 problem. Let $A = (a_1, a_2, \ldots, a_n)$ be an instance to the RMQ ± 1 problem.[1] The algorithm starts by dividing the list A into $2n/\log n$ shorter sublists $A[1, \frac{\log n}{2}]$, $A[\frac{\log n}{2} + 1, \log n], \ldots, A[n -$

[1] For simplicity, we assume n is a power of two.

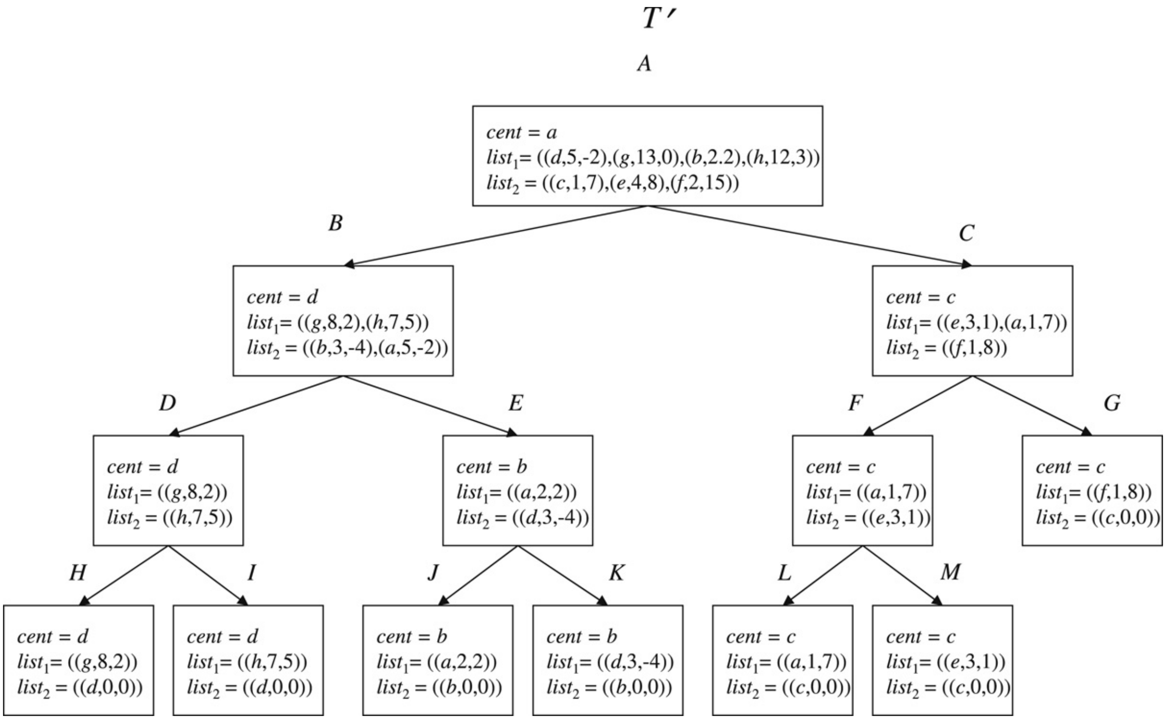

Fig. 2. A centroid decomposition tree T' of the tree in Fig. 1.

$\frac{\log n}{2}+1, n]$, each of length $\frac{\log n}{2}$. Each sublist $A[\frac{(i-1)\log n}{2}+1, \frac{i\log n}{2}]$ is represented by the maximum element r_i in it. They then run the simple RMQ algorithm described in the beginning on these $O(n/\log n)$ representatives in $O(\frac{n}{\log n}\log(\frac{n}{\log n})) = O(n)$ preprocessing time. By the property that adjacent elements in the list A differs by exactly one, they use a table-lookup technique to pre-compute the indices of the maximum elements in all sublists of A with lengths $\leq \frac{2n}{\log n}$ in $O(n)$ time. Given a query interval $[i, j]$, let $i' = \lceil \frac{2i}{\log n} \rceil$ and $j' = \lfloor \frac{2j}{\log n} \rfloor$. Let r_k be the maximum of $\{r_{i'+1} r_{i'+2}, \ldots, r_{j'-1}\}$, a_{i^*} be the maximum element in $A[i, \frac{i' \log n}{2}]$, and a_{j^*} be the maximum element in $A[\frac{j' \log n}{2}, j]$. Because we have run the simple RMQ algorithm on $(r_1, r_2, \ldots, r_{\frac{2n}{\log n}})$, k can be found in constant time given $[i'+1, j'-1]$. Because both $A[i, \frac{i' \log n}{2}]$ and $A[\frac{j' \log n}{2}, j]$ have lengths $\leq \frac{2n}{\log n}$, we can also find a_{i^*} and a_{j^*} in constant time. Note that the maximum of $\{r_k, a_{i*}, a_{j*}\}$ is also the maximum element in $A[i, j]$. Thus, if a_{i^*} is the maximum of $\{r_k, a_{i*}, a_{j*}\}$, then we can directly return i^*. Similarly, if a_{j^*} is the maximum of $\{r_k, a_{i*}, a_{j*}\}$, then return j^*. Otherwise, if r_k is the the maximum of $\{r_k, a_{i*}, a_{j*}\}$, then find and return the index of the maximum element in $A[\frac{(k-1)\log n}{2}+1, \frac{k\log n}{2}]$, which can be done in constant time because $A[\frac{(k-1)\log n}{2}+1, \frac{k\log n}{2}]$ has length equal to $\frac{2n}{\log n}$.

Theorem 2 (*RMQ [5,18,24]*). *The RMQ problem can be solved in $O(n)$ preprocessing time and $O(1)$ time per query.*

For our purposes, a D-heap is a rooted degree-D tree in which each node contains a field *value*, satisfying the restriction that the value of any node is larger than or equal to the values of its children. Note that we do not require the tree to be balanced. Frederickson [17] proposed an algorithm for finding the k largest elements in a D-heap in $O(k)$ time. When Frederickson's algorithm traverses the heap to find the k largest nodes, it does not access a node unless it has ever accessed the node's parent. This property makes it possible to run the Frederickson's algorithm without first explicitly building the entire heap in the memory as long as we have a way to obtain the information of a node given the information of its parent.

