Database Technology
Indexing and Hashing
Previously on Database Technology

• We can find information in databases
  – e.g., employees by name:
    SELECT * FROM employee WHERE name = ‘Brandt’
  – e.g., employees within a range of salary
    SELECT * FROM employee WHERE salary > 50000
Finding Information in Databases

- How does that work, actually?
  - `SELECT * FROM employee WHERE name = 'Brandt'

- Naive approach (called *linear search*):
  - Go through the table from top to bottom
  - Find and return all employees with name ‘Brandt’

- Complexity:
  - If there are N records in the table, this takes (up to) N steps
  - We call this complexity: O(N)
  - Note that even if we find a “Brandt” earlier, we need to search further, since there might be more people named “Brandt”
Finding Information in Databases

- How does that work, actually?
  - SELECT * FROM employee WHERE name = 'Brandt'

- Better approach
  - Let’s assume we have sorted the table by name
  - We can now apply *binary search*
    - Get element in the middle of the table
    - If the searched element is “smaller”
      - Search the upper half table
    - Else
      - Search the lower half table
Finding Information in Databases

- Binary search
  - Works in $O(\log_2 N)$
- However
  - Sorting the table requires $O(N \times \log_2 N)$
  - This pays off only if we sort once and query often

- What if our next query is
  ```
  SELECT * FROM employee WHERE salary > 50000
  ```
- Now, the table is sorted by name, not salary
  - If we re-sort before every query, it gets even worse than by linear search
Finding Information in Databases

• Naive solution
  – Provide copies of each table sorted by each attribute we may need

• Hey, wait…
  – We’ve always tried to reduce redundancy
  – Not to increase it…

• More sophisticated solution:
  – Index structures
Index Files

• Index files
  – Provide a compromise between re-sorting
  – and copying the table

• Idea
  – Provide a sorted file of a single attribute only
    • Allows linear search
  – Index file contains pointers to actual file
    • Which may or may not be sorted
Index Files

• Basic idea
  – Search in index is $O(\log_2 N)$
  – Following link is $O(1)$
  – Each index can remain sorted
  – Create an index for each attribute which you may use in a query

• Trade-off
  – Faster queries
  – Some redundancy
    • But this is handled by the DBMS!
    • i.e., mainly a storage capacity problem, not so much a consistency problem
Index Files and Joins

• Understanding the need for an index file
  – Analyzing possible queries
  – Search attributes are quite straightforward

• Second use case: joins

• Suppose we want to query for the building of an instructor by name
  – *name* on *instructor* is straightforward for an index candidate
  – Query processing:
    • find instructor by name
    • read *dept_name*
    • look up *dept_name* in *department*

  hence, we need an index on *dept_name* in *department*!
Index Files – Basic Concepts

• Indexing mechanisms used to speed up access to desired data
  – e.g., searching by a specific attribute
  – but also: joins!

• Search Key - attribute to set of attributes used to look up records in a file
  – An index file consists of records (called index entries) of the form

   search-key | pointer

• Two basic kinds of indices:
  – Ordered indices: search keys are stored in sorted order
  – Hash indices: search keys are distributed uniformly across “buckets” using a “hash function”
Metrics for Evaluating Index Structures

• Access types supported efficiently
  – records with a specified value in the attribute
  – or records with an attribute value falling in a specified range of values

• Access time

• Insertion time
  – Note: index needs to be updated as well

• Deletion time
  – Note: may require deletion from index

• Storage space overhead
Ordered Indices

• In an ordered index, index entries are stored sorted on the search key value
  – Allows $O(\log_2 N)$ search

• Primary index: in a sequentially ordered file, the index whose search key specifies the sequential order of the file
  – Also called clustering index
  – Search key: usually (but not necessarily) the primary key

• Secondary index: an index whose search key specifies an order different from the sequential order of the file
  – Also called non-clustering index
Dense vs. Sparse Index Files

- Dense index: index record appears for every search-key value
  - e.g., index on ID attribute of instructor relation

