A Selectable Sloppy Heap

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Abstract

We study the selection problem, namely that of computing the i-th order statistic of n given elements. Here we offer a data structure handling a dynamic version in which upon request: (i) a new element is inserted or (ii) an element of a prescribed quantile group is deleted from the data structure. Each operation is executed in (ideal!) constant time—and is thus independent of n (the number of elements stored in the data structure). The design demonstrates how slowing down a certain computation can reduce the response time of the data structure.

Keywords: median selection, i-th order statistic, comparison algorithm, dynamic set, amortization.

1 Introduction

The following problem has been devised by Fredman about 25 years ago, for inclusion in homework assignments for an algorithms course. This paper both generalizes and strengthens that result.

A “very sloppy heap” (abbreviated vsh) is a data structure for performing the following operations on a set S: (i) insert and (ii) delete-small. The latter operation deletes (and returns) an element x which is among the ⌈n/2⌉ smallest elements in the set, where n is the current size of the set. Explain how to implement a vsh in constant amortized time per operation.

Together with sorting, selection is one of the most widely used procedure in computer algorithms. Given a sequence A of n numbers and an integer (selection) parameter 1 ≤ i ≤ n, the selection problem asks to find the i-th smallest element in A. Sorting trivially solves the selection problem; however, a higher level of sophistication is required by a linear time algorithm. A now classic approach for selection [6, 21, 31, 33] from the 1970s is to use an element in A as a pivot to partition A into two smaller subsequences and recurse on one of them with a (possibly different) selection parameter i.

The time complexity of this kind of algorithms is sensitive to the pivots used. If a good pivot is used, many elements in A can be discarded, while if a bad pivot is used, the size of the problem may be only reduced by a constant in the worst case, leading to a quadratic worst-case running time. But carefully choosing a good pivot can be time consuming. Choosing the pivots randomly (and thus without much effort) yields a well-known randomized selection algorithm with expected linear running time; see e.g., [8, Ch. 9.2], [26, Ch. 13.5], or [29, Ch. 3.4]; however its worst case running time is quadratic in n.

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The first deterministic linear time selection algorithm {	extsc{Select}} is due to Blum et al. \cite{6}; it is recursive in nature. By using the median of medians of small disjoint groups of the input array (of constant size at least 5) good pivots that reduce the size of the problem by a constant fraction and thereby lead to $O(n)$ time overall, can be chosen at low cost in each recursive invocation. More recently, suitable variants of {	extsc{Select}} with groups of 3 and 4 also running in $O(n)$ time have been also put forward \cite{7,34}. The selection problem, and computing the median in particular are in close relation with the problem of finding the quantiles of a set, that we describe next.

**Quantiles.** The $k$th quantiles of an $n$-element set are the $k-1$ order statistics that divide the sorted set in $k$ equal-sized groups (to within 1); see, e.g., \cite[p. 223]{8}. It is known that the $k$th quantiles of a set can be computed by a recursive algorithm running in $O(n \log k)$ time. Such an algorithm can be modified, if needed, so that the $k$ groups can be also output, say, each as a linked list, within the same overall time. For $2 \leq i \leq k-1$, the $i$th group of elements (bounded by the $(i-1)$th and the $i$th quantile) is referred to as the $i$th quantile group; the first quantile group consists of the elements less or equal to the first quantile, and the $k$th quantile group consists of the elements greater or equal to the $(k-1)$th quantile.

Our main result is the following; for the optimality of the dependence in $k$, see the first remark in Section 4.

**Theorem 1.** For any fixed integer $k$, a data structure for dynamic sets exists accommodating each of the following operations in constant time: (i) Insert a new element and (ii) Delete (and return) an element of the $i$th quantile group of the current set, where $1 \leq i \leq k$. The time per operation is $O(\log k)$, which is optimal for an amortized setting.

**Background and related problems.** Since the selection problem is of primary importance, the interest in selection algorithms has remained high ever since; see for instance \cite{2,4,5,9,11,12,13,14,15,16,17,18,19,23,24,30,32,33}. In particular, determining the comparison complexity for computing various order statistics including the median has lead to many exciting questions, some of which are still unanswered today; in this respect, Yao’s hypothesis on selection remains an inspiring endeavor \cite{12,30,31}. A comprehensive review of early developments in selection is provided by Knuth \cite{27}. Computational results on the exact comparison complexity of finding the $i$th smallest out of $n$ for small $i,n$, have been obtained in \cite{17,20}. We also refer the reader to the dedicated book chapters on selection in \cite{1,3,8,10,26} and the more recent articles \cite{7,22,25}.