We sketch an $O(k \log\log k)$-time algorithm [17] for enumerating the k largest value nodes in a heap as follows. For simplicity, we assume all nodes in the heap have different values. A node is said to be of rank i if it is the ith largest node. The algorithm runs by first finding a node u in the heap in $O(k \log\log k)$ time such that the rank of u is between k and ck for some constant c. Then the algorithm identifies all nodes in the heap not smaller than u in $O(ck) = O(k)$ time and returns the k largest nodes among them. To find u, we form at most $2\lceil k/\lfloor \log k \rfloor \rceil + 1$ groups of nodes, called clans. Each clan is of size at most $\lfloor \log k \rfloor$ and represented by the smallest node in it; representatives are managed in an auxiliary heap. We form the first clan C_1 in $O(\log k \log\log k)$ time by grouping the largest $\lfloor \log k \rfloor$ nodes in the original heap and initialize the auxiliary heap with the representative of C_1. Set the *offspring* $os(C_1)$ of C_1 to the set of nodes in the original heap which are children of C_1 but not in C_1, and set the poor relations $pr(C_1)$ of C_1 to the empty set. Then for i from 1 to $\lfloor \log k \rfloor$, do the following. Extract the largest element in the auxiliary heap and let C_j be the clan represented by the element extracted. If $os(C_j)$ is not empty, then form a new clan C_{i+1} in $O(\log k \log\log k)$ time by grouping the $\lfloor \log k \rfloor$ largest nodes from the subheaps rooted at $os(C_j)$ in the original heap. Insert the representative of C_{i+1} into the auxiliary heap. Set $os(C_{i+1})$ to the group of nodes in the original heap which are children of C_{i+1} but not in C_{i+1}, and set $pr(C_{i+1})$ to the group of nodes which are members of $os(C_j)$ but not included in C_{i+1}. If $pr(C_j)$ is not empty, then form a new clan C_{i+2} in $O(\log k \log\log k)$ time by grouping the $\lceil k/\lfloor \log k\rfloor\rceil$ largest nodes from the subheaps rooted at $pr(C_j)$ in the original heap. Insert the representative of C_{i+2} into the auxiliary heap. Set $os(C_{i+1})$ to the group of nodes in the original heap which are children of C_{i+2} but not in C_{i+2}, and set $pr(C_{i+2})$ to the group of nodes which are members of $pr(C_j)$ but not included in C_{i+2}. When the loop terminates, set u to the last element extracted from the auxiliary heap. Since at most $2\lceil k/\lfloor \log k\rfloor\rceil + 1$ clans are formed and each clan can be formed in $O(\log k \log\log k)$ time, the total time is $O(k \log\log k)$.

By applying the above approach recursively, plus some speed-up techniques, Frederickson [17] obtained an $O(k)$-time algorithm.

Theorem 3 (*Frederickson [17]*). *For any constant D, we can find the k largest value nodes in any D-heap, in $O(k)$ time.*

2.2. Finding the weight-constrained k longest paths

For simplicity, we only consider paths with at least two distinct vertices, and we do not distinguish between the path from u to v and the path from v to u, i.e., the path from u to v and the path from v to u are considered the same. Thus each path is uniquely determined by the unordered pair of its end vertices. We define the length and weight of an unordered pair $\{u, v\}$ to be the length and weight of the path from u to v, respectively. We say an unordered pair $\{u, v\}$ of vertices is feasible if and only if its weight is in the interval $[L, U]$. Our task is to find the k longest feasible unordered pairs of vertices in T.

Before moving on to the details of the algorithm, let us pause here to sketch our main idea. First, we divide T into two subtrees T_1 and T_2 of roughly the same size and find all the feasible unordered pairs $\{u, v\}$ satisfying $u \in V(T_1)$ and $v \in V(T_2)$. Next, we recursively compute all feasible unordered pairs of vertices in T_1 and all feasible unordered pairs of vertices in T_2, respectively. After finishing this recursive process, we have all feasible unordered pairs of vertices in T. We then build a heap consisting of all these unordered pairs and find the k longest unordered pairs in this heap by applying the Frederickson's algorithm [17]. The major difficulty is that the number of feasible unordered pairs of vertices in T may be much larger than $|V|\log|V| + k$. Thus, we have to represent the set of all feasible unordered pairs of vertices in T in a succinct way such that we are still able to build an implicit representation of the heap stated above and run the Frederickson's algorithm [17] on this implicitly-represented heap without loss of efficiency.

We now describe our algorithm in detail. First, we construct a centroid decomposition tree $T' = (V', E', r)$ of T in $O(V \log V)$ time by Theorem 1. For each $v \in V'$ and $i \in \{1, 2\}$, let $(v_{i,j}, \ell(v.cent, v_{i,j}), w(v.cent, v_{i,j}))$ be the jth element of $v.list_i$ if it exists. Note that since $\sum_{v\in V'}(|v.list_1| + |v.list_2| + 1) = O(V \log V)$, we can find $\ell(v.cent, v_{i,j})$ and $w(v.cent, v_{i,j})$ for all $v \in V'$, $i \in \{1, 2\}$ and $1 \le j \le |v.list_i|$ in total $O(V \log V)$ time. By the next lemma, in total $O(V \log V)$ time, for all $v \in V'$ and $1 \le i \le |v.list_1|$, we can find an interval $[p_i^v, q_i^v]$ such that

1. $w(v.cent, v_{1,i}) + w(v.cent, v_{2,j}) = w(v_{1,i}, v_{2,j}) \in [L, U]$ for all $j \in [p_i^v, q_i^v]$;
2. $w(v_{1,i}, v_{2,j}) \notin [L, U]$ for all $j \notin [p_i^v, q_i^v]$.

It follows that the set of all feasible unordered pairs of vertices in T is equal to the set $\bigcup_{v\in V'} \bigcup_{i=1}^{|v.list_1|} \{\{v_{1,i}, v_{2,j}\} : j \in [p_i^v, q_i^v]\}$.

