

Secondary Indexing in One Dimension: Beyond B-trees and Bitmap Indexes*

Rasmus Pagh[†]

S. Srinivasa Rao[‡]

ABSTRACT

Let Σ be a finite, ordered alphabet, and consider a string $\mathbf{x} = x_1x_2\dots x_n \in \Sigma^n$. A *secondary index* for \mathbf{x} answers alphabet range queries of the form: Given a range $[a_l, a_r] \subseteq \Sigma$, return the set $I_{[a_l, a_r]} = \{i \mid x_i \in [a_l, a_r]\}$. Secondary indexes are heavily used in relational databases and scientific data analysis. It is well-known that the obvious solution, storing a dictionary for the set $\bigcup_i \{x_i\}$ with a position set associated with each character, does not always give optimal query time. In this paper we give the first theoretically optimal data structure for the secondary indexing problem. In the I/O model, the amount of data read when answering a query is within a constant factor of the minimum space needed to represent the set $I_{[a_l, a_r]}$, assuming that the size of internal memory is $(|\Sigma| \lg n)^\delta$ blocks, for some constant $\delta > 0$. The space usage of the data structure is $O(n \lg |\Sigma|)$ bits in the worst case, and we further show how to bound the size of the data structure in terms of the 0th order entropy of \mathbf{x} . We show how to support updates achieving various time-space trade-offs.

We also consider an approximate version of the basic secondary indexing problem where a query reports a superset of $I_{[a_l, a_r]}$ containing each element not in $I_{[a_l, a_r]}$ with probability at most ε , where $\varepsilon > 0$ is the false positive probability. For this problem the amount of data that needs to be read by the query algorithm is reduced to $O(|I_{[a_l, a_r]}| \lg(1/\varepsilon))$ bits.

*The main ideas for this work were conceived during Dagstuhl seminar No. 08081 on Data Structures, 2008.

[†]IT University of Copenhagen, Denmark. Email: pagh@itu.dk. This work was supported by the Danish National Research Foundation, as part of the project “Scalable Query Evaluation in Relational Database Systems”.

[‡]MADALGO (Center for Massive Data Algorithmics, a center of the Danish National Research Foundation), Aarhus University, Denmark. Email: ssrao@madalgo.au.dk

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

PODS'09, June 29–July 2, 2009, Providence, Rhode Island, USA.
Copyright 2009 ACM 978-1-60558-553-6 /09/06 ...\$5.00.

Categories and Subject Descriptors. E.1 [Data Structures]: Trees; E.1 [Data Storage Representations]: Composite Structures; H.2.2 [Database Management]: Physical Design; H.3.1 [Information Storage and Retrieval]: Content Analysis and Indexing

General Terms. Algorithms, theory

Keywords. Bitmap index, B-tree, range query

1. Introduction

Indexing capability is a vital part of database systems, and hundreds of indexing methods exist. In this paper we consider indexes that store a multiset of keys from an ordered set Σ , where each key has some associated data. The goal is to support *range queries* finding all keys (and associated data) in a given interval. In databases a distinction is made between *primary* indexes, where the data associated with each key is stored in the index itself, and *secondary* indexes where the index provides references to the associated data, which is stored in a way not controlled by the index. The distinction is especially important in the I/O model, where the time to read the references is usually much smaller than the time to retrieve the associated data. This is because the associated data is, in general, unlikely to be located in a small number of disk blocks.

At first glance it would seem that the performance of secondary indexes is not too important in the case where the set of returned references is a large fraction of all data (in database jargon, where the *selectivity* is low), since then the time to read the associated data will dominate. However, it is common to use several secondary indexes in conjunction. For example, in a database of people we may want to find all married men of age 33. This can be done by combining information found in secondary indexes for the attributes specifying marital status, sex, and age. Only associated data matching all three conditions needs to be returned. This means that the time spent by the secondary indexes may be dominant, even when the time for retrieving the associated data is taken into account, given that the *combined* selectivity of all conditions is high. This way of using secondary

indexes, often referred to as *RID intersection*, is particularly common in On-Line Analytical Processing (OLAP) systems, information retrieval, and scientific data analysis (see e.g. [15, 16, 18] for details). In some applications, queries may be answered by just consulting the secondary indexes, e.g., if we are interested in *counting* the number of tuples matching several range conditions.

From a worst case query time perspective it would seem better to support queries like the above using a data structure for orthogonal range queries in three dimensions, e.g., a range tree. This would ensure good query performance in terms of data size and result size. However, when the number of dimensions d is more than a small constant (say, 3) known range reporting data structures either:

- Use excessive space (e.g., *range trees* [11, Section 5.3] have space usage that grows with $(\lg n)^{d-1}$), or
- Have no (provably) good worst-case performance (e.g., *kD-trees* [11, Section 5.2] have worst case query time $n^{1-1/d}$).

This is one reason why it is common to perform multi-dimensional range queries by intersection of the set of matching points in each dimension, as explained above. Another reason is that one-dimensional search structures are usually simpler and have lower constant factors than multi-dimensional data structures.

Finally, using a collection of one-dimensional search structures allows answering queries that are more general than orthogonal range queries. Examples are approximate range searches (“find points that are in the range in at least d_1 out of d dimensions”) and partial match queries (“find points that match range conditions in d_1 given dimensions, where $d_1 \ll d$ ”). For many of these problems, all known solutions (for high dimensions) are not much better than the brute force solutions (either represent all answers, or let queries read most of the data).

1.1 Problem definition

Let Σ be a finite, ordered alphabet, and consider a string $\mathbf{x} = x_1x_2 \dots x_n \in \Sigma^n$. For $i \leq j$, we denote the set containing an interval of consecutive values $\{i, i+1, \dots, j\}$ by $[i, j]$. For $[a_l; a_r] \subseteq \Sigma$ we define $I_{[a_l; a_r]}(\mathbf{x}) = \{i \mid x_i \in [a_l; a_r]\}$, and for notational convenience let $I_a = I_{[a; a]}$. When the string \mathbf{x} is understood we omit it. We formalize the *secondary indexing problem* as follows: A secondary index for \mathbf{x} answers alphabet range queries that, given $a_l, a_r \in \Sigma$, return the set $I_{[a_l; a_r]}(\mathbf{x})$. We let $z = |I_{[a_l; a_r]}|$ and $\sigma = |\Sigma|$. Without loss of generality we assume $\sigma \leq n$ (if it is larger, use a dictionary to map to a smaller alphabet). In this paper we will consider data structures that output the query result in compressed format, using $O(\lg \binom{n}{z})$ bits. In fact, the output will simply be a compressed bitmap, so combining several such outputs to perform RID intersection is done just like combining compressed bitmap indexes. The size of the data structure can be expressed either in terms of n and σ , or more generally in terms of the 0th order entropy of \mathbf{x} .