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Department</th>
<th>Salary</th>
</tr>
</thead>
<tbody>
<tr>
<td>10101</td>
<td>Srinivasan</td>
<td>Comp. Sci.</td>
<td>65000</td>
</tr>
<tr>
<td>12121</td>
<td>Wu</td>
<td>Finance</td>
<td>90000</td>
</tr>
<tr>
<td>15151</td>
<td>Mozart</td>
<td>Music</td>
<td>40000</td>
</tr>
<tr>
<td>22222</td>
<td>Einstein</td>
<td>Physics</td>
<td>95000</td>
</tr>
<tr>
<td>32343</td>
<td>El Said</td>
<td>History</td>
<td>60000</td>
</tr>
<tr>
<td>33456</td>
<td>Gold</td>
<td>Physics</td>
<td>87000</td>
</tr>
<tr>
<td>45565</td>
<td>Katz</td>
<td>Comp. Sci.</td>
<td>75000</td>
</tr>
<tr>
<td>58583</td>
<td>Califieri</td>
<td>History</td>
<td>62000</td>
</tr>
<tr>
<td>76543</td>
<td>Singh</td>
<td>Finance</td>
<td>80000</td>
</tr>
<tr>
<td>76766</td>
<td>Crick</td>
<td>Biology</td>
<td>72000</td>
</tr>
<tr>
<td>83821</td>
<td>Brandt</td>
<td>Comp. Sci.</td>
<td>92000</td>
</tr>
<tr>
<td>98345</td>
<td>Kim</td>
<td>Elec. Eng.</td>
<td>80000</td>
</tr>
</tbody>
</table>
Dense vs. Sparse Index Files

- Dense index: index record appears for every search-key value
  - e.g., index on *department* attribute of *instructor* relation

<table>
<thead>
<tr>
<th>Department</th>
<th>ID</th>
<th>Name</th>
<th>Department</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biology</td>
<td>76766</td>
<td>Crick</td>
<td>Biology</td>
</tr>
<tr>
<td>Comp. Sci.</td>
<td>10101</td>
<td>Srinivasan</td>
<td>Comp. Sci.</td>
</tr>
<tr>
<td>Elec. Eng.</td>
<td>45565</td>
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<td>Finance</td>
<td>83821</td>
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<td>History</td>
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<tr>
<td></td>
<td>32343</td>
<td>El Said</td>
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<td>Mozart</td>
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<td></td>
<td>22222</td>
<td>Einstein</td>
<td>Physics</td>
</tr>
<tr>
<td></td>
<td>33465</td>
<td>Gold</td>
<td>Physics</td>
</tr>
</tbody>
</table>
Dense vs. Sparse Index Files

- **Sparse Index**: contains index records for only some values
  - Applicable when records are sequentially ordered on search-key
- To locate a record with search-key value $K$ we:
  - Find index record with largest search-key value $< K$
  - Search file sequentially starting at that record
Dense vs. Sparse Index Files

• Dense index
  – Guaranteed search time of $O(\log_2 N)$
  – Requires $O(N)$ storage space

• Sparse index (storing every k-th value)
  – Search time $O(\log_2 N + \log_2 k)$
  – Requires $O(N/k)$ storage time

• Comparison
  – Dense index is faster
  – Sparse index takes less space
Secondary Index

• Frequently, one wants to find all the records whose values in a certain field (which is not the search-key of the primary index) satisfy some condition
  – Example 1: In the instructor relation stored sequentially by ID, we may want to find all instructors in a particular department
  – Example 2: as above, but where we want to find all instructors with a specified salary or with salary in a specified range of values

• We can have a secondary index with an index record for each search-key value
Secondary Index

- Primary index: index on the attribute by which a file is ordered
- Secondary index: index on any other attribute
  - Index record points to a bucket that contains pointers to all the actual records with that particular search-key value
  - Secondary indices have to be dense — why?
Multi-Level Indices

• Computer storage:
  – RAM: fast, but limited
  – Disk: slow, but large

• Fast access
  – Keep primary index in memory, actual data on disk

• What if the primary index does not fit in memory?
  – Treat primary index kept on disk as a sequential file
  – Construct a sparse index on it, keep that index in memory

• Outer vs. inner index
  – outer index – a sparse index of primary index
  – inner index – the primary index file
Insertion into Index

• Single-level index insertion
  – Perform a lookup using the search-key value appearing in the record to be inserted
  – Dense indices – if the search-key value does not appear in the index, insert it
  – Sparse indices – if index stores an entry for each block of the file, no change needs to be made to the index unless a new block is created
    • If a new block is created, the first search-key value appearing in the new block is inserted into the index

• Multilevel insertion: algorithms are simple extensions of the single-level algorithms
Deletion from Index

- If deleted record was the only record in the file with its particular search-key value, the search-key is deleted from the index also.

