Query Processing with Indexes

CPS 216
Advanced Database Systems

Announcements

- Recitation session this Friday (March 21)
  - Graded midterms and sample solution
  - Midterm common problems
- Homework #3 will be assigned next Monday (March 24)

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
- Sort or partition $R$ according to the join attribute

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>Tuples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>108</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!

<table>
<thead>
<tr>
<th>TID</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>108</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>-</td>
</tr>
</tbody>
</table>

Projection 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

```sql
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 $\text{SUM}(\text{dollar_sales})$ for tuples in $B_f$
SUM without any index

- For each tuple in $B_f$, go fetch the actual tuple, and add \textit{dollar_sales} to a running sum.
- I/O’s: number of \textit{Sales} blocks with $B_f$ tuples
  - Assuming we fetch them in sorted order.

SUM with a value-list index

- Assume a value-list index on \textit{Sales(dollar_sales)}
- Idea: the index stores \textit{dollar_sales} values and their counts (in a pretty compact form)

```
sum = 0;
Scan \textit{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 projection index on \textit{Sales(dollar_sales)}
- Idea: merge join $B_f$ and the projection index, add joining tuples’ \textit{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 \textit{dollar_sales} values
- Also: simpler algorithm, fewer CPU operations
**SUM with a bit-sliced index**

- Assume a bit-sliced index on Sales(dollar_sales), with slices $B_{k-1}, \ldots, B_1, B_0$
- $\text{sum} = 0$
  - for $i = 0$ to $k - 1$
    - $\text{sum} += 2^i \times \text{count-1-bits}(B_i \text{ AND } B_f)$
- 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

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**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

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**MEDIAN**

```sql
SELECT MEDIAN(dollar_sales)
FROM Sales
WHERE condition;
```

- Same deal: already found $B_f$ (a bitmap or a sorted list of TID's that point to Sales tuples that satisfy condition)
- Need to find the $dollar_sales$ value that is greater than or equal to $\frac{1}{2} \times \text{count-1-bits}(B_f)$ $dollar_sales$ 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 $B_i$ until the count reaches $\frac{1}{2} \times \text{count-1-bits}(B_i)$
- 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 $B_i$ 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 the this fact

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

- \( \text{median} = 0; \)
- \( B_{\text{current}} = B_i; \) // which tuples we are considering
- \( \text{sofar} = 0; \) // number of values that are less
- // than what we are considering
  
  for \( i = k - 1 \) to 0:
  
  if \( (\text{sofar} + \text{count-1-bits}(B_{\text{current}} AND \text{NOT}(B_i))) \leq \frac{1}{2} \times \text{count-1-bits}(B_i)) \):
    
    \( B_{\text{current}} = B_{\text{current}} \text{AND} B_i; \)
    
    \( \text{sofar} += \text{count-1-bits}(B_{\text{current}} \text{AND} \text{NOT}(B_i)); \)
    
    \( \text{median} += 2^i; \)
  
  else:
    
    \( B_{\text{current}} = B_{\text{current}} \text{AND} \text{NOT}(B_i); \)

- 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**

  - MIN/MAX
  - And fun with range query using bit-sliced index!