Query Processing
(And Even More Indexing!)

CPS 216
Advanced Database Systems

Review

- Many different ways of implementing the same logical query operator
  - Scan
    - Nested-loop join
  - Sort
    - External merge sort
    - Sort-merge join
  - Hash
    - Hash join
  - » Index (today)

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 $R(A, B)$

Index versus table scan (slide 1)

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 (slide 2)

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

Sorting using an ordered index

Use an index on the sort key

- Go through the index and output tuples in order
- Very efficient for a primary index clustered according to sort key
- Terrible for a secondary, non-clustered index
  - I/O's: $|R|$
  - I/O's required by two-pass external merge sort: $3 \cdot B(R)$
  - Yes, it makes sense to sort even though the index already does it!

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 $|R|$ isn't too big
  - Better pick R to be the smaller relation
- Memory requirement: 2

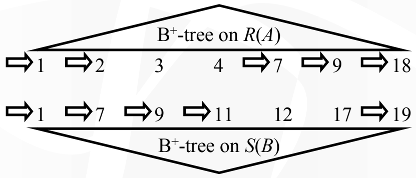
Tricks for index nested-loop join

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
- Sorting or partitioning 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 don't 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?

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

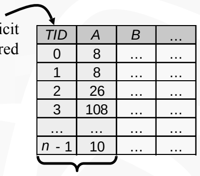
- How do we go from a bitmap index (0 to $n - 1$) to the actual tuple?
- » One more level of indirection solves everything
- » Or, given a bitmap index, directly calculate the physical block number and the slot number within the block for the tuple
- In either case, certain block/slot may be invalid
  - – 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
- Really the same idea of storing rows in the matrix
  - – 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	…	…

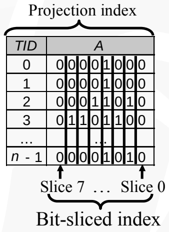
Projection index

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



TID	*A*							
0	0	0	0	0	1	0	0	0
1	0	0	0	0	1	0	0	0
2	0	0	0	1	1	0	1	0
3	0	1	1	0	1	1	0	0
…					…			
n - 1	0	0	0	0	1	0	1	0

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
- Now, need to compute 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: number of 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 Sales(dollar_sales)
- Idea: the index contains dollar_sales values and their counts
- sum = 0;
  Scan 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

- 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 is 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_1, B_2, …, B_{k-1}
- 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 doesn't 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 didn't 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*)
- Now, 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

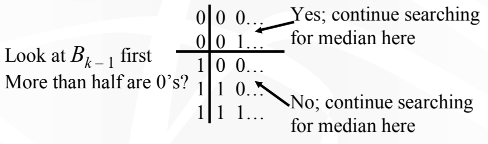
- Idea: take advantage of the fact that the index is ordered by dollar_sales
- Scan the index in order, count the number of tuples that appeared in B_f until the count reaches ½ × count-1-bits(B_f)
- I/O's: roughly half of the index

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 take advantage of the this fact



Look at B_{k-1} first
More than half are 0's?

0 | 0 0…
0 | 0 1…
1 | 0 0…
1 | 1 0…
1 | 1 1…

Yes; continue searching for median here

No; continue searching for median here

MEDIAN Using a bit-sliced index

```
median = 0;
$B_{current} = B_f$;     // which tuples we are considering
sofar = 0;               // number of values that are less
                         // than what we are considering
for $i = k - 1$ to 0:                                   Is the median not with the 0's?
    if (sofar + count-1-bits($B_{current}$ AND NOT($B_i$)) ↙
            $\leq$ ½ × count-1-bits($B_f$)):
        $B_{current} = B_{current}$ AND $B_i$;   Median is with the 1's
All 0's are
less than these    sofar += count-1-bits($B_{current}$ AND NOT($B_i$));
        median += $2^i$;
    else:
        $B_{current} = B_{current}$ AND NOT($B_i$);   Median is with the 0's
```

- 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_f is "clustered"
    - Only need to retrieve the corresponding segment

More variant indexes

- O'Neil and Quass, "Improved Query Performance with Variant Indexes," SIGMOD 97
  - MIN/MAX
  - And fun with range query using bit-sliced index!