The selection problem is also of interest in a dynamic setting, where elements are inserted or deleted. A balanced binary search tree on $n$ distinct elements can be augmented with a size attribute for each node, thereby allowing the retrieval of an element of a given rank in $O(\log n)$ time \cite[Ch. 14]{8}. (We say that the $i$th smallest element has rank $i$, where $i=1,\ldots,n$, with ties broken arbitrarily.) Further, determining the rank of an element in the data structure can also be done in $O(\log n)$ time. Consequently, a dynamic order statistic operation (inserting a new element or deleting an element of a given rank) can be accomplished within the same time bound.

**Definition.** Let $k$ be a fixed positive integer. A “selectable sloppy heap” (abbreviated ssh) is a data structure for performing the following operations on a set $S$ with $n$ elements:

(a) Insert $x$: a new element $x$ is inserted.

(b) Delete $i$: this deletes (and returns) some element $x$ which belongs to the $i$th quantile group of the current set, where $1 \leq i \leq k$; if $n < k$, the deleted element is not subject to any requirement.
Outline and history of the paper. To explain the main challenges and introduce the main ideas, we first sketch several preliminary implementations of the data structure, meeting suboptimal (in k) benchmarks: (i) $O(k \log k)$ amortized time per operation for the first variant in Section 2; (ii) $O(k \log k)$ worst-case time per operation for the second variant in Section 2; (iii) $O(\log k)$ amortized time per operation for the third variant in Section 2.

We then further refine these methods in Section 3 to obtain an optimal implementation of the data structure running in $O(\log k)$ worst-case time per operation. In the process it is shown how parallel execution of several sequential procedures can lead to a speed up of the data structure. We conclude in Section 4 with some remarks.

While this paper has been initially envisioned as being co-authored with M. Fredman, it was mutually preferred in the end that each of us finalize its own writing as a separate paper. An alternative solution (to that appearing in Section 3) also achieving $O(\log k)$ worst-case time per operation was conceived by Fredman, and is expected to appear under separate cover.

Comments and notations. Duplicate elements are easily handled by the design. Each operation request is associated with a discrete time step, i.e., the $j$th operation occurs during the $j$th time step, where $j = 1, 2, \ldots$. Without affecting the results, the floor and ceiling functions are omitted in the descriptions of the algorithms and their analyses.

Let $A$ be a set; we write $x \leq A$ if $x \leq a$ for every $a \in A$. The size of a bucket $b$, i.e., the number of elements in $b$, is denoted by $s(b)$. If buckets $b'$ and $b''$ merge into a new bucket $b$, written as $b' \cup b'' \rightarrow b$, we clearly have $s(b') + s(b'') = s(b)$. Similarly, if a bucket $b$ splits into two buckets $b', b''$, written as $b \rightarrow b' \cup b''$, then we have $s(b) = s(b') + s(b'')$ as well.

2 Some ideas and preliminary solutions

A first variant with $O(k \log k)$ amortized time per operation. Let $n$ denote the current number of elements in the data structure, with the elements being stored in a linear list (or an array). By default (if $n$ is large enough) the algorithm proceeds in phases.

If $n < 3k$, and no phase is under way, proceed by brute force: for INSERT, add the new element to the list; for DELETE $i$, compute the elements in the $i$th quantile group and delete (return) one of them arbitrarily. Since $k$ is constant, each operation takes $O(3k)$, i.e., runs in constant time.

If $n \geq 3k$, and no phase is under way, start a new phase: reorganize the data structure by computing the $3k$th quantiles of the set and the corresponding groups; store each group in a list (bucket) of size $n/(3k)$. The next $n/(3k)$ operations make up the current phase. Process each of these $n/(3k)$ operations by using exclusively elements stored in these $3k$ buckets. For INSERT, add the new element to an initially empty overflow list; i.e., an empty overflow list is created at each reorganization. For DELETE $i$, remove any element from the bucket $(i-1)n/k + n/3k$, i.e., from the middle third of the $i$th quantile group (out of the total $k$).

