Query Processing

Introduction to Databases
CompSci 316 Fall 2019
Announcements (Wed., Nov. 6)

• Project milestone 2 due today
  • No Piazza update needed this week
• Homework 4 (last one!) assigned; due in 2½ weeks
• Gradiance Indexes exercise due next Mon.
Announcements (Mon., Nov. 11)

• Homework 4 (last one!) due in 2 weeks
• Gradiance Indexes exercise due today
• Remember your weekly update on Piazza this Wed.
• Project milestone 2 feedback to be returned later this week
Overview

• Many different ways of processing the same query
  • Scan? Sort? Hash? Use an index?
  • All have different performance characteristics and/or
    make different assumptions about data

• Best choice depends on the situation
  • Implement all alternatives
  • Let the query optimizer choose at run-time
Notation

• Relations: $R, S$
• Tuples: $r, s$
• Number of tuples: $|R|, |S|$
• Number of disk blocks: $B(R), B(S)$
• Number of memory blocks available: $M$
• Cost metric
  • Number of I/O’s
  • Memory requirement
Scanning-based algorithms
Table scan

• Scan table $R$ and process the query
  • Selection over $R$
  • Projection of $R$ without duplicate elimination

• I/O’s: $B(R)$
  • Trick for selection: stop early if it is a lookup by key

• Memory requirement: 2

• Not counting the cost of writing the result out
  • Same for any algorithm!
  • Maybe not needed—results may be pipelined into another operator
Nested-loop join

$R \bowtie_p S$

• For each block of $R$, and for each $r$ in the block:
  For each block of $S$, and for each $s$ in the block:
    Output $rs$ if $p$ evaluates to true over $r$ and $s$
  • $R$ is called the outer table; $S$ is called the inner table
  • I/O’s: $B(R) + |R| \cdot B(S)$
• Memory requirement: 3

Improvement: block-based nested-loop join

• For each block of $R$, for each block of $S$:
  For each $r$ in the $R$ block, for each $s$ in the $S$ block: ...
  • I/O’s: $B(R) + B(R) \cdot B(S)$
  • Memory requirement: same as before
More improvements

• Stop early if the key of the inner table is being matched

• Make use of available memory
  • Stuff memory with as much of $R$ as possible, stream $S$ by, and join every $S$ tuple with all $R$ tuples in memory

  • I/O’s: $B(R) + \left\lceil \frac{B(R)}{M-2} \right\rceil \cdot B(S)$
    • Or, roughly: $B(R) \cdot B(S)/M$
  • Memory requirement: $M$ (as much as possible)

• Which table would you pick as the outer?
Sorting-based algorithms

http://en.wikipedia.org/wiki/Mail_sorter#mediaviewer/File:Mail_sorting,1951.jpg
External merge sort

Remember (internal-memory) merge sort?
Problem: sort $R$, but $R$ does not fit in memory

- **Pass 0**: read $M$ blocks of $R$ at a time, sort them, and write out a level-0 run

- **Pass 1**: merge $(M - 1)$ level-0 runs at a time, and write out a level-1 run

- **Pass 2**: merge $(M - 1)$ level-1 runs at a time, and write out a level-2 run

... 

- **Final pass** produces one sorted run
Toy example

• 3 memory blocks available; each holds one number
• Input: 1, 7, 4, 5, 2, 8, 9, 6, 3
• Pass 0
  • 1, 7, 4 → 1, 4, 7
  • 5, 2, 8 → 2, 5, 8
  • 9, 6, 3 → 3, 6, 9
• Pass 1
  • 1, 4, 7 + 2, 5, 8 → 1, 2, 4, 5, 7, 8
  • 3, 6, 9
• Pass 2 (final)
  • 1, 2, 4, 5, 7, 8 + 3, 6, 9 → 1, 2, 3, 4, 5, 6, 7, 8, 9
Analysis

• **Pass 0**: read $M$ blocks of $R$ at a time, sort them, and write out a level-0 run
  • There are $\left\lceil \frac{B(R)}{M} \right\rceil$ level-0 sorted runs

• **Pass $i$**: merge $(M - 1)$ level-$(i - 1)$ runs at a time, and write out a level-$i$ run
  • $(M - 1)$ memory blocks for input, 1 to buffer output
  • # of level-$i$ runs = $\left\lceil \frac{\text{# of level-}(i-1) \text{ runs}}{M-1} \right\rceil$

• **Final pass** produces one sorted run
Performance of external merge sort

- Number of passes: \( \left\lceil \log_{M-1} \left( \frac{B(R)}{M} \right) \right\rceil + 1 \)

- I/O’s
  - Multiply by \( 2 \cdot B(R) \): each pass reads the entire relation once and writes it once
  - Subtract \( B(R) \) for the final pass
  - Roughly, this is \( O(B(R) \times \log_M B(R)) \)

- Memory requirement: \( M \) (as much as possible)
Some tricks for sorting

• Double buffering
  • Allocate an additional block for each run
  • Overlap I/O with processing
  • Trade-off: smaller fan-in (more passes)

• Blocked I/O
  • Instead of reading/writing one disk block at time, read/write a bunch (“cluster”)
  • More sequential I/O’s
  • Trade-off: larger cluster → smaller fan-in (more passes)
Sort-merge join

\[ R \bowtie_{R.A=S.B} S \]

- Sort \( R \) and \( S \) by their join attributes; then merge \( r, s = \) the first tuples in sorted \( R \) and \( S \)
  Repeat until one of \( R \) and \( S \) is exhausted:
    If \( r.A > s.B \) then \( s = \) next tuple in \( S \)
    else if \( r.A < s.B \) then \( r = \) next tuple in \( R \)
    else output all matching tuples, and \( r, s = \) next in \( R \) and \( S \)