In the *semi-dynamic* version we allow insertions of a new character at the end of \mathbf{x} . In the *fully dynamic* version we additionally allow changing the character in a given position. We discuss in Section 4 how this is enough to also handle deletions.

We also consider a generalization of the secondary indexing problem. In the *approximate secondary indexing problem* with parameter $\varepsilon \geq 0$ (Section 3) the result of queries should be a set $\hat{I}_{[a_l; a_r]} \supseteq I_{[a_l; a_r]}$ such that for every $i \notin I_{[a_l; a_r]}$, $\Pr[i \in \hat{I}_{[a_l; a_r]}] \leq \varepsilon$, where the probability is over random choices made by the algorithm. The motivation for this problem is that it may be enough to filter away almost all points in the d -dimensional range query application. If a point is inside the range in k dimensions, the probability that it will be reported by all d approximate range queries is at most ε^{d-k} . False positives can be filtered away when accessing the associated data, assuming that the d keys are stored with the associated data (which is typically the case in database applications).

1.2 Previous work

If Σ has constant size, an optimal secondary index (up to constant factors) is to store for every $a \in \Sigma$ a *bitmap index* for the set $I_{\{a\}}$, i.e., the bit string $\mathbf{x}_a \in \{0, 1\}^n$ where there is a 1 in position i if and only if $x_i = a$. A range query can be answered by simply reading the bitmap of each character in the range.

If Σ is large it is clear that some bitmaps will be very sparse, and hence storing an explicit bitmap for each character will be inefficient in terms of space. This problem can be addressed by compressing each bitmap to a representation that uses close to the information-theoretic minimum space for representing bitmaps of a given sparsity. A bit string of length n with $m \leq n/2$ 1s requires space at least $\lg \binom{n}{m} = m \lg(n/m) + \Theta(m)$ bits.¹ One well-known optimal encoding (within a constant factor) is the run-length encoding, where the length x of each run of 0s is encoded using a gamma code [12] using $2\lceil \lg(x+1) \rceil + 2$ bits. Even though the bitmaps are not independent, compressing them independently gives a total size of the data structure that is within a constant factor of the size of the original string \mathbf{x} , i.e., $O(n \lg \sigma)$ bits. While gamma coding is asymptotically optimal, compression schemes used in practice also take into account the computational effort needed to compress and uncompress [18], with some reduction in worst-case compression rate.² In this paper we focus on the number of bits read and written, and hence use run-length encoding with gamma codes (or more generally, any method that compresses to

¹We use \lg to denote the logarithm base 2.

²Some bitmap indexing schemes such as [18] claim space optimality, but this is in comparison with indexes that represent all data explicitly, using at least $\log n$ bits per key, which is not optimal for dense sets. A bitmap of length $n \lg n$ with n 1s may use $\geq n \lg n$ bits of space in the representation of [18], whereas the optimal bound is $n \lg n + O(n)$ bits.

within a constant factor of minimum size). More formally, we will analyze our data structure in the *I/O model* [1] where the cost measure is the number of memory blocks read and written. (Note that in this model the minimum amount of data read is 1 block, i.e., we count block I/Os and not merely the amount of data read.) While recent studies [18, 17] indicate that computation time can be a bottleneck when handling (compressed) bitmap indexes, we find it likely that I/O is going to be a future bottleneck, as the parallel processing power of CPUs is rapidly increasing.

Performing a range query by reading the compressed bitmap for each character in the range does not always give the best query time we could hope for. For example, if each character occurs n/σ times and we make a range query of size ℓ the output is a set of size $n\ell/\sigma$, which can be represented in $O(\frac{n\ell}{\sigma} \lg(\sigma/\ell))$ bits. However, the total size of the individual bitmaps is $\Theta(\frac{n\ell}{\sigma} \lg \sigma)$, meaning that we are reading a factor $\Omega(\lg(\sigma)/\lg(\sigma/\ell))$ more bits than the output size. When $\ell = \Omega(\sigma)$ this is a factor $\Omega(\lg \sigma)$ from optimal.

There have been a number of papers trying to use some kind of precomputation to allow faster range queries. Some of these, such as *range encoding* [14] and *interval encoding* [9, 10] use space $n\sigma^{1-o(1)}$ bits [16]. In this paper we are interested in schemes where the precomputed data structure uses space close to the minimum possible for representing \mathbf{x} . A more space-conscious approach to range queries is *binning* (see [16]). In its simplest form the idea is to divide Σ into bins of w characters and represent a compressed bitmap for each bin corresponding to all occurrences of its characters. This means that a range query where the range has size ℓ can be answered by combining less than $\lfloor \ell/w \rfloor + 2w$ compressed bitmaps. Using this idea recursively one gets *multi-resolution bitmap indexes* [16], illustrated in Figure 1. Though not analyzed in [16] the worst-case space usage of such an index, when each bitmap is optimally compressed, is $\Theta(n \lg^2(\sigma)/\lg w)$ bits. Queries may in the worst case require reading a factor $O(\lg w)$ more data than in the size of the output. This means that there is a time-space trade-off, and one can never simultaneously achieve optimal space for the data structure and optimal query time. In fact, a more general scheme is discussed in [16] that allows the bucket size to be different on the various resolution levels, but even this does not seem to yield any worst-case improvement.

1.3 Our results

In the static setting, we obtain a data structure that simultaneously achieves two goals:

- Space usage that is within a constant factor of the size of the string \mathbf{x} . In fact, the size of our data structure is within a constant factor of the 0th order entropy of \mathbf{x} , plus $O(n)$ bits. This is up to a factor $\Omega(\lg \sigma)$ less than the explicit representation of \mathbf{x} .
- Time usage for range queries that is within a constant factor of what would be needed to read the result, had it been precomputed. This is up to a factor $\Omega(\lg n)$ less

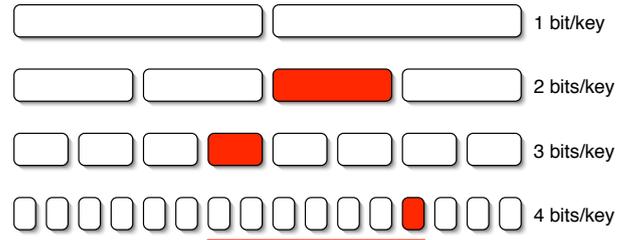


Figure 1: Illustration of multi-resolution bitmap indexing (with $w = 2$). The horizontal axis corresponds to Σ (in this case containing 16 elements), and each rectangle corresponds to a (compressed) bitmap containing the result of a range query for the covered interval. A range query on the interval drawn at the bottom can be answered by taking the union (bitwise or) of the three colored bitmaps. The space usage of each level has been stated on the right, slightly simplified, by considering the case where all characters have the same number of occurrences, and assuming that a bitmap with n 1s and size kn can be compressed to $n \lg k$ bits (ignoring a cost of up to $\lg e$ bits per key).

