Query Processing with Indexes

CPS 216
Advanced Database Systems

Announcements (February 19)

- Reading assignment for next week
  - Buffer management (due next Wednesday)
- Homework #1 has been graded
  - Grades will posted on Blackboard
  - Sample solution available outside my office
    - Bugs will be corrected in email
- Homework #2 due next Thursday
- Midterm and course project proposal in two weeks

Review

- Many different ways of processing the same query
  - Scan (e.g., nested-loop join)
  - Sort (e.g., sort-merge join)
  - Hash (e.g., hash join)
  - Index
### Selection using index

- **Equality predicate:** $\sigma_{A = v}(R)$
  - Use an ISAM, B⁺-tree, or hash index on $R(A)$
- **Range predicate:** $\sigma_{A > v}(R)$
  - Use an ordered index (e.g., ISAM or B⁺-tree) on $R(A)$
  - Hash index is not applicable
- Indexes other than those on $R(A)$ may be useful
  - Example: B⁺-tree index on $R(A, B)$
  - How about B⁺-tree index on $R(B, A)$?

### Index versus table scan

**Situations where index clearly wins:**

- Index-only queries which do not require retrieving actual tuples
  - Example: $\pi_A(\sigma_{A > v}(R))$
- Primary index clustered according to search key
  - One lookup leads to all result tuples in their entirety

**Index versus table scan (cont’d)**

**BUT(!):**

- Consider $\sigma_{A > v}(R)$ and a secondary, non-clustered index on $R(A)$
  - Need to follow pointers to get the actual result tuples
  - Say that 20% of $R$ satisfies $A > v$
    - Could happen even for equality predicates
  - I/O’s for index-based selection:
  - I/O’s for scan-based selection: $B(R)$
  - Table scan wins if
Index nested-loop join

- $R \bowtie_{R.A = S.B} S$
- Idea: use the value of $R.A$ to probe the index on $S(B)$
- For each block of $R$, and for each $r$ in the block:
  - Use the index on $S(B)$ to retrieve $s$ with $s.B = r.A$
  - Output $rs$
- I/O's: $B(R) + |R| \cdot \text{index lookup}$
  - Typically, the cost of an index lookup is 2-4 I/O's
  - Beats other join methods if $|R|$ is not too big
  - Better pick $R$ to be the smaller relation
- Memory requirement: 2

Tricks for index nested-loop join

Goal: reduce $|R| \cdot \text{index lookup}$
- For tree-based indexes, keep the upper part of the tree in memory
- For extensible hash index, keep the directory in memory

Zig-zag join using ordered indexes

- $R \bowtie_{R.A = S.B} S$
- Idea: use the ordering provided by the indexes on $R(A)$ and $S(B)$ to eliminate the sorting step of sort-merge join
- Trick: use the larger key to probe the other index
  - Possibly skipping many keys that do not match
More indexes ahead!

- Bitmap index
  - Generalized value-list index
- Projection index
- Bit-sliced index

Search key values × tuples

<table>
<thead>
<tr>
<th>Search key values</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>...</th>
<th>k – 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>108</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

1 means tuple has the particular search key value
0 means otherwise

Bitmap index

- Value-list index—stores the matrix by rows
  - Traditionally list contains pointers to tuples
  - $B^+$-tree: tuples with same search key values
  - Inverted list: documents with same keywords
- If there are not many search key values, and there are lots of 1’s in each row, pointer list is not space-efficient
  - How about a bitmap?
  - Still a $B^+$-tree, except leaves have a different format
Technicalities

- How do we go from a bitmap index (0 to \( n - 1 \)) to the actual tuple?
  - One more level of indirection solves everything
  - Or, given a bitmap index, directly calculate the physical block number and the slot number within the block for the tuple
- In either case, certain block/slot may be invalid
  - Because of deletion, or variable-length tuples
  - Keep an existence bitmap: bit set to 1 if tuple exists

Bitmap versus traditional value-list

- Operations on bitmaps are faster than pointer lists
  - Bitmap AND: bit-wise AND
  - Value-list AND: sort-merge join
- Bitmap is more efficient when the matrix is sufficiently dense; otherwise, pointer list is more efficient
  - Smaller means more in memory and fewer I/O’s
- Generalized value-list index: with both bitmap and pointer list as alternatives

Projection index

- Just store \( \pi_A(R) \) and use it as an index!
Why projection index?