- Single-level index entry deletion:
  - Dense indices – deletion of search-key is similar to file record deletion
  - Sparse indices
    - if an entry for the search key exists in the index, it is deleted by replacing the entry in the index with the next search-key value in the file (in search-key order)
    - If the next search-key value already has an index entry, the entry is deleted instead of being replaced

- Multilevel deletion: algorithms are simple extensions of the single-level algorithms
Summary Sequential Indices

• Access time: $O(\log_2 N)$
• Insertion time: $O(N)$
  – worst case: insertion at the top, all other entries need to be moved down
• Deletion time: $O(N)$
  – worst case: deletion from the top, all other entries need to be moved up
B⁺-Tree Index Files

• Disadvantage of indexed-sequential files
  – performance degrades as file grows, since many overflow blocks get created.
  – Periodic reorganization of entire file is required

• Advantage of B⁺-tree index files:
  – automatically reorganizes itself with small, local, changes, in the face of insertions and deletions
  – Reorganization of entire file is not required to maintain performance

• (Minor) disadvantage of B⁺-trees:
  – extra insertion and deletion overhead, space overhead

• Advantages of B⁺-trees outweigh disadvantages
• B⁺-trees are used extensively
• A B⁺-tree is a rooted tree satisfying the following properties:
  – All paths from root to leaf are of the same length
  – Each node that is not a root or a leaf has between $\lceil n/2 \rceil$ and $n$ children
  – A leaf node has between $\lceil (n−1)/2 \rceil$ and $n−1$ values
• Special cases:
  – If the root is not a leaf, it has at least 2 children.
  – If the root is a leaf (that is, there are no other nodes in the tree), it can have between 0 and $(n−1)$ values.
B\textsuperscript{+}-Trees: Example

\begin{itemize}
  \item \textbf{Root node}: Mozart
  \item \textbf{Internal nodes}: Einstein, Srinivasan, El Said, Katz, Kim
  \item \textbf{Leaf nodes}: Brandt, Califieri, Crick, Gold, Mozart, Singh, Wu, Srinivasan, Wu
\end{itemize}

\begin{tabular}{|c|c|c|c|}
  \hline
  ID & Name & Major & Salary \\
  \hline
  10101 & Srinivasan & Comp. Sci. & 65000 \\
  12121 & Wu & Finance & 90000 \\
  15151 & Mozart & Music & 40000 \\
  22222 & Einstein & Physics & 95000 \\
  32343 & El Said & History & 80000 \\
  33456 & Gold & Physics & 87000 \\
  45565 & Katz & Comp. Sci. & 75000 \\
  58583 & Califieri & History & 60000 \\
  76543 & Singh & Finance & 80000 \\
  76766 & Crick & Biology & 72000 \\
  83821 & Brandt & Comp. Sci. & 92000 \\
  98345 & Kim & Elec. Eng. & 80000 \\
  \hline
\end{tabular}
B⁺-Trees: Example

- Example: n=4
  - All paths from root to leaf are of the same length
  - Each node that is not a root or a leaf has between $\lceil n/2 \rceil = 2$ and n=4 children
  - A leaf node has between $\lceil (n-1)/2 \rceil = 2$ and n–1=3 values
  - Root has at least 2 children
B⁺-Tree Node Structure

• Typical node

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>$K_1$</td>
<td>$P_2$</td>
<td>...</td>
<td>$P_{n-1}$</td>
<td>$K_{n-1}$</td>
</tr>
<tr>
<td>$P_n$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• $K_i$ are the search-key values

• $P_i$ are pointers to children (for non-leaf nodes)
or pointers to records or buckets of records (for leaf nodes)

• The search-keys in a node are ordered

\[ K_1 < K_2 < K_3 < \ldots < K_{n-1} \]