Lemma 1. *Let $T' = (V', E', r)$ be a centroid decomposition tree of $T = (V, E)$. In total $O(V \log V)$ time, for all $v \in V'$ and $1 \le i \le |v.list_1|$, we can find an interval $[p_i^v, q_i^v]$ such that (1) $w(v_{1,i}, v_{2,j}) \in [L, U]$ for all $j \in [p_i^v, q_i^v]$ and (2) $w(v_{1,i}, v_{2,j}) \notin [L, U]$ for all $j \notin [p_i^v, q_i^v]$.*

Proof. Since $\sum_{v\in V'}(|v.list_1| + |v.list_2| + 1) = O(V \log V)$, we only have to show that for each $v \in V'$, we can compute $[p_i^v, q_i^v]$ for all $1 \le i \le |v.list_1|$ in total $O(|v.list_1| + |v.list_2| + 1)$ time. Given $v \in V'$, we claim the following procedure computes $[p_i^v, q_i^v]$ for all $1 \le i \le |v.list_1|$ in total $O(|v.list_1| + |v.list_2| + 1)$ time.

```
1. Let $n' = |v.list_1|$ and $m' = |v.list_2|$.
2. If $n' = 0$ or $m' = 0$ then stop.
3. Set $p$ and $q$ to $m'$.
4. For $i \leftarrow 1$ to $n'$ do
   (a) While($w(v_{1,i}, v_{2,p-1}) \ge L$ and $p - 1 \ge 1$) do $p \leftarrow p - 1$.
   (b) While($w(v_{1,i}, v_{2,q}) > U$ and $q \ge p$) do $q \leftarrow q - 1$.
   (c) $p_i^v \leftarrow p$ and $q_i^v \leftarrow q$.
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It is not hard to see the running time of this procedure is $O(|v.list_1| + |v.list_2| + 1)$ since both the values of p and q are nonincreasing. To verify the correctness, it suffices to note that since the list $v.list_i$, $i \in \{1, 2\}$, is sorted on $w(v.cent, v_{i,j})$, the sequence $(p_1^v, \dots, p_{|v.list_1|}^v)$ and the sequence $(q_1^v, \dots, q_{|v.list_1|}^v)$ must be nonincreasing. □

Next, for each $v \in V'$, we preprocess $v.list_2$ so that given any interval $[i, j]$, we can find the index k, denoted RMQ$(v.list_2, i, j)$, in $[i, j]$ such that $\ell(v.cent, v_{2,k})$ achieves maximum in $O(1)$ time. By Theorem 2, this preprocessing can be done in $O(\sum_{v\in V'} |v.list_2|) = O(V \log V)$ time.

Before moving on to the next point, we would like to define some data structures. For each $v \in V'$ and $1 \le i \le |v.list_1|$, define $H(v_{1,i})$ to be a rooted ordered binary tree which consists of nodes with fields *pair*, *value*, and *interval* and satisfies the following properties.

1. There are total $|v.list_1|$ nodes in $H(v_{1,i})$ and the interval of the root of $H(v_{1,i})$ is $[p_i^v, q_i^v]$.
2. For each node u of $H(v_{1,i})$, if $p < k$ then u's left child has interval $[p, k-1]$, and if $k < q$ then u's right child has interval $[k+1, q]$, where $[p, q] = u.interval$ and $k = \mathrm{RMQ}(v.list_2, p, q)$.
3. For each node u of $H(v_{1,i})$, if $u.interval = [p, q]$ then $u.pair = \{v_{1,i}, v_{2,k}\}$ and $u.value = \ell(v_{1,i}, v_{2,k})$, where $k = \mathrm{RMQ}(v.list_2, p, q)$.

Let us now return to describe our algorithm. Denote by $V(H(v_{1,i}))$ the set of nodes in $H(v_{1,i})$. It should be noticed that the set of all feasible unordered pairs of vertices in T is equal to the set

$$\bigcup_{v\in V'}\bigcup_{i=1}^{|v.list_1|}\{\{v_{1,i}, v_{2,j}\} : j \in [p_i^v, q_i^v]\} = \bigcup_{v\in V'}\bigcup_{i=1}^{|v.list_1|}\{u.pair : u \in V(H(v_i))\}.$$

Therefore, the remaining work is to find the k largest value nodes in $\bigcup_{v\in V'}\bigcup_{i=1}^{|v.list_1|} V(H(v_{1,i}))$. Clearly, we can not afford to construct $H(v_{1,i})$ explicitly for each $v_{1,i}$. But notice that given any node u of $H(v_{1,i})$, we can always construct u's children in $O(1)$ time since we have done the RMQ preprocessing on the list $v.list_2$. Thus we shall only construct the root of $H(v_{1,i})$ in the first instance and expand the tree as needed. Since we have known p_i^v and q_i^v for each $v \in V'$ and $1 \le i \le |v.list_1|$ and done the RMQ preprocessing on the list $v.list_2$ for each $v \in V'$, we can construct, in total $O(V \log V)$ time, the root of $H(v_{1,i})$ for all $v_{1,i}$. Then we place these roots into a balanced 2-heap of size up to $O(V \log V)$ by the *heapify* operation [14] in linear time, i.e., in $O(V \log V)$ time. Note that each $H(v_{1,i})$ is a 2-heap, so we have conceptually built a 4-heap for the set $\bigcup_{v\in V'}\bigcup_{i=1}^{|v.list_1|} V(H(v_{1,i}))$. Now by Theorem 3, we can apply Frederickson's algorithm [17] to find the k largest value nodes in that 4-heap in $O(k)$ time. Of course, except the roots of all $H(v_{1,i})$, all the nodes in that 4-heap are not physically created until they are needed in running Frederickson's [17] algorithm. We summarize the results of this section by the following theorem.

Theorem 4. *Let $T = (V, E)$ be a tree with a length function $\ell : E \to \mathbb{R}$ and a weight function $w : E \to \mathbb{R}$. Given T, a positive integer k and an interval $[L, U]$, we can find the k longest paths among all paths in T with weights in the interval $[L, U]$ in $O(V \log V + k)$ time.*

3. $\Omega(V \log V + k)$ lower bound for the weight-constrained k longest paths problem

We prove that the Weight-Constrained Longest Path problem has an $\Omega(V \log V)$ bound in the algebraic computation tree model. It follows that the Weight-Constrained k Longest Paths problem has an $\Omega(V \log V + k)$ lower bound in the algebraic computation tree model since extra $\Omega(k)$ time is necessary for outputting the answer.

Definition 4 (*Set Intersection Problem*). Given two sets $\{x_1, x_2, \ldots, x_n\}$ and $\{y_1, y_2, \ldots, y_n\}$, the Set Intersection problem asks whether there exist indices i and j such that $x_i = y_j$.

Lemma 2 (*Ben-Or [8]*). *The* Set Intersection *problem has an $\Omega(n \log n)$ lower bound in the algebraic computation tree model.*

Theorem 5. *The* Weight-Constrained Longest Path *problem has an $\Omega(V \log V)$ lower bound in the algebraic computation tree model.*

Proof. We reduce the Set Intersection problem to the Weight-Constrained Longest Path problem. Given two sets $\{x_1, x_2, \ldots, x_n\}$ and $\{y_1, y_2, \ldots, y_n\}$, we construct, in $O(n)$ time, a problem instance of the Weight-Constrained Longest Path problem as follows. We first construct a tree $T = (V, E)$, where $V = \{x'_1, \ldots, x'_n\} \cup \{y'_1, \ldots, y'_n\} \cup \{c_1, c_2\}$ and $E = \{\overline{x'_1c_1}, \ldots, \overline{x'_nc_1}\} \cup \{\overline{y'_1c_2}, \ldots, \overline{y'_nc_2}\} \cup \{\overline{c_1c_2}\}$. Define the length function $\ell : E \to \mathbb{R}$ by letting $\ell(e) = 1$ for all $e \in E$. Define the weight function $w : E \to \mathbb{R}$ by letting $w(\overline{x'_ic_1}) = x_i$ and $w(\overline{y'_ic_2}) = -y_i$ for all $i = 1, \ldots, n$, and $w(\overline{c_1c_2}) = 0$. Set both the weight lower bound L and the weight upper bound U of paths to 0. It can be verified that the longest path in T with weight $= 0$ has length 3 if and only if there exist indices i and j such that $x_i = y_j$. Since in this reduction we have $|V| = 2n + 2$ and the Set Intersection problem has an $\Omega(n \log n)$ in the algebraic computation tree model by Lemma 2, we conclude that the Weight-Constrained Longest Path problem has an $\Omega(V \log V)$ lower bound in the algebraic computation tree model. □