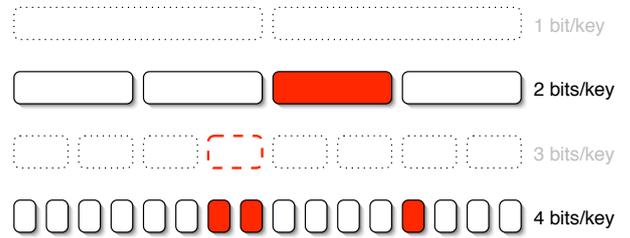


Figure 2: Illustration of our bucketing technique in the special case where all characters have the same number of occurrences. While multi-resolution bitmap indexing (with $w = 2$) stores $\lg \sigma$ levels of bitmaps, we store only $\lg \lg \sigma$ carefully chosen levels (above, the levels shown in dotted lines are not stored). The space usage per key is exponentially increasing (as opposed to linearly increasing), which means that the space usage is dominated by the lowest level. The space usage of each level has been stated on the right, slightly simplified, as explained in the caption of Figure 1. Since not all levels are stored, we generally need to take the union of more bitmaps to answer a range query (compare the colored bitmaps above with those of Figure 1). However, we show that it is possible to limit the I/O cost of this to a constant factor.

than the time needed to read the explicit list of positions in the result.

Our result improves previous results, all of which exhibit a time-space trade-off. We also show how to make our structure dynamic, which is something that has not been achieved by earlier data structures. Depending on the time allowed for updates, we achieve the same, or nearly the same, query time. Finally, we show how to support Bloom filter-like approximate queries with improved efficiency.

The main contributions of the paper are:

- Formulation of the theoretical problem: Secondary indexing with worst-case optimal space and query time. This gives a unified view of secondary index performance, with B-trees and uncompressed bitmap indexes at the extremes.
- A new multi-resolution bitmap indexing scheme that (ignoring constant factors) does not exhibit a trade-off between space and query time. Section 2.2.
- A dynamization of the data structure (Section 4). A component of this, which is of independent interest, is a dynamic, buffered bitmap index (Section 4.2). The dynamization is mainly a technical contribution, requiring the use of several known ideas.
- An I/O efficient way of supporting approximate range queries. The set returned by such a query is rather large, but we show how it can be highly compressed such that the representation is significantly smaller than that of an exact result.

Figure 2 illustrates our new bucketing idea in a special case, and compares it to multi-resolution bitmap indexing.

1.4 More notation

We define the *cardinality* of a bitmap S to be the number of 1s in it. Let T denote the size of the (optimally) compressed output in bits. It will be convenient for us to measure the block size B of the I/O model in *bits*, rather than words. Similarly, M will denote the size of internal memory in bits. We also use the parameter b to denote the block size in “words”, i.e., $b = \Theta(B/\lg n)$, where n is the size of the input. We assume that $B \geq \lg n$, and also that $b \geq 2$. Let $\Sigma = \{a_1, a_2, \dots, a_\sigma\}$ with $a_1 < a_2 < \dots < a_\sigma$.

2. Our secondary index

To simplify the description of the structure below, we assume σ to be a power of 2. The structure and its analysis can be easily modified to work for the general case.

2.1 A suboptimal solution.

As a warm-up we first describe a simpler structure that introduces some of the ideas used later, but only gives a suboptimal result. The data structure is a variant of multi-resolution bitmap indexes [16], and is not space optimal, but it is a suitable stepping stone for the optimal solution described in Section 2.2.

Consider the complete binary tree U with σ leaves identified from left to right with the sequence $a_1, a_2, \dots, a_\sigma$. With the leaf a_i we associate the bitmap $I_{a_i}(\mathbf{x})$, and with each internal node v , we associate the bitmap $I_{[a_l; a_r]}(\mathbf{x})$ where a_l and a_r are the leftmost and rightmost leaves below v , respectively.

Let v_1, v_2, \dots, v_{2^j} be the nodes, in left-to-right order, at level j (the root being at level 1), and let n_i be the cardinality of the bitmap associated with the node v_i . We store the compressed bitmaps of all the nodes at each level in their left-to-right order. The space used by all the compressed bitmaps at the j th level is $O\left(\sum_{i=1}^{2^j} \lg \binom{n}{n_i}\right)$. This summation is maximized when each of the n_i s is equal to $n/2^j$, and in this case the space used by the j th level compressed bitmaps is $O\left(\sum_{i=1}^{2^j} \lg \binom{n}{n/2^j}\right)$, which is $O(nj)$ bits. Hence the total space used by all the levels is $\sum_{j=0}^{\lg \sigma} O(nj) = O(n \lg^2 \sigma)$ bits. We store the bitmaps of all the nodes in their level order (from top to bottom, and from left to right in each level). For each node, we also store the position and length of its compressed bitmap, which takes $O(\sigma \lg n)$ bits overall.

We store an array A of length $\sigma + 1$ where $A[i]$ stores the cardinality of the bitmap $I_{[a_1; a_i]}(\mathbf{x})$, for $i = 1, \dots, \sigma$, and $A[0] = 0$. The cardinality of $I_{[a_l; a_r]}(\mathbf{x})$ is $z = A[r] - A[l-1]$. If $z > n/2$, then instead of computing the answer to the original query $I_{[a_l; a_r]}(\mathbf{x})$, we compute the answers to the two queries $I_{[a_1; a_{l-1}]}(\mathbf{x})$ and $I_{[a_{r+1}; a_\sigma]}(\mathbf{x})$, and return their union (which is the complement of the query result). We now show how to answer a query for $I_{[a_l; a_r]}(\mathbf{x})$ assuming $z \leq n/2$.