  – for the moment: assuming there are no duplicate keys,
    but extension to handling duplicate keys is easily possible
Leaf Nodes in $B^+$-Trees

- For $i = 1, 2, \ldots, n-1$, pointer $P_i$ points to a file record with search-key value $K_i$.
- If $L_i$, $L_j$ are leaf nodes and $i < j$, $L_i$’s search-key values are less than or equal to $L_j$’s search-key values.
- $P_n$ points to next leaf node in search-key order.
Inner Nodes in $B^+$-Trees

- Properties of an inner node with $m$ entries:
  - All the search-keys in the subtree to which $P_1$ points are less than $K_1$
  - For $2 \leq i \leq n - 1$, all the search-keys in the subtree to which $P_i$ points have values greater than or equal to $K_{i-1}$ and less than $K_i$
  - All the search-keys in the subtree to which $P_n$ points have values greater than or equal to $K_{n-1}$
Observations about B⁺-Trees

- Since the inter-node connections are done by pointers, “logically” close blocks need not be “physically” close
- The non-leaf levels of the B⁺-tree form a hierarchy of sparse indices
- The B⁺-tree contains a relatively small number of levels
  - Level below root has at least $2^* \lceil n/2 \rceil$ values
  - Next level has at least $2^* \lceil n/2 \rceil \times \lceil n/2 \rceil$ values
    - .. etc.
  - If there are $K$ search-key values in the file, the tree height is no more than $\lceil \log_{\lceil n/2 \rceil}(K) \rceil$
    - thus searches can be conducted efficiently
- Insertions and deletions to the main file can be handled efficiently (as we shall see)
Querying $B^+$-Trees

- Given a search value $V$ (e.g., “Einstein”)
  - In non-leaf nodes: follow non-null pointers $P_i$ where $V < K_i$, so that $i$ maximal
  - In leaf nodes: if there is a value $K_i = V$, follow $P_i$
- else: record does not exist
Querying B$^+$-Trees

• If there are $K$ search-key values in the file, the height of the tree is no more than $\left\lceil \log_{\frac{n}{2}}(K) \right\rceil$
  – i.e., this is the number of leaf nodes to inspect
  – supposing a disk-based index: the number of nodes to be retrieved

• A node is generally the same size as a disk block, typically 4 kilobytes
  – and $n$ is typically around 100 (40 bytes per index entry)

• With 1 million search key values and $n = 100$
  – at most $\log_{50}(1,000,000) = 4$ nodes are accessed in a lookup

  disk I/O is the crucial factor here
Updates on B⁺-Trees: Insertion

- Find the leaf node in which the search-key value would appear
- If the search-key value is already present in the leaf node
  - add record to the file
  - if necessary, add a pointer to the bucket
- If the search-key value is not present, then
  - add the record to the main file (and create a bucket if necessary)
  - If there is room in the leaf node
    - insert (key-value, pointer) pair in the leaf node
  - else
    - split the node (along with the new (key-value, pointer) entry) as discussed in the next slide.
Updates on B⁺-Trees: Insertion

• Splitting a leaf node:
  – take the $n$ (search-key value, pointer) pairs (including the one being inserted) in sorted order. Place the first $\lceil n/2 \rceil$ in the original node, and the rest in a new node $p$
  – let $k$ be the least key value in $p$. Insert $(k,p)$ in the parent of the node being split.
  – If the parent is full, split it and propagate the split further up.

• Splitting of nodes proceeds upwards till a node that is not full is found
  – In the worst case (i.e., root is full) the root node may be split increasing the height of the tree by 1

Result of splitting node containing Brandt, Califieri, Crick on inserting Adams
Next step: insert entry with (Califieri, pointer-to-new-node) into parent
Updates on B*-Trees: Insertion

• Inserting “Adams”
Updates on B⁺-Trees: Insertion

• Inserting “Lamport”
Updates on $B^+$-Trees: Deletion

- Find the record to be deleted, and remove it from the main file and from the bucket (if present)
- Remove (search-key value, pointer) from the leaf node if there is no bucket or if the bucket has become empty
- If the node has too few entries due to the removal, and the entries in the node and a sibling fit into a single node, then *merge siblings*
- Otherwise, if the node has too few entries due to the removal, but the entries in the node and a sibling do not fit into a single node, then *redistribute pointers*
Updates on B\(^+\)-Trees: Deletion