Corollary 1. *The* Weight-Constrained k Longest Paths *problem has an $\Omega(V \log V + k)$ lower bound in the algebraic computation tree model.*

4. $O(n + k)$-time algorithm for the length-constrained k maximum-sum segments problem

Given a sequence $A = (a_1, a_2, \ldots, a_n)$ of numbers, we define the sum and length of a segment $A[i, j]$ to be $a_i + a_{i+1} + \cdots + a_j$ and $j - i + 1$, respectively. The Length-Constrained k Maximum-Sum Segments problem is to find the k maximum-sum segments among all segments with lengths in a specified interval $[L, U]$. In the following, we show how to solve the Length-Constrained k Maximum-Sum Segments problem in $O(n + k)$ time.

4.1. Preliminaries

Let P denote the prefix-sum array of the input sequence A, i.e., $P[0] = 0$ and $P[i] = a_1 + a_2 + \cdots + a_i$ for $i = 1, \ldots, n$. P can be computed in linear time by set $P[0]$ to 0 and $P[i]$ to $P[i-1] + a_i$ for $i = 1, 2, \ldots, n$. Let $S[i, j]$ denote the sum of $A[i, j]$. Since $S[i, j] = P[j] - P[i-1]$, the sum of any segment can be computed in constant time after the prefix-sum array is constructed.

Now we describe the RANGE MAXIMUM-SUM SEGMENT QUERY (RMSQ) problem. In the RMSQ problem, a sequence $A = (a_1, a_2, \ldots, a_n)$ of n numbers is given to be preprocessed such that any range maximum-sum segment query can be answered quickly. A range maximum-sum segment query specifies two intervals $[i, j]$ and $[k, l]$, and the goal is to find a pair of indices (x, y) with $i \leqslant x \leqslant j$ and $k \leqslant y \leqslant \ell$ that maximizes $S[x, y]$.

Chen and Chao [10] have showed that RMSQ is linearly equivalent to RMQ. For ease of explanation, in the following description of the algorithm we use RMSQ instead of RMQ.

Theorem 6 (*Chen and Chao [10]*). *The RMSQ problem can be solved in $O(n)$ preprocessing time and $O(1)$ time per query.*

4.2. Finding the length-constrained k maximum-sum segments

The algorithm is similar to the one in Section 2.2, but this time we can achieve linear running time. First we preprocess the input sequence A so that given any two intervals $[i, j]$ and $[k, l]$, we can find the pair (x, y), denoted RMSQ(i, j, k, l), with $i \leqslant x \leqslant j$ and $k \leqslant y \leqslant \ell$ that maximizes $S[x, y]$. By Theorem 6, this preprocessing can be done in $O(n)$ time. In the following, we say a segment $A[i, j]$ is feasible if and only if $L \leq j - i + 1 \leq U$. Set $p_i = \max\{i - U + 1, 1\}$ and $q_i = i - L + 1$ for all $i = 1, \ldots, n$. For simplicity, we assume $p_i \leq q_i$ for all $i = 1, \ldots, n$. Then $\bigcup_{i=1}^{n}\{A[h, i] : h \in [p_i, q_i]\}$ is the set of all feasible segments. Our task is to find the k maximum-sum segments in this set.

Before moving on to the algorithm, let us define some data structures. For each index i, define $H(i)$ to be a rooted ordered binary tree which consists of nodes with fields *pair*, *value*, and *interval* and satisfies the following properties.

1. There are total $q_i - p_i + 1$ nodes in $H(i)$ and the interval of the root of $H(i)$ is $[p_i, q_i]$.
2. For each node u of $H(i)$, if $p < k$ then u's left child has interval $[p, k-1]$, and if $k < q$ then u's right child has interval $[k+1, q]$, where $[p, q] = u.interval$ and $(k, i) =$ RMSQ(p, q, i, i).
3. For each node u of $H(i)$, if $u.interval = [p, q]$ then $u.pair = (k, i)$ and $u.value = S[k, i]$, where $(k, i) =$ RMSQ(p, q, i, i).

We now describe our algorithm. Let $V(H(i))$ denote the set of nodes in $H(i)$. It is clear that the k largest value nodes in $\bigcup_{i=1}^{n} V(H(i))$ correspond to the k maximum-sum feasible segments. Thus the remaining work is to find the k largest value nodes in $\bigcup_{i=1}^{n} V(H(i))$. Notice that given any node u of $H(i)$, we can always construct u's children in $O(1)$ time since we have done the RMSQ preprocessing on $A[1..n]$. Thus we only construct the root of $H(i)$ in the first instance and expand the tree as needed. Since we have known p_i and q_i for each index i and done the RMSQ preprocessing on $A[1..n]$, we can construct, in total $O(n)$ time, the root of $H(i)$ for each index i. Then we place these roots into a balanced 2-heap by the *heapify* operation [14] in $O(n)$ time. Note that each $H(i)$ is a 2-heap, so we have conceptually built a 4-heap for the set $\bigcup_{i=1}^{n} V(H(i))$. Now by Theorem 3, we can apply Frederickson's algorithm [17] to find the k largest value nodes in that 4-heap in $O(k)$ time. As before, except the roots of all $H(i)$, all the nodes in that 4-heap are not physically created until they are needed in running Frederickson's [17] algorithm. The following theorem summarizes the results of this section.

Theorem 7. *Given a sequence $A = (a_1, \ldots, a_n)$ of numbers, a positive integer k, and an interval $[L, U]$, we can find, in $O(n + k)$ time, the k maximum-sum segments of A with lengths in $[L, U]$.*

Definition 5. Let $A = ((a_1, \ell_1), \ldots, (a_n, \ell_n))$ be a sequence of pairs of numbers, where $\ell_i > 0$ for all $i = 1, \ldots, n$. We define the sum, length, and density of a segment $A[i, j]$ to be $\sum_{i \leq h \leq j} a_h$, $\sum_{i \leq h \leq j} \ell_h$, and $\frac{\sum_{i \leq h \leq j} a_h}{\sum_{i \leq h \leq j} \ell_h}$, respectively.

We prove the following stronger theorem by slightly modifying the above algorithm.

Theorem 8. *Given a sequence of pairs of numbers $A = ((a_1, \ell_1), \ldots, (a_n, \ell_n))$, where $\ell_i > 0$ for $i = 1, \ldots, n$, a positive integer k, and an interval $[L, U]$, we can find, in $O(n + k)$ time, the k maximum-sum segments of A with lengths in $[L, U]$.*

Proof. We show how to modify the above algorithm to achieve this theorem. In fact, we only need to change the settings of p_i's and q_i's. The remaining parts are the same. For all $i = 1, \ldots, n$, we redefine p_i to be the minimum index $1 \leq h \leq i$ such that $\$[h, i] \leq U$ and q_i to be the maximum index $1 \leq h' \leq i$ such that $\$[h', i] \geq L$. For simplicity, we assume p_i and q_i exist for all $i = 1, \ldots, n$. Since ℓ_i is positive for all $i = 1, \ldots, n$, the sequences $(p_1, \ldots, p_n)$ and $(q_1, \ldots, q_n)$ must be nondecreasing. Thus we can compute p_i and q_i for all $i = 1, \ldots, n$ by the following procedure in $O(n)$ time.