To answer an alphabet range query, $I_{[a_l; a_r]}(\mathbf{x})$, we first observe that any consecutive range of leaves can be covered by the disjoint union of $O(\lg \sigma)$ subtrees of U (by taking the maximal subtrees for which all leaves are within the range – at each level, there will be at most two maximal subtrees whose leaves are within the range). We compute the compressed bitmap of their union by merging the bitmaps. Assuming that the size M of internal memory is at least $B \log \sigma$ this can be done in a single pass.

Since the cardinalities of the bitmaps associated with subtrees decrease by a factor of 2 as we go down by one level in the tree, we can argue that the sum of the sizes of these $O(\lg \sigma)$ subtrees (where there are at most two subtrees at each level) is at most 4 times the size of a subtree that is present at the highest level. Also, the length of the compressed bitmap associated with a subtree that is present at the highest level is a lower bound on T , since $z \leq n/2$. Thus

the overall number of I/Os is $O(\lg \sigma)$ plus an $O(T/B)$ term for reading the bitmaps.

The result of the warm-up case is the following theorem, which we improve later.

Theorem 1. *A string $\mathbf{x} = x_1x_2 \dots x_n \in \Sigma^n$ over a finite alphabet Σ of size σ can be stored using $O(n \lg^2 \sigma)$ bits³ such that range queries can be answered in $O(T/B + \lg \sigma)$ I/Os.*

2.2 Optimal space structure.

We now describe how to reduce the space to optimal (assuming $\sigma \ll n$), while still retaining the query performance. For simplicity we assume that no character has more than $n/2$ occurrences. If this is not the case we may expand the alphabet and substitute half of the occurrences of the most common character with a new character, increasing the 0th order entropy by $O(n)$ bits. A main tool is to use a “weight balanced tree” W on the multi-set of characters occurring in \mathbf{x} , instead of the complete binary tree U on the alphabet (used in the case of uniform distribution). Each of the n characters is associated with its position in \mathbf{x} ; their ordering in the tree is determined primarily by the order on Σ , secondarily by the ordering of positions.

Our starting point is a weight-balanced B-tree from [4] with constant maximum degree. As in other B-tree variants, all leaves are at the same distance from the root. The essential property we need is that in a weight-balanced B-tree with branching parameter $c > 4$ (a constant) and leaf parameter 1 we can efficiently maintain that the *weight* of a node v (number of leaves in the subtree below v) at level i from the bottom is between $\frac{1}{2}c^i$ and $2c^i$. This implies that the maximum degree is $4c$ and the depth is $O(\lg n)$. The weight of a node is stored with the node. Note that the weight of a node at level i from the top is $\Theta(n/c^i)$ (this is the bound we will actually use).

We take a weight balanced tree with n leaves, and with the i th leaf (in the left-to-right order) we associate the character a_j where $A[j-1] < i \leq A[j]$ (recall that $A[j]$ is the cardinality of the bitmap $I_{[a_1, a_j]}(\mathbf{x})$, for $1 \leq j \leq \sigma$, and $A[0] = 0$). With each internal node v of the tree, we associate a compressed representation of a bitmap S_v of length n where $S_v[i] = 1$ if the character in position i is in the subtree rooted at v , and $S_v[i] = 0$ otherwise. We now prune this tree by removing all the children of an internal node v if all leaves below v contain the same character. In this pruned tree, each character appears at most $8c$ times at each level as a leaf (if it appears more than $8c$ times as a leaf at a particular level, then since all these leaves must be adjacent, a subset of them will be the only children of their parent and hence should have been removed by the pruning procedure as their parent would be associated with a single character). Thus the total number of leaves, and hence the total number of nodes in the pruned tree is $O(\sigma \lg n)$, for constant c . We

³The space bound can be improved to $O(n \lg \sigma + \sigma \lg^2 n)$ bits while improving the query time to $O(T/B + \lg \lg \sigma + \lg_b \sigma)$ I/Os by using the ideas described in Section 2.2.

use W to denote this pruned tree. We define the weight of a node in the pruned tree to be the cardinality of the bitmap associated with it (which is same as its “weight” in the tree before pruning).

2.2.1 A naive upper bound

Since the sum of the cardinalities of all bitmaps stored with nodes at any particular level is at most n and since each bitmap of a node at level i has cardinality $\Theta(n/c^i)$, the compressed bitmap of a node at level i takes $\Theta(ni/c^i)$ bits (recall that c is constant). Since there are $O(c^i)$ nodes at level i the total space at this level is $O(ni)$ bits, and because the height of the tree is $O(\lg n)$, the overall space used by all the levels is $O(n \lg^2 n)$ bits. The tree structure (including pointers to the bitmaps at each node, but not including the bitmaps themselves) is laid out on the disk such that any root-to-leaf path can be traversed using $O(\lg_b n)$ I/Os. More specifically, starting from the root, we store the top $d = \Theta(\lg b)$ levels in a block with pointers to each of the subtrees at level $d+1$. Each of the subtrees at level $d+1$ are recursively stored in the same fashion. We merge the blocks so that no block is more than half empty. Thus the total space is within a constant factor of the space needed to store the tree without “blocking”. Since we can traverse $\Theta(\lg b)$ levels in any root-to-leaf path using one I/O, any root-to-leaf path can be traversed using $O(\lg_b n)$ I/Os. The compressed bitmaps of all nodes are stored in level order.

A range query $I_{[a_l, a_r]}(\mathbf{x})$ can be partitioned into $O(\lg n)$ subtrees where there are only a constant number of subtrees at each level. These subtrees can be identified by traversing the tree top down to find the leftmost and rightmost leaves associated with the characters a_l and a_r , respectively, using $O(\lg_b n)$ I/Os. More specifically, starting from the root, at each level we go to the leftmost (rightmost) child of the current node which is associated with a_l (a_r), while including subtrees rooted at all the right (left) siblings of the child to the list of subtrees to be merged. If z is the cardinality of the query result, then there are $O(1)$ subtrees of weight between z and z/c , $O(1)$ subtrees of size between z/c and $z/c^2, \dots, O(1)$ subtrees of size 1. Thus the total size of all the compressed bitmaps we need to read (to compute their union) is at most $O(1)(z \lg(n/z) + (z/c) \lg(cn/z) + \dots + \lg n) = O(z \lg(n/z))$, which is asymptotically optimal. For each compressed bitmap read we may use up to 2 I/Os to read blocks that do not contain B bits of the compressed bitmap. That is, we waste $O(\lg n)$ I/Os compared to the smallest possible number of I/Os required to read the compressed bitmaps.

