# Query Processing with Indexes

CPS 216

Advanced Database Systems

## Announcements (February 24)



- More reading assignment for next week
  - Buffer management (due next Wednesday)
- Homework #2 due next Thursday
- Course project proposal due in 1½ weeks
- Midterm in two weeks

- Christos Faloutsos (CMU) talk
  - "Data Mining Using Fractals and Power Laws"
  - 4-5pm, Monday, February 28
  - 130A North Building (telecast from UNC)

## 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: lookup + 20% $|R|$
  - I/O's for scan-based selection: $B(R)$
  - Table scan wins if a block contains more than 5 tuples

# 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: $B(R) + |R| \cdot$ (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

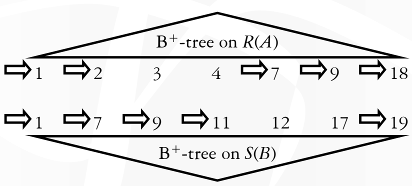
Goal: reduce $|R| \cdot$ (index lookup)

- 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
  - Improves locality: subsequent lookup may follow the same path or go to the same bucket



# 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



Tuples

| Search key values | 0 | 1 | 2 | | $n-1$ |
|---|---|---|---|---|---|
| 8 | 1 | 1 | 0 | … | 0 |
| 9 | 0 | 0 | 0 | … | 0 |
| 10 | 0 | 0 | 1 | … | 1 |
| 26 | 0 | 0 | 0 | … | 0 |
| 108 | 0 | 0 | 0 | … | 0 |
| | … | … | … | … | … |

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

- Looks familiar?
  - Keywords × documents

## 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!

Could be implicit and not explicitly stored

| $TID$ | $A$ | $B$ | … |
|---|---|---|---|
| 0 | 8 | … | … |
| 1 | 8 | … | … |
| 2 | 26 | … | … |
| 3 | 108 | … | … |
| … | … | … | … |
| $n-1$ | 10 | … | … |

Projection index

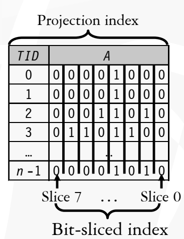
# Why projection index?

- 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?



# 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 SUM(*dollar_sales*) for tuples in $B_f$

## SUM without any index

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

## SUM with a value-list index

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- 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 += $v \times$ count-1-bits($B_v$ 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

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- 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 *Sales*(*dollar_sales*), with slices $B_{k-1}, \ldots, B_1, B_0$
- sum = 0;
  for $i = 0$ to $k - 1$:
  sum += $2^i \times$ count-1-bits($B_i$ 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

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 ½ × 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 $B_f$ until the count reaches ½ × count-1-bits($B_f$)
- I/O's: roughly half of the index



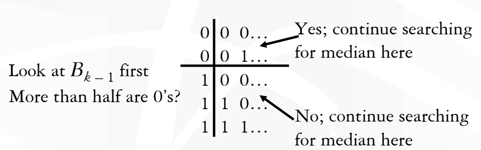
## MEDIAN with a projection index

- 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 $B_f$ 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




By looking at $B_{k-1}$ we know the $(k-1)$-th bit of the median

## MEDIAN with a bit-sliced index

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- median = 0;
  $B_{current} = B_f$; // which tuples we are considering
  sofar = 0; // number of tuples whose values are less
  // than what we are considering
  for $i = k - 1$ to 0:
  if (sofar + count-1-bits($B_{current}$ AND NOT($B_i$ ))
  $\leq$ ½ × count-1-bits($B_f$ )):
  $B_{current} = B_{current}$ AND $B_i$;
  sofar += count-1-bits($B_{current}$ AND NOT($B_i$);
  median += $2^i$;
  else:
  $B_{current} = B_{current}$ AND NOT($B_i$);
- I/O's: still need to scan the entire index

## Summary of MEDIAN

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- Best: ordered value-list index
  - It helps to be ordered!
- Pretty good: bit-sliced index
  - Could beat ordered value-list index if $B_f$ is "clustered"
    - Only need to retrieve the corresponding segment

## More variant indexes

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"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?
- How did the paper get away with that?