- **Merge siblings**
  - Insert all the search-key values in the two nodes into a single node (the one on the left), and delete the other node
  - Delete the pair \((K_{i-1}, P_i)\), where \(P_i\) is the pointer to the deleted node, from its parent, recursively using the above procedure

- **Redistribute pointers**
  - Redistribute the pointers between the node and a sibling such that both have more than the minimum number of entries
  - Update the corresponding search-key value in the parent of the node

- The node deletions may cascade upwards till a node which has \(\lceil n/2 \rceil\) or more pointers is found
  - If the root node has only one pointer after deletion, it is deleted and the sole child becomes the root
Updates on B⁺-Trees: Deletion

- Deleting “Srinivasan”

Diagram showing the process of deleting “Srinivasan” from a B⁺-tree, highlighting the updated node and the merged leaf.
Indexing Strings

- Variable length strings as keys
  - Variable fanout
  - Use space utilization as criterion for splitting, not number of pointers

- Prefix compression
  - Key values at internal nodes can be prefixes of full key
    - Keep enough characters to distinguish entries in the subtrees separated by the key value
      - E.g. “Silas” and “Silberschatz” can be separated by “Silb”
    - Keys in leaf node can be compressed by sharing common prefixes
Bulk Loading into $B^+$-Trees

• Inserting entries one-at-a-time into a $B^+$-tree requires $\geq 1$ IO per entry
  – assuming leaf level does not fit in memory
  – can be very inefficient for loading a large number of entries at a time (bulk loading)

• Efficient alternative 1:
  – sort entries first, insert in sorted order
  – heavy reorganizations are avoided
  – much improved IO performance, but most leaf nodes half full

• Efficient alternative 2: **Bottom-up $B^+$-tree construction**
  – As before sort entries
  – And then create tree layer-by-layer, starting with leaf level
  – Implemented as part of bulk-load utility by most database systems
Bulk Loading into $B^+$-Trees

• Bottom-up bulk loading
  – Leads to a compact tree representation
  – Fast, since no reorganizations are required

• Start with ordered sequence
  – Create full leaves
  – Create upper levels
Indices on Multiple Attributes

- Use multiple indices for certain types of queries
- Example:

  ```sql
  select ID
  from instructor
  where dept_name = "Finance" and salary = 80000
  ```

- Possible strategies for processing query using indices on single attributes:
  1. Use index on `dept_name` to find instructors with department name Finance; test `salary = 80000`
  2. Use index on `salary` to find instructors with a salary of $80000; test `dept_name = "Finance"`
  3. Use both indices, take intersection of sets of pointers obtained
Indices on Multiple Attributes

• Composite search keys are search keys containing more than one attribute
  – e.g. (dept_name, salary)

• Lexicographic ordering: \((a_1, a_2) < (b_1, b_2)\) if either
  – \(a_1 < b_1\), or
  – \(a_1=b_1\) and \(a_2 < b_2\)

• Use this ordering to create an index (sequential or \(B^+\)-tree)
Indices on Multiple Attributes

• Suppose we have an index on (dept_name, salary)
• With the where clause
  \textbf{where} \textit{dept\_name} = “Finance” \textbf{and} \textit{salary} = 80000
  the index on (\textit{dept\_name}, \textit{salary}) can be used to fetch only records
  that satisfy both conditions
• Using separate indices in less efficient — we may fetch many
  records (or pointers) that satisfy only one of the conditions
Indices on Multiple Attributes

• Note:
  – Ordering is sensitive to order of attributes
  – i.e., (salary,dept_name) would lead to a different ordering!