2.2.2 Space improvement

We now show how to improve the space of the above scheme to $O(nH_0)$ bits, where H_0 is the 0th order entropy of the string \mathbf{x} , while retaining the query time. The main idea is to store bitmaps only on a few levels of the tree explicitly instead of storing all of them. More specifically, if h is the height of the tree W , we store the $O(\lg h)$ levels numbered

1, 2, 4, 8, ... (from the top), and also store all the leaves explicitly. We refer to the levels that are stored explicitly (including the leaf level) as the *materialized levels*. In addition, we store the structure of the entire tree W , without removing any levels.

We now analyze the space usage. Consider an instance of a character that is stored at level i in the tree. It contributes to the space usage of one bitmap index at each of levels $1, 2, 4, \dots, 2^{\lceil \lg i \rceil}$, which means a total of $O(i)$ bits. In other words, the total space is within a constant factor of the space needed for the bitmap indexes stored at the leaves.

Now consider the leaves corresponding to a single character $a \in \Sigma$ with z_a occurrences. As noted above, at any level there are at most $8c$ leaves associated with a . Further, the heaviest leaf associated with a has weight $\Theta(z_a/c)$ (because a constant fraction of the total weight must come from the uppermost level). As argued earlier, the exponential decrease in weight down the tree means that the space usage is dominated by the uppermost level, which uses space $O(z_a \lg(n/z_a))$. Summing over all characters we get $\sum_{a \in \Sigma} O(z_a \lg(n/z_a)) = O(nH_0)$ bits, where H_0 is the 0th order entropy of the string \mathbf{x} . In addition, the tree has $O(\sigma \lg n)$ nodes, each of which stores a pointer to the bitmap corresponding to that node. Since each pointer can be represented using $O(\lg n)$ bits, the total space used by the tree structure is $O(\sigma \lg^2 n)$ bits.

To answer a query we use the same algorithm as in the “naive upper bound”, except that when we need a bitmap index that is not explicitly stored, it is computed by merging the bitmaps stored with all the descendants that are in the materialized level immediately below. The weight of a node is used to figure out the total cardinality of the bitmaps to be read from the next materialized level. We store the bitmaps of all the internal nodes at each materialized level by concatenating them in their left-to-right order. The set of all bitmaps to be read at a level form two consecutive chunks in the concatenated sequence of bitmaps. So at each materialized level, and at the leaf level, $O(1)$ I/Os are wasted reading the data that is not needed to form the answer. Assuming that $M = B(\sigma \lg n)^{\Omega(1)}$ we can merge these $O(\sigma \lg n)$ bitmaps in $O(1)$ passes (the weights of the nodes can be used to find the starting positions of the compressed bitmaps), meaning that the number of I/Os is within a constant factor of the I/Os needed to read the individual bitmaps.

We now analyze the query time. Searching the tree W to find all the relevant subtrees to be merged requires $O(\lg_b n)$ I/Os. From these subtrees, one can compute the starting positions and the lengths of all the bitmaps to be read from all the materialized levels (without any additional I/Os). The space needed to represent the compressed bitmap of a node at level i in the tree is bounded by a constant factor (two) times the space used by its lowest ancestor that is stored explicitly (i.e., the ancestor of the node at level $2^{\lceil \lg i \rceil}$). This means that the number of bits we need to read is within a constant factor of the case where all bitmaps are explicitly stored, which is the case analyzed in the “naive upper bound” above. In addition, we waste $O(1)$ I/Os in reading the relevant bitmaps

at each materialized level, and hence overall $O(\lg \lg n)$ I/Os are wasted.

Theorem 2. *A string $\mathbf{x} = x_1x_2 \dots x_n \in \Sigma^n$ over a finite alphabet Σ of size σ can be stored using $O(nH_0 + n + \sigma \lg^2 n)$ bits, where H_0 is the 0th order entropy of \mathbf{x} , such that range queries can be answered in $O(z \lg(n/z)/B + \lg_b n + \lg \lg n)$ I/Os, where z is the cardinality of the answer to the query, assuming $M = B(\sigma \lg n)^{\Omega(1)}$.*

3. Approximate queries

We now consider how to reduce the query time by allowing queries to return false positives, in the spirit of Bloom filters [6, 8]. More precisely, we have a randomized data structure for which a query reports a set $\hat{I}_{[a_l; a_r]} \supseteq I_{[a_l; a_r]}$, where for each $i \notin I_{[a_l; a_r]}$ the probability that $i \in \hat{I}_{[a_l; a_r]}$ is at most ε . The parameter ε is supplied as an argument to the query algorithm. Approximate secondary indexing was recently considered by Apaydin et al. [2], but their query algorithm is optimized for a RAM model meaning that it has many random accesses and thus poor performance in the I/O model. To the best of our knowledge, approximate queries of this kind has not previously been considered in the I/O model (though some weaker results can be obtained in a simple way).

We use the technique of Carter et al. [8], as further developed by Bille et al. [5], for converting the problem of storing a set with ε false positive rate to the problem of storing exactly a set within a smaller universe. Specifically, whenever the exact data structure described in Section 2.2 stores a set of positions $S \subseteq [n]$, the approximate data structure additionally stores a sequence of $k = \lceil \lg \lg n \rceil$ hashed sets $h_1(S), \dots, h_k(S)$, where $h_j : U \rightarrow [2^{2^j}]$ is a function chosen at random from a universal family. The same k functions are used in each node, and we group the sets according to what hash function was used. At a node where a set I is stored, the hashed sets occupy $O(\sum_{j=1}^k \lg \binom{2^{2^j}}{|I|}) = O(\lg \binom{n}{|I|})$ bits. This means that the total space needed to store the hashed sets, as compressed bitmaps, is dominated by the space needed to store S .

When processing a query for the interval $[a_l; a_r]$ the first step is to compute the size z of the result $I_{[a_l; a_r]}$. This can be done efficiently using the weight-balanced B-tree. Then we choose j as the smallest integer such that $2^{2^j} > z/\varepsilon$. If $j > k$ we cannot save anything by returning an approximate result, so we answer the query exactly as described in Section 2.2. Otherwise we compute $h_j(I_{[a_l; a_r]})$ by taking the union of the j th hashed sets (rather than the union of the position sets themselves). By the analysis in Section 2.2 the number of bits read is $O(\lg \binom{2^{2^j}}{z})$, which is $O(z \lg(1/\varepsilon))$ by our choice of j .

Finally, we let $\hat{I}_{[a_l; a_r]}$ be the preimage $h_j^{-1}(h_j(I_{[a_l; a_r]}))$ of the hashed result. For many common universal families the preimage can be computed with a small effort. Note that

we do not want to output the preimage (it is quite large), but only to generate it without using any further I/Os. In the context of high-dimensional range queries it is also important that we can efficiently compute the intersection of several approximate query results, but this is easy: Simply compute the preimage of the intersection.