```
1. Set $p = 1$ and $q = 1$.
2. For $i \leftarrow 1$ to $n$ do
   (a) While($\$[p, i] > U$ and $p \leq i$) do $p \leftarrow p + 1$.
   (b) While($\$[q + 1, i] \geq L$ and $q + 1 \leq i$) do $q \leftarrow q + 1$.
   (c) $p_i \leftarrow p$ and $q_i \leftarrow q$.
3. Output $(p_1, \ldots, p_n)$ and $(q_1, \ldots, q_n)$. □
```

5. Applications

In this section, we give some applications of our algorithms.

5.1. Finding the weight-constrained k largest elements of $X + Y$

Let X and Y be two sets associated with value functions $V_X : X \to \mathbb{R}$ and $V_Y : Y \to \mathbb{R}$, respectively. The Cartesian sum $X + Y$ is the set $\{(x, y) : (x, y) \in X \times Y\}$ associated with a value function $V : X \times Y \to \mathbb{R}$ defined by letting $V(x, y) = V_X(x) + V_Y(y)$ for all $(x, y) \in X \times Y$. For convenience, we just use $x + y$ to denote $V_X(x) + V_Y(y)$, and we call a set associated with a value function a *valued set*. Frederickson and Johnson [19] gave an optimal algorithm for finding the kth largest element in $X + Y$ in $O(m + p \log(k/p))$ time, where $m = |X| \le |Y| = n$ and $p = \min\{k, m\}$. Recently Bae and Takaoka proposed an efficient $O(n + k \log k)$-time algorithm [4] for finding the k largest elements of $X + Y$. In the following, we first show how to find the k largest elements of $X + Y$ in $O(n + k)$ time by using Eppstein's algorithm [15], and then we show how to cope with the weight-constrained case in $O(n \log n + k)$ time by using our algorithm.

Lemma 3 (*Eppstein [15]*). *Given a directed acyclic graph $G = (V, E)$ with a length function $\ell : E \to \mathbb{R}$ and two distinguished vertices s and t, we can find, in $O(V + E + k)$ time, an implicit representation of the k longest paths connecting s and t in G. And by using the implicit representation, we can list the edges of any path P in the set of the k longest paths in time proportional to the number of edges in P.*

Theorem 9. *Given two valued sets $X = \{x_1, \dots, x_n\}$ and $Y = \{y_1, \dots, y_n\}$, we can find the k largest elements of $X + Y$ in $O(n + k)$ time.*

Proof. We describe an $O(n + k)$ algorithm for finding the k largest elements of $X + Y$ as follows. We first construct, in $O(n)$ time, a directed acyclic graph $G = (V, E)$ where $V = \{s, t, c\} \cup \{x'_1, \dots, x'_n\} \cup \{y'_1, \dots, y'_n\}$ and $E = \{\overrightarrow{sx'_1}, \dots, \overrightarrow{sx'_n}\} \cup \{\overrightarrow{x'_1c}, \dots, \overrightarrow{x'_nc}\} \cup \{\overrightarrow{cy'_1}, \dots, \overrightarrow{cy'_n}\} \cup \{\overrightarrow{y'_1t}, \dots, \overrightarrow{y'_nt}\}$. Define $\ell : E \to \mathbb{R}$ by letting $\ell(\overrightarrow{sx'_i}) = 0$, $\ell(\overrightarrow{x'_ic}) = x_i$, $\ell(\overrightarrow{cy'_i}) = y_i$, and $\ell(\overrightarrow{x'_it}) = 0$ for all $i = 1, \dots, n$. It can be verified that (x_i, y_j) is the kth largest element of $X + Y$ if and only if (s, x'_i, c, y'_j, t) is the kth longest path connecting s and t in G. Thus, by Lemma 3, we can first find the k longest paths connecting s and t in G in $O(V + E + k) = O(n + k)$ time and then find the corresponding k largest elements of $X + Y$ in $O(k)$ time. □

Now we show how to cope with the weight-constrained case. Let X and Y be two valued sets associated with weight functions $W_X : X \to \mathbb{R}$ and $W_Y : Y \to \mathbb{R}$, respectively. Then for each $(x, y) \in X + Y$, we define the weight of (x, y) to be $W_X(x) + W_Y(y)$.

Theorem 10. *Let $X = \{x_1, \dots, x_n\}$ and $Y = \{y_1, \dots, y_n\}$ be two valued sets associated with weight functions $W_X : X \to \mathbb{R}$ and $W_Y : Y \to \mathbb{R}$, respectively. Given a positive integer k and an interval $[L, U]$, we can find, in $O(n \log n + k)$ time, the k largest elements of $X + Y$ with weights in the interval $[L, U]$.*

Proof. We construct, in $O(n)$ time, a tree $T = (V, E)$ where $V = \{x'_1, \dots, x'_n\} \cup \{y'_1, \dots, y'_n\} \cup \{c\}$ and $E = \{\overline{x'_1c}, \dots, \overline{x'_nc}\} \cup \{\overline{y'_1c}, \dots, \overline{y'_nc}\}$. Let δ be a large enough positive number, say, greater than $\max\{|U|, |L|\} + \max\{\max_{1 \le i \le n} |W_X(x_i)|, \max_{1 \le i \le n} |W_Y(y_i)|\}$. Define the weight function $w : E \to \mathbb{R}$ by letting $w(\overline{x'_ic}) = W_X(x_i) + \delta$ and $w(\overline{y'_ic}) = W_Y(y_i) - \delta$ for all $i = 1, \dots, n$. Define the length function $\ell : E \to \mathbb{R}$ by letting $\ell(\overline{x'_ic}) = V_X(x_i)$ and $\ell(\overline{y'_ic}) = V_Y(y_i)$ for all $i = 1, \dots, n$.