- Idea: still a table scan, but we are scanning a much smaller table (project index)
  - Savings could be substantial for long tuples with lots of attributes
- Looks familiar?
  - Except that we keep the original table

Bit-sliced index

- If a column stores binary numbers, then slice their bits vertically
  - Basically a projection index by slices

Aggregate query processing example

```
SELECT SUM(dollar_sales)
FROM Sales
WHERE condition;
```

- Already found $B_f$ (a bitmap or a sorted list of TID’s that point to Sales tuples that satisfy condition)
  - Probably used a secondary index
- Need to compute $\text{SUM}(dollar\_sales)$ for tuples in $B_f$
SUM without any index

- For each tuple in $B_f$, go fetch the actual tuple, and add $dollar_sales$ to a running sum
- I/O's:

SUM with a value-list index

- Assume a value-list index on $Sales(dollar_sales)$
- Idea: the index stores $dollar_sales$ values and their counts (in a pretty compact form)
- $sum = 0$;
  Scan $Sales(dollar_sales)$ index; for each indexed value $v$ with value-list $B_v$:
  $sum += v \times \text{count-1-bits}(B_v \text{ AND } B_f)$;
- I/Os: number of blocks taken by the value-list index
- Bitmaps can possibly speed up AND and reduce the size of the index

SUM with a projection index

- Assume a project index on $Sales(dollar_sales)$
- Idea: merge join $B_f$ and the projection index, add joining tuples' $dollar_sales$ to a running sum
  - Assuming both $B_f$ and the index are sorted on TID
- I/O's: number of blocks taken by the projection index
  - Compared with a value-list index, the projection index may be more compact (no empty space or pointers), but it does store duplicate $dollar_sales$ values
  - Also: simpler algorithm, fewer CPU operations
**SUM with a bit-sliced index**

- Assume a bit-sliced index on \textit{Sales(dollar_sales)}, with slices \(B_{k-1}, \ldots, B_1, B_0\).

- sum = 0;
  for \(i = 0\) to \(k - 1\):
    sum += \(2^i \times \text{count-1-bits}(B_i \text{ AND } B_f)\);

- I/O's: number of blocks taken by the bit-sliced index
- Conceptually a bit-sliced index contains the same information as a projection index
  - But the bit-sliced index does not keep TID
  - Bitmap AND is faster

**Summary of SUM**

- Best: bit-sliced index
  - Index is small
  - \(B_f\) can be applied fast!
- Good: projection index
- Not bad: value-list index
  - Full-fledged index carries a bigger overhead
    - The fact that we have counts of values helped
    - But we did not really need values to be ordered

**MEDIAN**

\[
\text{SELECT} \ \text{MEDIAN}(\text{dollar_sales})
\text{FROM} \ \text{Sales}
\text{WHERE condition;}
\]

- Same deal: already found \(B_f\) (a bitmap or a sorted list of TID's that point to \textit{Sales} tuples that satisfy \textit{condition})
- Need to find the \textit{dollar_sales} value that is greater than or equal to \(\frac{1}{2} \times \text{count-1-bits}(B_f)\) \textit{dollar_sales} values among \(B_f\) tuples
**MEDIAN with an ordered value-list index**

- Idea: take advantage of the fact that the index is ordered by dollar_sales
- Scan the index in order, count the number of tuples that appeared in $B_j$ until the count reaches $\frac{1}{2} \times \text{count-1-bits}(B_j)$
- I/O’s: roughly half of the index

**MEDIAN with a projection index**

- In general, need to sort the index by dollar_sales
  - Well, when you sort, you more or less get back an ordered value-list index!
- Not useful unless $B_j$ is small

**MEDIAN with a bit-sliced index**

- Tough at the first glance—index is not sorted
- Think of it as sorted
  - We won’t actually make use of this fact

<table>
<thead>
<tr>
<th>Look at $B_{k-1}$ first</th>
<th>More than half are 0’s?</th>
<th>Yes; continue searching for median here</th>
<th>No; continue searching for median here</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0…</td>
<td>0 1 0…</td>
<td>1 0 0…</td>
<td>1 0 1…</td>
</tr>
<tr>
<td>1 0 0…</td>
<td>1 1 0…</td>
<td>1 1 1…</td>
<td>1 1 1…</td>
</tr>
</tbody>
</table>
**MEDIAN with a bit-sliced index**

- median = 0;
- \( B_{\text{current}} = B_f \); // which tuples we are considering
-sofar = 0; // number of values that are less
- // than what we are considering

for \( i = k - 1 \) to 0:
  - if (sofar + count-1-bits(\( B_{\text{current}} \) AND NOT(\( B_i \)))
    \( \leq \frac{1}{2} \times \text{count-1-bits}(B_f) \)):
    - \( B_{\text{current}} = B_{\text{current}} \) AND \( B_i \);
    -sofar += count-1-bits(\( B_{\text{current}} \) AND NOT(\( B_i \)));
    - median += 2^i;
  - else:
    - \( B_{\text{current}} = B_{\text{current}} \) AND NOT(\( B_i \));

- I/O's: still need to scan the entire index

**Summary of MEDIAN**

- Best: ordered value-list index
  - It helps to be ordered!

- Pretty good: bit-sliced index
  - Could beat ordered value-list index if \( B_i \) is "clustered"
    - Only need to retrieve the corresponding segment

**More variant indexes**

"Improved Query Performance with Variant Indexes," by O’Neil and Quass. SIGMOD, 1997

- MIN/MAX, and range query using bit-sliced index
- Join indexes for star schema
  - Traditional: one for each combination of foreign columns
  - Bitmap: one for each foreign column
  - Precomputed query results (materialized views)?
Variant vs. traditional indexes

- What is the more glaring problem of these variant indexes that makes them not as widely applicable as the B*-tree?
  - Difficult to update
- How did the paper get away with that?
  - OLAP with periodic batch updates