The reorganization takes $O(n \log k)$ time and is executed about every $n/(3k)$ steps, where each operation counts as one step. The resulting amortized cost per operation is

$$O\left(\frac{n \log k}{n/k}\right) = O(k \log k),$$

namely $O(1)$ for constant $k$. The above idea is next refined so as to obtain this as a worst-case time bound per operation.
A second variant with $O(k \log k)$ worst-case time per operation. It suffices to consider the case of large $n$, namely $n \geq 3k$. The algorithm proceeds in phases: each phase starts with a reorganization, namely computing the $(3k)$th quantiles and the corresponding quantile groups; see [8, Ch.15]. The time taken is $O(n \log (3k)) = O(n \log k)$. There are $n/(3k)$ INSERT and DELETE operations, i.e., $n/(3k)$ steps following each reorganization until the results of the next reorganization become available: assume that the data structure holds $n$ items when the current reorganization starts ($n$ is redefined at the start of each reorganization) and there are old buckets to use until the reorganization is finalized. That is, after that many steps new buckets (however, with an old content) become available. Use these buckets for the next $n/(3k)$ operations, and so on.

To transform the constant amortized time guarantee into a constant worst-case guarantee for each operation, spread the execution of reorganization over the next $n/(3k)$ operations, i.e., over the entire phase. The resulting time per operation is bounded from above by

$$O\left(\frac{n \log k}{n/(3k)}\right) = O(k \log k).$$

Since INSERT is serviced from the existent buckets and DELETE is serviced using the overflow bucket, each operation involves inserting or deleting one element from a list; thus for constant $k$, each operation takes $O(1)$ overall time to process.

New buckets become available about every other $n/(3k)$ operations; this is a rather imprecise estimate because the current number of elements, $n$, changes. Since a reorganization is spread out over multiple steps, the result becomes available with some delay, and moreover, its content is (partially) obsolete. To verify that the data structure operates as intended, one needs to check that the rank of a deleted element belongs to the required interval (quantile group); we omit the calculation details. The key observation is that any one operation can affect the rank of any element by at most 1: to be precise, only INSERT or DELETE of a smaller element can increase the rank of an element by 1 or decrease the rank of an element by 1, respectively.

A third variant with $O(\log k)$ amortized time per operation. We briefly describe an implementation achieving $O(\log k)$ amortized time per operation that is tailored on the idea of a B-tree; this variant is due to Fredman [15]. Use a balanced binary search tree with $\Theta(\log k)$ levels storing $O(k)$ splitting keys at the leafs. Each leaf comprises a bucket of $\Theta(n/k)$ items, with order maintained between buckets, but not within buckets. When an insertion causes a bucket to become too large, it gets split into two buckets by performing a median selection operation. Small buckets (due to deletions) get merged. A bucket of size $m$, once split, won’t get split sooner than another $\Omega(m)$ operations.

When the number of elements doubles (or halves), a tree reorganization is triggered that partitions the present items into $6k$ uniform sized buckets, so that the new common bucket size $m$ is $n/(6k)$ items. These event-triggered reorganizations ensure that buckets do not become too small unless they are target of deletions; similarly, buckets do not become too large unless they are target of insertions. Since the reorganization cost is $O(n \log k)$, and $\Omega(n)$ operation requests take place between successive reorganizations, this scheme yields $O(\log k)$ amortized time per operation, namely $O(1)$ for constant $k$.

3 A variant with optimal $O(\log k)$ worst-case time per operation

A brief examination of the approach in the 3rd variant reveals two bottlenecks in achieving $O(\log k)$ worst-case time per operation: the median computation that comes with splitting large buckets and
the tree reorganization that occurs when \( n \) doubles (or halves). We briefly indicate below how ideas from the 2nd and 3rd early variants are refined to obtain \( O(\log k) \) worst-case time per operation.

A balanced BST for \( \Theta(k) \) keys is used, splitting the data into \( O(k) \) buckets. A size attribute is associated with each node reflecting the number of elements stored in the subtree rooted at the respective node. Modifications in the data structure at each operation are reflected in appropriate updates of the size attributes at the \( O(\log k) \) nodes of the \( O(1) \) search paths involved, in \( O(\log k) \) time overhead per operation.