- I/O’s: \textit{sorting + } \( 2B(R) + 2B(S) \)
  - In most cases (e.g., join of key and foreign key)
  - Worst case is \( B(R) \cdot B(S) \): everything joins
Example of merge join

\[ R \bowtie_{R.A = S.B} S:\]

- \( r_1.A = 1 \)
- \( r_2.A = 3 \)
- \( r_3.A = 3 \)
- \( r_4.A = 5 \)
- \( r_5.A = 7 \)
- \( r_6.A = 7 \)
- \( r_7.A = 8 \)

- \( s_1.B = 1 \)
- \( s_2.B = 2 \)
- \( s_3.B = 3 \)
- \( s_4.B = 3 \)
- \( s_5.B = 8 \)

- \( r_1s_1 \)
- \( r_2s_3 \)
- \( r_2s_4 \)
- \( r_3s_3 \)
- \( r_3s_4 \)
- \( r_7s_5 \)
Optimization of SMJ

• **Idea:** combine join with the (last) merge phase of merge sort

• **Sort:** produce sorted runs for \( R \) and \( S \) such that there are fewer than \( M \) of them total

• **Merge and join:** merge the runs of \( R \), merge the runs of \( S \), and merge-join the result streams as they are generated!
Performance of SMJ

• If SMJ completes in two passes:
  • I/O’s: \(3 \cdot (B(R) + B(S))\)
  • Memory requirement
    • We must have enough memory to accommodate one block from each run: \(M > \frac{B(R)}{M} + \frac{B(S)}{M}\)
    • \(M > \sqrt{B(R) + B(S)}\)

• If SMJ cannot complete in two passes:
  • Repeatedly merge to reduce the number of runs as necessary before final merge and join
Other sort-based algorithms

• Union (set), difference, intersection
  • More or less like SMJ

• Duplication elimination
  • External merge sort
    • Eliminate duplicates in sort and merge

• Grouping and aggregation
  • External merge sort, by group-by columns
    • Trick: produce “partial” aggregate values in each run, and combine them during merge
      • This trick doesn’t always work though
        • Examples: SUM(DISTINCT ...), MEDIAN(...)


Hashing-based algorithms

Hash join

\[ R \bowtie_{R.A=S.B} S \]

• Main idea
  • Partition \( R \) and \( S \) by hashing their join attributes, and then consider corresponding partitions of \( R \) and \( S \)
  • If \( r.A \) and \( s.B \) get hashed to different partitions, they don’t join

![Diagram of hash join and nested-loop join](diagram.png)

- Nested-loop join considers all slots
- Hash join considers only those along the diagonal!
Partitioning phase

- Partition $R$ and $S$ according to the same hash function on their join attributes
Probing phase

- Read in each partition of $R$, stream in the corresponding partition of $S$, join
  - Typically build a hash table for the partition of $R$
    - Not the same hash function used for partition, of course!

![Diagram of disk and memory partitions with arrows indicating load, stream, and join operations.](image-url)
Performance of (two-pass) hash join

• If hash join completes in two passes:
  • I/O’s: $3 \cdot (B(R) + B(S))$
  • Memory requirement:
    • In the probing phase, we should have enough memory to fit one partition of $R$: $M - 1 > \frac{B(R)}{M - 1}$
    • $M > \sqrt{B(R)} + 1$
    • We can always pick $R$ to be the smaller relation, so:
      $$M > \sqrt{\min(B(R), B(S))} + 1$$
Generalizing for larger inputs

• What if a partition is too large for memory?
  • Read it back in and partition it again!
    • See the duality in multi-pass merge sort here?
Hash join versus SMJ

(Assuming two-pass)

• I/O’s: same

• Memory requirement: hash join is lower
  \[ \sqrt{\min(B(R), B(S))} + 1 < \sqrt{B(R) + B(S)} \]
  • Hash join wins when two relations have very different sizes

• Other factors
  • Hash join performance depends on the quality of the hash
    • Might not get evenly sized buckets
  • SMJ can be adapted for inequality join predicates
  • SMJ wins if \( R \) and/or \( S \) are already sorted
  • SMJ wins if the result needs to be in sorted order
What about nested-loop join?

• May be best if many tuples join
  • Example: non-equality joins that are not very selective

• Necessary for black-box predicates
  • Example: WHERE user_defined_pred(R.A, S.B)
Other hash-based algorithms

• Union (set), difference, intersection
  • More or less like hash join

• Duplicate elimination
  • Check for duplicates within each partition/bucket

• Grouping and aggregation
  • Apply the hash functions to the group-by columns
  • Tuples in the same group must end up in the same partition/bucket
  • Keep a running aggregate value for each group
    • May not always work
Duality of sort and hash

• Divide-and-conquer paradigm
  • Sorting: physical division, logical combination
  • Hashing: logical division, physical combination

• Handling very large inputs
  • Sorting: multi-level merge
  • Hashing: recursive partitioning

• I/O patterns
  • Sorting: sequential write, random read (merge)
  • Hashing: random write, sequential read (partition)
Index-based algorithms

http://i1.trekearth.com/photos/28820/p2270994.jpg
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: \( \text{lookup} + 20\% \ |R| \)
• 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 a 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: 3
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
- Use the larger key to probe the other index
  - Possibly skipping many keys that don’t match
Summary of techniques

• Scan
  • Selection, duplicate-preserving projection, nested-loop join

• Sort
  • External merge sort, sort-merge join, union (set), difference, intersection, duplicate elimination, grouping and aggregation

• Hash
  • Hash join, union (set), difference, intersection, duplicate elimination, grouping and aggregation

• Index
  • Selection, index nested-loop join, zig-zag join