Let P be a path of T. Consider the following cases. First, if P has both of its end vertices in $\{x'_1, \dots, x'_n\}$, i.e., $P = (x'_i, c, x'_j)$ for some i and j, then we have $w(P) = W_X(x_i) + W_X(x_j) + 2\delta > U$. Second, if P has one end vertex in $\{x'_1, \dots, x'_n\}$ and the other end vertex being c, i.e., $P = (x'_i, c)$ for some i, then we also have $w(P) = W_X(x_i) + \delta > U$. Similarly, if P has both of its end vertices in $\{y'_1, \dots, y'_n\}$ or P has one end vertex in $\{y'_1, \dots, y'_n\}$ and the other end vertex being c, then we have $w(P) < L$. Finally, if P has one end vertex in $\{x'_1, \dots, x'_n\}$ and the other in $\{y'_1, \dots, y'_n\}$, i.e., $P = (x'_i, c, y'_j)$ for some i and j, then we have $w(P) = W_X(x_i) + W_Y(y_j)$ and $v(P) = V_X(x_i) + V_Y(y_j)$.

From the above discussion, we conclude that (x_i, y_j) is the kth largest element of $X + Y$ with weight in $[L, U]$ if and only if (x'_i, c, y'_j) is the kth longest path of T with weight in $[L, U]$. Thus, by Theorem 4, we can first find the k longest paths of T with weights in $[L, U]$ in $O(V \log V + k) = O(n \log n + k)$ time and then find the corresponding k largest elements of $X + Y$ with weights in $[L, U]$ in $O(k)$ time. □

5.2. Finding the sum-constrained k longest segments

In biological sequence analysis, several researchers have devoted to the problem of finding the longest segment whose sum is not less than a specified lower bound L [1,11,34]. Allison [1] gave an algorithm which runs in linear time if the input sequence is a 0–1 sequence and L is a rational number. For real number sequences and real number lower bound, Wang and Xu [34] provided the first linear time algorithm, and Chen and Chao [11] gave an alternative linear time algorithm which runs in an online manner. We consider a more general problem in which both the lower bound L and the upper bound U of the sums of the segments are given and we want to find the k longest segments whose sums satisfy both the lower bound condition and the upper bound condition.

Theorem 11. *Given a sequence $A = (a_1, a_2, \ldots, a_n)$ of real numbers and an interval $[L, U]$, we can find, in $O(n \log n + k)$ time, the k longest segments whose sums are in the interval $[L, U]$.*

Proof. Directly from Theorem 4. □

5.3. Finding k length-constrained maximum-density segments satisfying a density lower bound

Given a sequence of pairs of numbers $A = ((a_1, \ell_1), \ldots, (a_n, \ell_n))$, where $\ell_i > 0$ for all $i = 1, \ldots, n$, a positive integer k, an interval $[L, U]$, and a number δ, let $k_{\text{out}} = \min\{k, n_\delta\}$, where n_δ is the total number of segments of A with lengths in $[L, U]$ and densities $\geq \delta$. We show how to find k_{out} segments of A with lengths in $[L, U]$ and densities $\geq \delta$ in $O(n + k_{\text{out}})$ time. A segment $A[i, j]$ is called a feasible segment if and only if the length of $A[i, j]$ is in $[L, U]$. Let $\delta_{\max}$ be the density of the feasible segment which has the maximum density among all feasible segments. The Length-Constrained Maximum-Density Segment problem is to find a feasible segment with density equal to $\delta_{\max}$. The Length-Constrained Maximum-Density Segment problem is well studied in [13,23,25,26,28,29] and can be solved in linear time by [13,23]. Let $n_{\delta_{\max}}$ be the total number of feasible segments with density equal to $\delta_{\max}$. If we are not satisfied by finding only one feasible segments with density equal to $\delta_{\max}$, then by first computing $\delta_{\max}$ by $O(n)$-time algorithms in [13,23] and setting δ to $\delta_{\max}$, our algorithm can list $k_{\text{out}} = \min\{k, n_{\delta_{\max}}\}$ feasible segments with density equal to $\delta_{\max}$ in $O(n + k_{\text{out}})$ time.

Theorem 12. *Given a sequence of pairs of numbers $A = ((a_1, \ell_1), \ldots, (a_n, \ell_n))$, where $\ell_i > 0$ for all $i = 1, \ldots, n$, a positive integer k, an interval $[L, U]$, and a number δ, let $k_{\text{out}} = \min\{k, n_\delta\}$, where n_δ is the total number of segments of A with lengths in $[L, U]$ and densities $\geq \delta$. Then we can find, in $O(n + k_{\text{out}})$ time, k_{out} segments of A with lengths in $[L, U]$ and densities $\geq \delta$.*

Proof. In what follows, a segment is called a feasible segment if and only if its length is in $[L, U]$. Let $A' = ((a_1 - \ell_1\delta, \ell_1), (a_2 - \ell_2\delta, \ell_2), \ldots, (a_n - \ell_n\delta, \ell_n))$. Since $A[i, j]$ has density $\frac{a_i + \cdots + a_j}{\ell_i + \cdots + \ell_j} \geq \delta$ if and only if $A'[i, j]$ has sum $\sum_{i \leq h \leq j}(a_h - \ell_h\delta) \geq 0$, it suffices to show how to find k_{out} feasible segments of A' with sums ≥ 0 in $O(n + k_{\text{out}})$ time. As in the proof of Theorems 7 and 8, we first implicitly construct a heap for all feasible segments of A' in $O(n)$ time. Let $2^{t-1} \leq k < 2^t$. We then execute the following procedure to find k_{out} feasible segments of A' with sums ≥ 0 in $O(k_{\text{out}} + 1)$ time, so the total time is $O(n + k_{\text{out}})$.