If \( n \) is the current number of elements, each bucket holds at most \( n/(3k) \) elements, and so each of the \( k \) quantile groups contains at least one of the buckets entirely. By choosing one such bucket at the bottom of the search path in the BST for executing a DELETE operation from the \( i \)th quantile group guarantees its correctness.

The \( n \) elements are kept in \( \Theta(k) \) buckets of maximum size \( O(n/k) \) that form the \( \Theta(k) \) leaves of a balanced binary search tree \( A \). As in the third variant (in Section 2), each leaf holds a bucket, with order maintained between buckets, but not within buckets. Buckets that become too large are split in order to enforce a suitable upper limit on the bucket size. Median finding procedures along with other preparatory and follow-up procedures accompanying bucket splits are scheduled as background computation, as in the second variant (in Section 2).

Our data structure merges small buckets in order to keep the number of buckets under control and renounces the periodic tree reorganizations by introducing new elements of design: a round robin process and a priority queue jointly control the maximum bucket size and the number of buckets in the BST. These mechanisms are introduced to prevent buckets becoming too small or too large as an effect of changes in the total number of elements, \( n \), and not necessarily as an effect of operations directed to them.

Outline and features. Let \( N := 12k \). For illustrating the main ideas, assume now that \( n \geq N \). The buckets are linked in a doubly-linked linear list \( B \), in key order; adding two links between the last and the first bucket yields a circular list \( C \), referred to as the round robin list. We note that \( B \) and \( C \) are two views of the same data structure.

Each operation request translates to locating a suitable bucket for implementing the request. The circular list is traversed in a round robin fashion, so that the current round robin bucket in the list is also examined during the current operation request. The round robin process ensures that (i) the buckets do no exceed their maximum capacity, and (ii) certain “long-term” preparatory bucket-splitting procedures are run in the background over a succession of non-consecutive discrete time steps allocated to the same bucket.

Each operation request entails a merge tests for the pair of adjacent buckets with the minimum sum of sizes. The process of merging adjacent buckets in \( B \) is controlled by a priority queue in the form a binary min-heap \( H \). If \(|B| = t\), i.e., there are \( t \) buckets, \( H \) holds the \( t-1 \) sums of sizes \( s(b) + s(b^+) \), for buckets \( b \in B \); here \( b^+ \) denotes the bucket that follows \( b \) in \( B \). A merge is made provided the minimum value at the top of \( H \) is below some threshold; and \( A, B \) and \( H \) are updated. Merging adjacent buckets ensures that the total number of buckets remains under control, regardless of which buckets are accessed by operation requests.

Elements of the design. We highlight two: (i) use of the priority queue \( H \) to keep the number of buckets under control, and (ii) running the procedures involved at different rates as needed to ensure that certain task deadlines and precedence constraints among them are met. The data structure maintains the following two invariants:
Each bucket contains between 1 and \( n/(3k) \) elements; there is no limit from below imposed on the bucket size.

The number of buckets is between \( 3k \) and \( N = 12k \), as implied by the maximum bucket size, and a later argument based on the rules of operation (on merging adjacent buckets); see Action 2 and Lemma \[1\].

Recall that all \( \Theta(k) \) buckets are linked in a circular round robin list: in key order, and with the last bucket linked to the first one. A pointer to the current round robin bucket (initialized arbitrarily, say, to the first bucket) is maintained. Each operation request advances this position in the list by one slot. Observe that every bucket becomes the round robin bucket about every \( \Theta(k) \) discrete time steps. Further, each operation request leads via the search path in \( \mathcal{A} \) to one of the buckets, referred to as the operation bucket. Executing one operation is done by a sequence of actions performed in the operation bucket and the round robin bucket; these are referred to as the current buckets. All these actions are therefore associated with the same discrete time step.

A bucket is declared large if its current size exceeds \( 9/10 \) of the maximum allowed, i.e., if the current size exceeds \( 9n/(30k) \). All other buckets are declared regular. Each operation may cause an update in the status of the round robin bucket and the operation bucket (among large and regular).

**Action 1.** Execute the requested operation: either add a new element to the respective bucket list, or delete an arbitrary element from it. If the operation bucket becomes empty as a result of the current DELETE operation, it is deleted, and the BST is correspondingly updated in \( O(\log k) \) time. Check for status updates in the current two buckets. If a median finding procedure or a follow up procedure is under way in the current operation bucket or the current round robin bucket (see details below), the next segment consisting of 500 (or less) elementary operations of this procedure is executed.