We describe a well-known and particularly attractive universal family. Split a number $i \in [n]$ into two parts (i_1, i_2) where i_2 is the 2^j least significant bits of i and i_1 is the $\lceil \lg(n+1) \rceil - 2^j$ most significant bits of i . Then take any universal family \mathcal{H} mapping to $[2^j]$, pick $g_j \in \mathcal{H}$ uniformly at random and let $h_j(i_1, i_2) = g_j(i_1) \oplus i_2$ where \oplus denotes bitwise exclusive or. The family from which h_j is chosen can easily be seen to be universal. Then the set of indices (i_1, i_2) that map to $s \in \{0, 1\}^{2^j}$ is $h_j^{-1}(s) = \{(i_1, s \oplus g_j(i_1)) \mid i_1 = 0, 1, 2, \dots\}$.

To argue that the desired error bound is met, consider $i \notin I_{[a_l; a_r]}$. By universality, the probability that $h_j(i) \in h_j(I_{[a_l; a_r]})$ is at most $z/2^j \leq \varepsilon$. Since $i \in \hat{I}_{[a_l; a_r]}$ if and only if $h_j(i) \in h_j(I_{[a_l; a_r]})$ this completes the argument. We get the following approximate variant of Theorem 2.

Theorem 3. *A string $\mathbf{x} = x_1 x_2 \dots x_n \in \Sigma^n$ over a finite alphabet Σ of size σ can be stored using $O(nH_0 + n + \sigma \lg^2 n)$ bits, where H_0 is the 0th order entropy of \mathbf{x} , such that approximate range queries with false positive probability ε can be answered in $O(z \lg(1/\varepsilon)/B + \lg_b n + \lg \lg n)$ I/Os, where z is the cardinality of the answer to the query, assuming $M = B(\sigma \lg n)^{\Omega(1)}$. The I/O bound captures the time for generating the result, but not for outputting it.*

As shown by Carter et al. [8] the space needed to represent a set of size z approximately, with false positive probability ε , is $O(z \lg(1/\varepsilon))$ bits, so the query time is optimal whenever z is not small (e.g., when $z > \lg n$).

4. Supporting updates

Given a string \mathbf{x} over the alphabet Σ , we consider the following update operations, for some $\alpha \in \Sigma$:

- *append*(\mathbf{x}, α): append the character α at the end of \mathbf{x} ,
- *change*(\mathbf{x}, i, α): change the i th character of \mathbf{x} to α .

We note that deletions are indirectly supported through these operations: Extend the alphabet with a new character ∞ that is never matched by a range query. Deleting a character can be done by simply changing it to ∞ . If deletion markers are similarly used in the table being indexed this yields the desired semantics: The positions of characters do not change when deletions are performed. It is, however, simple to extend this to the more natural semantics where character positions are always relative to the current string: Maintain a B-tree over the deleted positions with subtree sizes maintained in all nodes — this allows translating positions

back and forth between the two systems using $O(\log_b n)$ I/Os, and space $O(n)$ bits (positions in leaf nodes should be efficiently encoded, e.g., using gamma-coded differences). If the number of deleted characters exceeds a constant fraction of all characters, global rebuilding is performed to reduce the space. It is easy to see that global rebuilding does not increase the asymptotic (amortized) complexity of the data structure.

4.1 Semi-dynamic version

We first consider only updates that append characters to the end of the string. This is motivated by the fact that OLAP and scientific data, for which bitmap indexes have been shown to be very effective, are typically *read and append only* [16]. We describe two ways to modify the weight balanced B-tree structure used in Section 2.2 to support *append*, achieving different time-space trade-offs.

A straightforward way of supporting updates to the structure described in Section 2.2 is to perform the update on all the bitmaps that are affected by it. Since one bitmap in each materialized level (namely the one corresponding to the last occurrence of that character) will be affected by an update, we need to update $O(\lg \lg n)$ bitmaps. This can be done efficiently by maintaining an array of size $O(\lg \lg n)$ for each character $a \in \Sigma$. The i th entry in the array corresponding to a stores a pointer to the disk block containing the last occurrence of a among all bitmaps at the i th materialized level. We also maintain back pointers so as to update these arrays efficiently whenever the blocks pointed to by the array are reorganized. This requires an additional $O(\sigma \lg \lg n)$ pointers, using $O(\sigma \lg n \lg \lg n)$ bits.

After performing an update, if the weight-balancing condition at a node is violated, then the subtree rooted at the parent of that node is rebuilt to maintain the weight-balancing condition. More formally, let v be a node at level i from the top, and let u be the parent of v . Let v be the highest level node at which the weight-balancing condition is violated after an update. To maintain the weight-balancing condition, we rebuild the subtree rooted at u , and recompute the new bitmaps associated with all the nodes in the subtree. This can be done bottom-up in level order. The bitmaps associated with leaves need not be recomputed. The bitmaps associated with all the nodes at a materialized level can be computed by merging the bitmaps of all the descendants at the materialized level immediately below. Computing the compressed bitmap of a node by merging the compressed bitmaps of all its descendants (in the materialized level immediately below) requires $O(1)$ passes assuming $M = B\sigma^{\Omega(1)}$, where each pass scans all the bitmaps that need to be merged exactly once. Also the size of all the bitmaps at any level within a given subtree is at most the size of all the bitmaps at the leaves within the subtree. Thus overall, the number of I/Os needed to compute the bitmaps of all the nodes in the subtree is at most $\lg \lg n$ (the number of levels) times the number of I/Os needed to scan the bitmaps of all the leaves in the subtree. As the weight of u is $\Theta(n/c^{i-1})$, the size of the bitmaps associated with all the leaves below u is $O((n/c^{i-1}) \lg(c^{i-1}))$ bits. Hence the

cost of scanning the bitmaps associated with all the leaves in the subtree rooted at u is

$$(1/B)(\lg \lg n - i)O((n/c^{i-1}) \lg(c^{i-1})) \text{ I/Os.}$$

The total cost of rebalancing u can be charged to the $\Theta(n/c^i)$ updates performed in the subtree rooted at v (which caused the violation in the weight-balancing condition at v), making the amortized cost of rebalancing $O(\frac{(\lg \lg n)^3}{B})$ which is $O(1/b)$ I/Os.