• With (dept_name,salary), we can efficiently retrieve
  \[ dept\_name = \text{“Finance”} \text{ and } salary < 80000 \]

• But not
  \[ dept\_name < \text{“Finance”} \text{ and } balance = 80000 \]

• Ordering of index is by dept_name first, then salary
Multi-Attribute Indices vs. Multiple Indices

- Multi-Attribute are faster than multiple indices
  - Make sure you only retrieve the records you are interested in
  - Avoid unnecessary lookups, comparisons, and/or intersections

- On the other hand
  - Storing an index for all combinations of attributes would be costly
  - Think: storage capacity
  - Think: cost of insert/update/delete operations

- Typical considerations
  - Heavily used attribute combinations
  - Expected runtime disadvantage of individual indices
Indexing vs. Hashing

• Index structures:
  – Look up value
  – Retrieve storage location (e.g., row number in table)

• Hashing:
  – Compute storage location directly from the value using a *hash function*
Static Hashing

• A **bucket** is a unit of storage containing one or more records (a bucket is typically a disk block)

• In a **hash file organization** we obtain the bucket of a record directly from its search-key value using a **hash function**

• Hash function $h$ is a function from the set of all search-key values $K$ to the set of all bucket addresses $B$

• Hash function is used to locate records for access, insertion as well as deletion

• Records with different search-key values may be mapped to the same bucket; thus entire bucket has to be searched sequentially to locate a record
Example for a Hash Function

- There are 10 buckets
- The binary representation of the $i$th character is assumed to be the integer $i$
- The hash function returns the sum of the binary representations of the characters modulo 10
- e.g., $h(\text{Music}) = 1$  $h(\text{History}) = 2$  $h(\text{Physics}) = 3$  $h(\text{Elec. Eng.}) = 3$
A hash function should be
- *uniform*, i.e., each bucket is assigned the same number of search-key values
- *random*, i.e., the size of buckets should be independent of the actual distribution of search-key values
  - e.g., language is not uniformly distributed

Worst case hash function maps all search-key values to the same bucket
- access time proportional to the number of search-key values in the file

Typical hash functions perform computation on the internal binary representation of the search-key
- e.g., for a string search-key, the binary representations of all the characters in the string could be added and the sum modulo the number of buckets could be returned
Bucket Overflow

• Typical implementation:
  – Buckets have fixed size (e.g., block size on disk)
• Bucket overflow: insufficient bucket for records to store
• Possible reasons:
  – multiple records have same search-key value
  – chosen hash function produces non-uniform distribution of key values
• Bucket overflow cannot be avoided completely
  – Solution: use overflow buckets
• ...but its probability can be minimized by the choice of a good (i.e., almost uniform) hash function and suitable bucket size
Bucket Overflow

- **Overflow chaining** (also called *closed hashing*)
  - the overflow buckets of a given bucket are chained together in a linked list

![Diagram of bucket chaining](image)
Hash Indices

- Hashing can be used not only for file organization, but also for index-structure creation
  
  - A **hash index** organizes the search keys, with their associated record pointers, into a hash file structure.
Drawbacks of Static Hashing

• In static hashing, function $h$ maps search-key values to a fixed set of $B$ of bucket addresses
  – But databases may grow or shrink over time

• Growing database
  – performance degrades due to many overflow buckets

• Shrinking database
  – space is wasted by underfull buckets

• Possible solution: periodic re-organization of the file with a new hash function
  – Expensive, disrupts normal operations

• Better solution
  – allow the number of buckets to be modified dynamically
  – aka dynamic hashing
Dynamic Hashing

• Good for database that grows and shrinks in size
• Allows the hash function to be modified dynamically
• **Extendable hashing** – one form of dynamic hashing
  – Hash function generates values over a large range
  – Typically $b$-bit integers, e.g., $b = 32$.
• At any time use only a prefix of the hash function to index into a table of bucket addresses
  – Let the length of the prefix be $i$ bits, $0 \leq i \leq 32$.
  – Bucket address table size = $2^i$. Initially $i = 0$
• Value of $i$ grows and shrinks as the size of the database grows and shrinks
• Multiple entries in the bucket address table may point to a bucket (why?)
  – Thus, actual number of buckets is $< 2^i$
  – Number of buckets also changes dynamically by merging and splitting buckets
Extendable Hash Structure

- Example:
  - more hash values with prefix “1” than with prefix “0”
Extendable Hashing