**Action 2 (merge-test).** Let \( \sigma := s(b) + s(b^+) \) be the minimum value at the top of the heap \( \mathcal{H} \). If \( \sigma \leq 5n/(30k) \), merge the two buckets into one: \( b \cup b^+ \rightarrow b \), and update the tree \( \mathcal{A} \), the bucket list \( \mathcal{B} \) and the binary heap \( \mathcal{H} \) to reflect this change: (i) delete the two buckets that are merged and insert the new one that results into \( \mathcal{A} \) and \( \mathcal{B} \); (ii) extract the minimum element from \( \mathcal{H} \) and insert the two new sum of sizes of two adjacent buckets formed by the new bucket into \( \mathcal{H} \) (if they exist).

Handling of \( \mathcal{A}, \mathcal{B} \) and \( \mathcal{H} \) take \( O(\log k) \) time, \( O(1) \) time, and \( O(\log k) \) time, respectively. In particular, this action ensures that the size of any new bucket obtained by merge is at most \( 5n/(30k) \). It is worth noting that a bucket for which a partitioning procedure is under way, as described below, cannot be part of a pair of buckets to merge (i.e., passing the merge-test).

**Action 3 (finalizing a split).** Similar to the merge operations in Action 3, finalizing the split can be completed in \( O(\log k) \) time: it essentially involves updating \( \mathcal{A}, \mathcal{B} \) and \( \mathcal{H} \). It will be shown subsequently that the size of any new bucket resulting from a split is in the range \([4n/(30k), 6n/(30k)]\).

Besides Actions 1 – 3, there are actions associated with procedures running in the background, whose execution is spread out over a succession of non-consecutive discrete time steps allocated to the same bucket. The procedures are in preparation of splitting large buckets.

**Splitting a large bucket.** For simplicity of exposition, we assume that \( n = \Omega(k) \), for a sufficiently large constant factor. If the current bucket \( b \) is large, i.e., \( s(b) \geq 9n/(30k) \), and no procedure is active in the current bucket, let \( n_0 := n \) (the number of elements existent when the procedure is initiated); and place \( 8.8n_0/(30k) \) elements into (a main part) \( P_1 \) and the remaining
procedure, by comparing each element of \( P \) with one of the elements in the two quantile groups of the same size, \( 4 \).

Discrete steps, a balanced partition of the current bucket is obtained. The follow up procedure terminates when the median element of \( P \) is determined. Any insertions and deletions from the current bucket until the split is finalized are performed using \( P \). A balanced partition of the current bucket will be obtained in at most \( n_0/10 \) time steps.

Consider the following \( n_0/10 \) operation requests. By Lemma 4 below, the number of buckets \( P \) starts with the two quantile groups of the same size, \( 4 \).

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Remark. Let \( b \) be a new bucket produced in the current operation. If \( b \) is generated by a split operation, then \( \frac{4n_0}{30k} \leq s(b') \leq \frac{6n_0}{30k} \) by Lemma 4. If \( b \) is generated by a merge operation, then \( s(b) \leq \frac{5n_0}{30k} \) by the merge-test.

This qualification refers to the time when the partitioning procedure was initiated.
Analysis of merging buckets and maintaining the two invariants. To prove that the two invariants \( I_1 \) and \( I_2 \) are maintained, we need the following key fact.

**Lemma 1.** The number of buckets is at most \( N = 12k \) at any time.

**Proof.** Let \( t \) denote the number of buckets after the current operation is executed, and \( j = 1, 2, \ldots \) denote the discrete time steps. Let \( B_1, \ldots, B_t \) be the buckets after the current step in key order. Write \( a_i = s(B_i) \), for \( i = 1, \ldots, t \). We proceed by induction on \( j \) and show that, if the number of buckets in \( A \) (and \( B \)) is at most \( N \) after each of the preceding \( N \) time steps, it remains at most \( N \) after the current time step. Observe that the number of buckets can only increase by at most one after a bucket split. The induction basis is \( j \leq N \), and then indeed, we have \( t \leq j \leq N \), as required.