```
1. For $i \leftarrow 0$ to $t$ do
   (a) $S \leftarrow$ the $2^i$ maximum-sum feasible segments of $A'$.
   (b) If some segment in $S$ has sum less than 0, then stop the loop.
2. If $S$ contains more than $k$ segments with sums $\geq 0$, then return $k$ of them; otherwise, return all segments in $S$ with sums $\geq 0$.
```

We now prove that the procedure runs in $O(k_{\text{out}} + 1)$ time. By Theorem 3, the ith iteration of the loop in Step 1 can be done in $O(2^i)$ time. If $n_\delta = 0$, then it is clear that this procedure returns in constant time; otherwise, there are two cases to consider.

Case 1: $n_\delta \geq k$. In this case, the loop continues until the tth iteration, so the total time spent on Step 1 is $O(1 + 2 + 4 + \cdots + 2^t) = O(2^{t+1}) = O(k) = O(\min\{k, n_\delta\}) = O(k_{\text{out}})$. After the loop stops, the size of S is at most 2^t, so Step 2 can also be done in $O(2^t) = O(k) = O(\min\{k, n_\delta\}) = O(k_{\text{out}})$ time.

Case 2: $n_\delta < k$. Let $2^{\hat{t}-1} \leq n_\delta < 2^{\hat{t}}$. In this case, the loop continues until the $\hat{t}$th iteration, so the total time spent on Step 1 is $O(1 + 2 + 4 + \cdots + 2^{\hat{t}}) = O(2^{\hat{t}+1}) = O(n_\delta) = O(\min\{k, n_\delta\}) = O(k_{\text{out}})$. After the loop stops, the size of S is at most $2^{\hat{t}}$, so Step 2 can also be done in $O(2^{\hat{t}}) = O(n_\delta) = O(\min\{k, n_\delta\}) = O(k_{\text{out}})$ time. □

5.4. Finding the area-constrained k maximum-sum subarrays

Given an $n \times n$ array $A[1..n][1..n]$, define the sum and area of a subarray $A[k..l][i..j]$ to be $\sum_{p=k}^{l} \sum_{q=i}^{j} A[p][q]$ and $(l - k + 1)(j - i + 1)$, respectively. The k Maximum-Sum Subarrays problem is well studied in [2–4,6,9,12,30,31] and can be solved in $O(n^3 + k)$ time by Brodal and Jørgensen [9] and $O(n^3 \cdot \sqrt{\frac{\log \log n}{\log n}} + k \log n)$ time by Bae and Takaoka [4].

We will now prove that the Area-Constrained k Maximum-Sum Subarrays problem can be solved in $O(n^3 + k)$ time by applying Theorem 8.

Theorem 13. *Given an $n \times n$ array $A[1..n][1..n]$ and an interval $[L, U]$, we can find, in $O(n^3 + k)$ time, the k maximum-sum subarrays with areas in $[L, U]$.*

Proof. First we have to construct strips $S_{i,j} = ((\sum_{i \leq h \leq j} A[h][1], j - i + 1), (\sum_{i \leq h \leq j} A[h][2], j - i + 1), \ldots, (\sum_{i \leq h \leq j} A[h][n], j - i + 1))$ for all $1 \leq i \leq j \leq n$ in $O(n^3)$ time. Then we construct a sequence S by concatenating these strips with pairs $(0, U + 1)$. Noting that pairs $(0, U + 1)$ play the role of a stopper, it is not hard to see that each segment of S with length in $[L, U]$ corresponds to a subarray of A with area in $[L, U]$, and vice versa. Thus we can first apply Theorem 8 to find k maximum-sum segments of S with lengths in $[L, U]$ in $O(n^3 + k)$ time and then output their corresponding subarrays of A. □

6. Concluding remarks

In this work, we have shown how to efficiently enumerate all the weight-constrained k longest paths in a tree and all the length-constrained k maximum-sum segments of a sequence. In the future, it will be interesting to consider problems like selecting the weight-constrained kth longest path in a tree and the length-constrained kth largest sum segment of a sequence.

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References

[1] Lloyd Allison, Longest biased interval and longest non-negative sum interval, Bioinformatics 19 (10) (2003) 1294–1295.
[2] Sung Eun Bae, Tadao Takaoka, Algorithms for the problem of k maximum sums and a VLSI algorithm for the k maximum subarrays problem, in: Proceedings of the 7th International Symposium on Parallel Architectures, Algorithms and Networks, 2004, pp. 247–253.
[3] Sung Eun Bae, Tadao Takaoka, Improved algorithms for the k-maximum subarray problem for small k, in: Proceedings of the 11th Annual International Computing and Combinatorics Conference, 2005, pp. 621–631.
[4] Sung Eun Bae, Tadao Takaoka, A sub-cubic time algorithm for the k-maximum subarray problem, in: Proceedings of the 18th Annual International Symposium on Algorithms and Computation, 2007, pp. 751–762.
[5] Michale A. Bender, Martin Farach-Colton, The LCA problem revisited, in: Proceedings of the 4th Latin American Symposium on Theoretical Informatics, 2000, pp. 88–94.
[6] Fredrik Bengtsson, Jingsen Chen, Efficient algorithms for k maximum sums, in: Proceedings of the 15th Annual International Symposium on Algorithms and Computation, 2004, pp. 137–148.
[7] Jon Bentley, Programming pearls: Algorithm design techniques, Communications of the ACM (1984) 865–871.
[8] Michael Ben-Or, Lower bounds for algebraic computation trees, in: Proceedings of the 15th Annual ACM Symposium on Theory of Computing, 1983, pp. 80–86.