Thus this structure extends the structure of Theorem 2 by supporting updates in $O(\lg \lg n)$ amortized I/Os (while retaining the space and query bounds).

Theorem 4. *A string $\mathbf{x} = x_1x_2 \dots x_n \in \Sigma^n$ over a finite alphabet Σ of size σ can be stored using $O(nH_0 + n + \sigma \lg^2 n)$ bits to support range queries in $O(z \lg(n/z)/B + \lg \lg n + \lg_b n)$ I/Os, and append in amortized $O(\lg \lg n)$ I/Os.*

4.1.1 Trading off space for faster updates.

To get faster updates, the main idea is to use buffers with the internal nodes to store the updates, similar to buffer trees [3] and buffered B-trees [7, 13], instead of performing them right away. With each internal node of the tree W , we associate a buffer of size B bits. (Note that we also associate buffers with nodes that have no explicitly stored bitmap.) The total space used by all the buffers is $O(B\sigma \lg n)$ bits, as W contains $O(\sigma \lg n)$ nodes, each of which is associated with a buffer of B bits.

We now describe how to support *append*. To perform $\text{append}(\alpha, \mathbf{x})$, we first insert the instruction into the buffer of the root, which is always kept in the internal memory. When the buffer at a node u becomes full, we find a child v of u on which at least a (fixed) constant fraction of these updates have to be performed. Since the degree of each node in W is bounded by $4c$ (a constant), such a node always exists. If node u is stored explicitly, then we perform these updates on the bitmap associated with u . We then delete those updates from the buffer at u and insert them into the buffer at node v . Since the buffer size is B bits, $\Theta(B/\lg n) = \Theta(b)$ updates are moved from u to v . Thus the amortized number of I/Os required to perform an update on all the nodes on a root-to-leaf path is $O(\frac{\lg n}{b})$. The amortized cost of rebalancing the weight-balanced tree can be shown to be $O(\frac{1}{b})$ I/Os as mentioned before (the amortized cost of reading all the buffers in the subtree being rebalanced is negligible).

To answer a query, apart from performing the query algorithm described in Section 2.2, we also need to read each of the buffers associated with all nodes that could potentially contain updates that are part of the answer to the query. Also, whenever we read the bitmap stored at a node, we do not need to look at the buffers associated with any of its descendants, as all the updates stored in the buffers at the descendants of a node have already been performed on the bitmap associated with that node. Hence the number of buffers we need to read to answer a query is only $O(\lg n)$. Thus we have

Theorem 5. *A string $\mathbf{x} = x_1x_2 \dots x_n \in \Sigma^n$ over a finite alphabet Σ of size σ can be stored using $O(nH_0 + n + \sigma \lg n(B + \lg n))$ bits to support range queries in $O(z \lg(n/z)/B + \lg n)$ I/Os, and append in amortized $O(\frac{\lg n}{b})$ I/Os.*

4.2 Buffered compressed bitmap index

Let $\mathbf{x} = x_1x_2 \dots x_n$ be a string over a finite alphabet Σ . Given $\alpha \in \Sigma$, a *point query* returns (a compressed representation of) the set $I_{\{\alpha\}}(\mathbf{x}) = \{i | x_i = \alpha\}$. In this section, we first develop a structure that dynamizes the standard bitmap index while supporting point queries efficiently. We then use this structure (in Section 4.3) to obtain a fully dynamic structure supporting alphabet range queries efficiently. The structure described below supports point queries in $O(\lg n + T/B)$ I/Os where T is the total size of the output, and updates in $O(\frac{\lg n}{b})$ I/Os.

The main idea is to store the compressed bitmaps of all the characters in a buffer tree. First, each bitmap is represented in compressed form as a list of positions of 1s, in increasing order in the bitmap, and this list is stored in a sequence of blocks. The first position in each block is stored as an absolute value, and all the others are stored relative to the previous position (i.e., the gaps are encoded) using gamma codes. We concatenate the representations of all bitmaps together and store them as a sequence of blocks.

Let $s = O(nH_0/B)$ be the number of blocks used by the compressed bitmaps of all the characters. Assuming $B \geq 4 \lg n$, we can bound the number of blocks used by the representation described in the previous paragraph in terms of s . Store the compressed bitmaps of all the characters with blocks of $B/2$ bits each, and hence an overall $2s$ blocks. By increasing the block size to $B/2 + 2 \lg n$, we can make the first gamma code in each block to be an absolute value instead of the being relative to the previous position (using at most $\lg n$ additional bits), and the last code to be completely contained within the block in case it is split between two adjacent blocks (by using an additional $\lg n$ bits). Thus the new representation of the blocks requires at most $2s$ blocks of size at most B bits each.

With these blocks as the leaves, we construct a tree with branching factor c , for some fixed constant $c \geq 2$. With each internal node of this tree, we associate a buffer of size B bits that stores a set of updates that are yet to be performed in one of the leaves in the subtree rooted at that node. Each non-leaf block also stores an identifier for the first bitmap that is (partially) stored in the subtree, to allow fast navigation to a particular bitmap.

An update is simply stored in the buffer corresponding to the root, which is always kept in the internal memory. Whenever a buffer becomes full, a constant fraction of the updates in that buffer are moved to one of its children. The amortized cost of updates can be shown to be $O(\frac{\lg n}{b})$ I/Os as before. The space usage of this structure is of the same order as the total space used by all the individual compressed bitmaps, as the space usage is dominated by the leaf level bitmaps.

A point query can be answered by following a root-to-leaf path in the tree followed by reading the compressed bitmap stored in the consecutive leaves starting at the end of the search path. In addition, we also need to merge this compressed bitmap with all the updates corresponding to the character, stored in the buffers. The number of buffers storing updates corresponding to a given character can be shown to be $O(T/B + \lg n)$ where T is the size of the compressed bitmap of the given character. Assuming $M \geq B \lg n$, we can perform this merging in $O(1)$ passes. Thus we have

Theorem 6. *A string $\mathbf{x} = x_1x_2 \dots x_n \in \Sigma^n$ over a finite alphabet Σ of size σ can be stored using $O(nH_0)$ bits to support point queries in $O(T/B + \lg n)$ I/Os, where T is the size of the answer (assuming $M \geq B \lg n$), and updates in amortized $O(\frac{\lg n}{b})$ I/Os.*

4.3 Fully dynamic version

We first observe that all the bitmaps stored at any particular materialized level of the optimal space structure described in Section 2.2 can be thought of as representing a bitmap index over an alphabet containing one character corresponding to each node in that level. Thus we can obtain a fully dynamic secondary bitmap index by representing each of the materialized levels as a buffered bitmap index.