For the induction step, assume that the number of buckets is at most \( N \) after the previous operation. Let \( \sigma := s(b) + s(b^+) \) be the minimum value at the top of the heap \( H \). There are two cases:

- **Case 1.** \( \sigma \leq 5n/(30k) \), and thus the merge is executed. Consequently, the number of buckets after the current operation is still at most \( N \), as required.
- **Case 2.** \( \sigma > 5n/(30k) \), and thus no merge is executed. Since \( H \) is a min-heap, we have

\[
a_i + a_{i+1} > \frac{5n}{30k}, \quad \text{for } i = 1, \ldots, t - 1.
\]

Adding these \( t - 1 \) inequalities yields

\[
2n = 2 \sum_{i=1}^{t} a_i > (t - 1) \frac{5n}{30k},
\]

or \( t \leq 12k = N \), as claimed, and concluding the induction step. \( \square \)

**Summary of the analysis.** As seen from the preceding paragraphs and the fact that the number of buckets is \( t = O(k) \), the total time per operation is \( O(\log t) + O(\log k) + O(1) = O(\log k) \), as required.

4 Concluding remarks

1. A brief argument due to Fredman [15] shows that executing a sequence of \( n \) operations (from among INSERT and DELETE \( i \), where \( 1 \leq i \leq k \)) requires \( \Omega(n \log k) \) time in the worst case, regardless of the implementation of the data structure. The argument relies on the information theory lower bound [27, Ch. 5.3.1].

2. As mentioned in Section 1 an alternative solution (to that outlined in Section 3) achieving \( O(\log k) \) worst-case time per operation was conceived by Fredman. His solution avoids the need to merge small buckets (in order to keep the number of buckets under control) by maintaining two running copies of the data structure and performing periodic tree reorganizations that create uniform-sized buckets. Buckets that become large are split using a mechanism similar to that devised in Section 3.

3. In addition to the two operations provided INSERT and DELETE \( i \), the following operation can be also accommodated at no increase in cost: READ \( i \): this returns some element \( x \) which belongs to the \( i \)th quantile group of the current set, where \( 1 \leq i \leq k \); the element remains part of the data structure.
4. The new data structure finds applications in settings with large dynamic sets where insertions and deletions need to be handled fast, and there is no need to be very precise with the ranks of the elements handled. One such application is approximate sorting. An array of \( n \) elements is said to be \( L \)-sorted if for every \( i \in [n] \), we have \( |\text{rank}(a_i) - i| \leq L \); see also \cite{28}. One can show that our data structure can be used to \( L \)-sort \( n \) elements in \( O(n \log (n/L)) \) time.

5. This is a continuation of our earlier discussion in Section 1 on using BSTs in the context of dynamic selection taking into account the new data structure. Traditionally, search trees do not allow duplicate keys; it is however an easy matter to augment each node of such a tree with a multiplicity attribute associated with each distinct key. In particular, the multiplicity attribute is taken into account when computing the size attribute of a node. Now having a balanced search tree augmented as described, insertion, deletion and search all take \( O(\log n) \) time.

Our construction method can be used for any parameter \( k \), with \( 2 \leq k \leq n \). The data structure obtained in this way can be viewed as an approximate search tree. In particular, one can search for a given key and the approximate rank of a search key can be determined. To be precise, the following hold: (1) For any \( 2 \leq k \leq n \), an approximate search tree on \( n \) items (duplicate keys allowed) can be constructed in \( O(n \log k) \) time. (2) Search for a given key can be accommodated in \( O(n/k + \log k) \) time per operation; its approximate rank, i.e., the quantile group to which it belongs (out of \( k \)), can be reported in \( O(\log k) \) time (regardless of the presence of the key!). (3) Insertion can be accommodated in \( O(\log k) \) time per operation. (4) Deletion of an unspecified key from a given quantile group (out of \( k \)) takes \( O(\log k) \) time; while deletion of a given key takes \( O(n/k + \log k) \) time.

It is now worth noting that the approximate search tree we just described appears competitive when \( k \) is set to be small and the search function is infrequently used. Then insertion and deletion of an unspecified key from a given quantile group (out of \( k \)) takes \( O(\log k) \) time (the deleted element is revealed after the operation); e.g., if \( k = O(\log n) \), these operations take \( O(\log \log n) \) time. On the other hand, the approximate search tree we just described is no real competitor for the “exact” solution previously discussed; indeed, no choice of \( k \) in our data structure would allow an improvement in the performance of all the basic three operations.

References


[34] U. Zwick, personal communication, September 2014.