[9] Gerth S. Brodal, Allan G. Jørgensen, A linear time algorithm for the k maximal sums problem, in: Proceedings of the 32nd International Symposium on Mathematical Foundations of Computer Science, 2007, pp. 442–453.
[10] Kuan-Yu Chen, Kun-Mao Chao, On the range maximum-sum segment query problem, Discrete Applied Mathematics 155 (16) (2007) 2043–2052.
[11] Kuan-Yu Chen, Kun-Mao Chao, Optimal algorithms for locating the longest and shortest segments satisfying a sum or an average constraint, Information Processing Letters 96 (6) (2005) 197–201.
[12] Chih-Huai Cheng, Kuan-Yu Chen, Wen-Chin Tien, Kun-Mao Chao, Improved algorithms for the k maximum-sums problems, Theoretical Computer Science 362 (13) (2006) 162–170.
[13] Kai-Min Chung, Hsueh-I Lu, An optimal algorithm for the maximum-density segment problem, SIAM Journal on Computing 34 (2) (2004) 373–387.
[14] Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest, Clifford Stein, Introduction to Algorithms, second ed., The MIT Press, 2001.
[15] David Eppstein, Finding the k shortest paths, SIAM Journal on Computing 28 (2) (1998) 652–673.
[16] Tsai-Hung Fan, Shufen Lee, Hsueh-I Lu, Tsung-Shan Tsou, Tsai-Cheng Wang, Adam Yao, An optimal algorithm for maximum-sum segment and its application in bioinformatics extended abstract, in: Proceeding of the 8th International Conference on Implementation and Application of Automata, 2003, pp. 251–257.
[17] Greg N. Frederickson, An optimal algorithm for selection in a min-heap, Information and Computation 104 (2) (1993) 197–214.
[18] Johannes Fischer, Volker Heun, Theoretical and practical improvements on the RMQ-problem, with applications to LCA and LCE, in: Proceedings of the 17th Annual Symposium on Combinatorial Pattern Matching, 2006, pp. 36–48.
[19] Greg N. Frederickson, Donald B. Johnson, The complexity of selection and ranking in $X + Y$ and matrices with sorted rows and columns, Journal of Computer and System Science 24 (2) (1982) 197–208.
[20] Greg N. Frederickson, Donald B. Johnson, Finding kth paths and p-centers by generating and searching good data structures, Journal of Algorithms 4 (1) (1983) 61–80.
[21] Takeshi Fukuda, Yasuhiko Morimoto, Shinichi Morishita, Takeshi Tokuyama, Data mining with optimized two-dimensional association rules, ACM Transactions on Database Systems 26 (2) (2001) 179–213.
[22] Ulf Grenander, Pattern Analysis, Springer-Verlag, New York, 1978.
[23] Michael Goldwasser, Ming-Yang Kao, Hsueh-I Lu, Linear-time algorithms for computing maximum-density sequence segments with bioinformatics applications, Journal of Computer and System Sciences 70 (2) (2005) 128–144.
[24] Dov Harel, Robert E. Tarjan, Fast algorithms for finding nearest common ancestors, SIAM Journal on Computing 13 (2) (1984) 338–355.
[25] Xiaoqiu Huang, An algorithm for identifying regions of a DNA sequence that satisfy a content requirement, Computer Applications in the Biosciences 10 (1994) 219–225.
[26] Sung Kwon Kim, Linear-time algorithm for finding a maximum-density segment of a sequence, Information Processing Letters 86 (6) (2003) 339–342.
[27] Sung Kwon Kim, Finding a longest nonnegative path in a constant degree tree, Information Processing Letters 93 (6) (2003) 275–279.
[28] Yaw-Ling Lin, Xiaoqiu Huang, Tao Jiang, Kun-Mao Chao, MAVG: Locating non-overlapping maximum average segments in a given sequence, Bioinformatics 19 (1) (2003) 151–152.
[29] Yaw-Ling Lin, Tao Jiang, Kun-Mao Chao, Efficient algorithms for locating the length-constrained heaviest segments with applications to biomolecular sequence analysis, Journal of Computer and System Sciences 65 (3) (2002) 570–586.
[30] Tien-Ching Lin, D.T. Lee, Randomized algorithm for the sum selection problem, in: Proceedings of the 16th Annual International Symposium on Algorithms and Computation, 2005, pp. 515–523.
[31] Tien-Ching Lin, D.T. Lee, Efficient algorithm for the sum selection problem and k maximum sums problem, in: Proceedings of the 17th Annual International Symposium on Algorithms and Computation, 2006, pp. 460–473.
[32] Nimrod Megiddo, Arie Tamir, Eitan Zemel, Ramaswamy Chandrasekaran, An $O(n \log^2 n)$ algorithm for the kth longest path in a tree with applications to location problems, SIAM Journal on Computing 10 (2) (1981) 328–337.
[33] Kalyan Perumalla, Narsingh Deo, Parallel algorithms for maximum subsequence and maximum subarray, Parallel Processing Letters 5 (1995) 367–373.
[34] Lusheng Wang, Ying Xu, SEGID: Identifying interesting segments in (multiple) sequence alignments, Bioinformatics 19 (2) (2003) 297–298.
[35] Bang Ye Wu, Kun-Mao Chao, Chuan Yi Tang, An efficient algorithm for the length-constrained heaviest path problem on a tree, Information Processing Letters 69 (2) (1999) 63–67.
[36] Bang Ye Wu, Kun-Mao Chao, Spanning Trees and Optimization Problems, first ed., Chapman & Hall/CRC, 2004.