More formally, we represent all the bitmaps at each materialized level of the structure described in Section 2.2 using buffered bitmap index structure. The total space usage is $O(nH_0 + n + \sigma \lg^2 n)$ bits (for representing all the bitmaps in all the materialized levels, and for the tree structure). To perform an update we perform it on each of the $O(\lg \lg n)$ materialized levels. Thus updates take amortized $O(\frac{\lg n \lg \lg n}{b})$ I/Os. An alphabet range query can be decomposed into $O(1)$ point queries on each materialized level, and can be answered using $O(\lg n \lg \lg n + z \lg(n/z)/B)$ I/Os, where z is the cardinality of the answer to the range query.

Theorem 7. *A string $\mathbf{x} = x_1x_2 \dots x_n \in \Sigma^n$ over a finite alphabet Σ of size σ can be stored using $O(nH_0 + n + \sigma \lg^2 n)$ bits to support range queries in $O(z \lg(n/z)/B + \lg n \lg \lg n)$ I/Os, and updates in amortized $O(\frac{\lg n \lg \lg n}{b})$ I/Os.*

One can also achieve other trade-offs between space and operation times by choosing to store all the levels of W explicitly and using buffers at the internal nodes.

4.4 Conclusion and open problems

We have formalized the secondary indexing problem, giving a unified view of bitmap indexes and indexes such as B-trees typically used for range queries.

For range queries that return a “dense” subset of $\{1, \dots, n\}$ the number of I/Os to answer a query is up to a factor $\log n$ smaller than any data structure that returns explicit row IDs

(e.g. B-trees). From a practical perspective, it would be interesting to investigate if the ideas of this paper can be engineered to yield improvements on real data and queries. In particular, this would probably require careful consideration of CPU costs for handling optimally compressed bitmaps.

An obvious theoretical problem is whether results analogous to the ones in this paper can be shown for other kinds of indexes, e.g. indexes for multi-dimensional orthogonal range queries.

5. References

- [1] Alok Aggarwal and Jeffrey S. Vitter. The input/output complexity of sorting and related problems. *Comm. ACM*, 31(9):1116–1127, 1988.
- [2] Tan Apaydin, Guadalupe Canahuate, Hakan Ferhatosmanoglu, and Ali Saman Tosun. Approximate encoding for direct access and query processing over compressed bitmaps. In *Proceedings of the 32nd International Conference on Very Large Data Bases*, pages 846–857. ACM, 2006.
- [3] Lars Arge. The buffer tree: A technique for designing batched external data structures. *Algorithmica*, 37(1):1–24, 2003.
- [4] Lars Arge and Jeffrey Scott Vitter. Optimal external memory interval management. *SIAM Journal on Computing*, 32(6):1488–1508, December 2003.
- [5] Philip Bille, Anna Pagh, and Rasmus Pagh. Fast evaluation of union-intersection expressions. In *Proceedings of the 18th International Symposium on Algorithms And Computation (ISAAC '07)*, volume 4835 of *Lecture Notes in Computer Science*, pages 739–750. Springer-Verlag, 2007.
- [6] Burton H. Bloom. Space/time trade-offs in hash coding with allowable errors. *Communications of the ACM*, 13(7):422–426, July 1970.
- [7] Gerth Stølting Brodal and Rolf Fagerberg. Lower bounds for external memory dictionaries. In *Proc. 14th Annual ACM-SIAM Symposium on Discrete Algorithms*, pages 546–554, 2003.
- [8] Larry Carter, Robert Floyd, John Gill, George Markowsky, and Mark Wegman. Exact and approximate membership testers. In *Proceedings of Symposium on Theory of Computation (STOC '78)*, pages 59–65. ACM Press, 1978.
- [9] Chee-Yong Chan and Yannis E. Ioannidis. Bitmap index design and evaluation. In *Proceedings of the 1998 ACM SIGMOD International Conference on Management of Data: June 1–4, 1998, Seattle, Washington, USA*, volume 27(2) of *SIGMOD Record (ACM Special Interest Group on Management of Data)*, pages 355–366. ACM Press, 1998.
- [10] Chee-Yong Chan and Yannis E. Ioannidis. An efficient bitmap encoding scheme for selection queries. In *Proceedings of the 1999 ACM SIGMOD International Conference on Management of Data: SIGMOD '99, Philadelphia, PA, USA, June 1–3, 1999*, volume 28(2) of *SIGMOD Record (ACM Special Interest Group on Management of Data)*, pages 215–226. ACM Press, 1999.
- [11] M. de Berg, O. Cheong, M. van Kreveld, and M. Overmars. *Computational Geometry: Algorithms and Applications*. Springer-Verlag, January 2007.
- [12] P. Elias. Universal codeword sets and representations of the integers. *IEEE Transactions on Information Theory*, 21(2):194–203, March 1975.
- [13] Goetz Graefe. B-tree indexes for high update rates. *SIGMOD Record (ACM Special Interest Group on Management of Data)*, 35(1):39–44, March 2006.
- [14] Patrick O’Neil and Dallan Quass. Improved query performance with variant indexes. In *Proceedings, ACM SIGMOD International Conference on Management of Data: SIGMOD 1997: May 13–15, 1997, Tucson, Arizona, USA*, volume 26(2) of *SIGMOD Record (ACM Special Interest Group on Management of Data)*, pages 38–49. ACM Press, 1997.
- [15] Vijayshankar Raman, Lin Qiao, Wei Han, Inderpal Narang, Ying-Lin Chen, Kou-Horng Yang, and Fen-Ling Ling. Lazy, adaptive rid-list intersection, and its application to index anding. In *SIGMOD '07: Proceedings of the 2007 ACM SIGMOD international conference on Management of data*, pages 773–784, New York, NY, USA, 2007. ACM.
- [16] Rishi Rakesh Sinha and Marianne Winslett. Multi-resolution bitmap indexes for scientific data. *ACM Trans. Database Syst.*, 32(3):16, 2007.
- [17] Rishi Rakesh Sinha, Marianne Winslett, Kesheng Wu, Kurt Stockinger, and Arie Shoshani. Adaptive bitmap indexes for space-constrained systems. In *ICDE*, pages 1418–1420. IEEE, 2008.
- [18] Kesheng Wu, Ekow J. Otoo, and Arie Shoshani. On the performance of bitmap indices for high cardinality attributes. In *Proceedings of the 30th International Conference on Very Large Data Bases (VLDB)*, pages 24–35. Morgan Kaufmann, 2004.