- Each bucket $j$ stores a value $i_j$
- All the entries that point to the same bucket have the same values on the first $i_j$ bits.
- To locate the bucket containing search-key $K_j$:
  1. Compute $h(K_j) = X$
  2. Use the first $i$ bits of $X$ as a displacement into bucket address table, and follow the pointer to appropriate bucket
- To insert a record with search-key value $K_j$
  - follow same procedure as look-up and locate the bucket, say $j$
  - If there is room in the bucket $j$ insert record in the bucket
  - else the bucket must be split and insertion re-attempted
- Deletion may cause a merge of buckets
- Overflow buckets may still be needed for key collisions
Extendable Hashing – Example

- Bucket size: 2

<table>
<thead>
<tr>
<th>dept_name</th>
<th>h(dept_name)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biology</td>
<td>0010 1101 1111 1011 0010 1100 0011 0000</td>
</tr>
<tr>
<td>Comp. Sci.</td>
<td>1111 0001 0010 0100 1001 0011 0110 1101</td>
</tr>
<tr>
<td>Elec. Eng.</td>
<td>0100 0011 1010 1100 1100 0110 1101 1111</td>
</tr>
<tr>
<td>Finance</td>
<td>1010 0011 1010 0000 1100 0110 1001 1111</td>
</tr>
<tr>
<td>History</td>
<td>1100 0111 1110 1101 1011 1111 0011 1010</td>
</tr>
<tr>
<td>Music</td>
<td>0011 0101 1010 0110 1100 1001 1110 1011</td>
</tr>
<tr>
<td>Physics</td>
<td>1001 1000 0011 1111 1001 1100 0000 0001</td>
</tr>
</tbody>
</table>
Extendable Hashing – Example

- After insertion of Mozart, Srinivisan, Wu

```
<table>
<thead>
<tr>
<th>dept_name</th>
<th>h(dept_name)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biology</td>
<td>0010 1101 1111 1011 0010 1100 0011 0000</td>
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<td>1111 0001 0010 0100 1001 0011 0110 1101</td>
</tr>
<tr>
<td>Elec. Eng.</td>
<td>0100 0011 1010 1100 1100 0110 1101 1111</td>
</tr>
<tr>
<td>Finance</td>
<td>1010 0011 1010 0000 1100 0110 1001 1111</td>
</tr>
<tr>
<td>History</td>
<td>1100 0111 1110 1101 1011 1111 0011 1010</td>
</tr>
<tr>
<td>Music</td>
<td>0011 0101 1010 0110 1100 1001 1110 1011</td>
</tr>
<tr>
<td>Physics</td>
<td>1001 1000 0011 1111 1001 1100 0000 0001</td>
</tr>
</tbody>
</table>
```

Bucket 0

| 15151 | Mozart | Music | 40000 |

Bucket 1

| 10101 | Srinivisan | Comp.Sci | 90000 |
| 12121 | Wu         | Finance  | 90000 |
Extendable Hashing – Example

• After insertion of Einstein

Pointers to same bucket

Bucket 0

<table>
<thead>
<tr>
<th>15151</th>
<th>Mozart</th>
<th>Music</th>
<th>40000</th>
</tr>
</thead>
</table>

Bucket 1

<table>
<thead>
<tr>
<th>12121</th>
<th>Wu</th>
<th>Finance</th>
<th>90000</th>
</tr>
</thead>
<tbody>
<tr>
<td>22222</td>
<td>Einstein</td>
<td>Physics</td>
<td>95000</td>
</tr>
</tbody>
</table>

Bucket 2

<table>
<thead>
<tr>
<th>10101</th>
<th>Srinivisan</th>
<th>Comp.Sci</th>
<th>90000</th>
</tr>
</thead>
</table>

Bucket 0, 1, and 2 illustrate the insertion of different records into buckets, with pointers to the same bucket indicating a collision resolution technique.
Extendable Hashing – Example

- After insertion of Gold, El Said

<table>
<thead>
<tr>
<th>Bucket 0</th>
<th>Bucket 1</th>
<th>Bucket 2</th>
<th>Bucket 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>15151</td>
<td>Mozart</td>
<td>Music</td>
<td>40000</td>
</tr>
<tr>
<td>22222</td>
<td>Einstein</td>
<td>Physics</td>
<td>95000</td>
</tr>
<tr>
<td>33456</td>
<td>Gold</td>
<td>Physics</td>
<td>87000</td>
</tr>
<tr>
<td>12121</td>
<td>Wu</td>
<td>Finance</td>
<td>90000</td>
</tr>
<tr>
<td>10101</td>
<td>Srinivisan</td>
<td>Comp.Sci</td>
<td>90000</td>
</tr>
<tr>
<td>32343</td>
<td>El Said</td>
<td>History</td>
<td>60000</td>
</tr>
</tbody>
</table>
Extendable Hashing – Example

- After inserting Feinman

### Bucket 0
- 15151 Mozart Music 40000

### Bucket 1
- 22222 Einstein Physics 95000
- 33456 Gold Physics 87000

### Bucket 1a
- 47035 Feinman Physics 92000

### Bucket 2
- 12121 Wu Finance 90000

### Bucket 3
- 10101 Srinivisan Comp.Sci 90000
- 32343 El Said History 60000
Extendable Hashing

• Benefits
  – Hash performance does not degrade with growth of file
  – Minimal space overhead

• Disadvantages
  – Extra level of indirection to find desired record
  – Bucket address table may itself become very big (larger than memory)
    • Cannot allocate very large contiguous areas on disk either
    • Solution: B⁺-tree structure to locate desired record in bucket address table
  – Changing size of bucket address table is an expensive operation
Comparison of Indexing and Hashing

• Expected type of queries:
  – Hashing is generally better at retrieving records having a specified value of the key.
  – If range queries are common, ordered indices are to be preferred

• Cost of periodic re-organization

• Relative frequency of insertions and deletions

• Average vs. worst case access time

• Which index type is supported by the DBMS at hand?
Bitmap Indices

• Special type of index designed for efficient querying on multiple keys
• Records in a relation are assumed to be numbered sequentially from, say, 0
  – Given a number \( n \) it must be easy to retrieve record \( n \)
• Applicable on attributes that take on a relatively small number of distinct values
  – e.g. gender, country, state, …
  – e.g. income-level (income broken up into a small number of levels such as 0-9999, 10000-19999, 20000-50000, 50000-infinity)
• A bitmap is simply an array of bits
• CPUs can process them very efficiently (i.e., 32 or 64 bits at once)
Bitmap Indices

- In its simplest form a bitmap index on an attribute has a bitmap for each value of the attribute
  - Bitmap has as many bits as records
  - In a bitmap for value v, the bit for a record is 1 if the record has the value v for the attribute, and is 0 otherwise

<table>
<thead>
<tr>
<th>record number</th>
<th>ID</th>
<th>gender</th>
<th>income_level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>76766</td>
<td>m</td>
<td>L1</td>
</tr>
<tr>
<td>1</td>
<td>22222</td>
<td>f</td>
<td>L2</td>
</tr>
<tr>
<td>2</td>
<td>12121</td>
<td>f</td>
<td>L1</td>
</tr>
<tr>
<td>3</td>
<td>15151</td>
<td>m</td>
<td>L4</td>
</tr>
<tr>
<td>4</td>
<td>58583</td>
<td>f</td>
<td>L3</td>
</tr>
</tbody>
</table>

Bitmaps for gender
- m: 10010
- f: 01101

Bitmaps for income_level
- L1: 10100
- L2: 01000
- L3: 00001
- L4: 00010
- L5: 00000
Bitmap Indices

• Bitmap indices are useful for queries on multiple attributes
  – not particularly useful for single attribute queries
• Queries are answered using bitmap operations
  – Intersection (and)
  – Union (or)
  – Negation (not)
• Each operation takes two bitmaps of the same size and applies the operation on corresponding bits to get the result bitmap
  – Males with income level L1: 10010 AND 10100 = 10000
  – People with income level L3 to L5: 00001 OR 00010 OR 00000 = 00011
  – Females with income above L1: 01101 AND (NOT 10100) = 01001
• Can then retrieve required tuples
  – Counting number of matching tuples is even faster!
Summary

• Index structures help making queries efficient
  – Practically, speedup by many orders of magnitude
• Trading off storage against computation time
• We’ve got to know different flavors
  – Table index
  – B+-Tree
  – Hash tables
  – Bitmap indices
• Choice of an index structure
  – Desired queries (single/multi attribute? range or value? counting?)
  – Frequency of updates
  – Real time requirements
Questions?