Query Processing

CPS 116
Introduction to Database Systems

Announcements (November 10)

- Course project milestone #2 due today
- My office hours today start from 3pm

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

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 (+1 for double buffering)
- 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 (+1 for double buffering)
- Improvement: block-based nested-loop join
  - For each block of R, and for each block of S:
    For each r in the R block, and for each s in the S block: …
  - I/O's: $B(R) + B(R) \cdot B(S)$
  - Memory requirement: same as before

More improvements of nested-loop join

- Stop early
  - If the key of the inner table is being matched
  - May reduce half of the I/O's
- 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: $B(R) + \lceil B(R) / (M - 2) \rceil \cdot B(S)$
    - Or, roughly: $B(R) \cdot B(S) / M$
  - Memory requirement: M (as much as possible)
- Which table would you pick as the outer?

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
  - There are $\lceil B(R) / M \rceil$ 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 = $\lceil$ # of level-$(i-1)$ runs / $(M - 1) \rceil$
- Final pass produces 1 sorted run

Example of external merge sort

- Input: 1, 7, 4, 5, 2, 8, 3, 6, 9
- 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

Performance of external merge sort

- Number of passes: $\lceil \log_{M-1} \lceil B(R) / M \rceil \rceil + 1$
- 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 $O(B(R) \cdot \log_M B(R))$
- Memory requirement: M (as much as possible)

Some tricks for sorting

- Double buffering
  - Allocate an additional block for each run
  - 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, and then merge

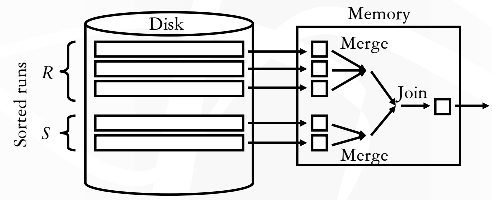
  r, s = the first tuples in sorted R and S
  Repeat until one of R and S is exhausted:
  If $r.A > s.B$ then s = next tuple in S
  else if $r.A < s.B$ then r = next tuple in R
  else output all matching tuples, and
  r, s = next in R and S
- I/O's: sorting + $2\ B(R) + 2\ B(S)$
  - In most cases (e.g., join of key and foreign key)
  - Worst case is $B(R) \cdot B(S)$: everything joins

Example

R:	S:	$R \bowtie_{R.A = S.B} S$:
⇨ $r_1.A = 1$	⇨ $s_1.B = 1$	$r_1 s_1$
⇨ $r_2.A = 3$	⇨ $s_2.B = 2$	$r_2 s_3$
$r_3.A = 3$	⇨ $s_3.B = 3$	$r_2 s_4$
⇨ $r_4.A = 5$	$s_4.B = 3$	$r_3 s_3$
⇨ $r_5.A = 7$	⇨ $s_5.B = 8$	$r_3 s_4$
⇨ $r_6.A = 7$		$r_7 s_5$
⇨ $r_7.A = 8$		

Optimization of SMJ

- Idea: combine join with the merge phase of merge sort
- Sort: produce sorted runs of size M for R and S
- 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 two-pass SMJ

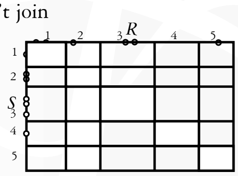
- I/O's: $3 \cdot (B(R) + B(S))$
- Memory requirement
  - To be able to merge in one pass, we should have enough memory to accommodate one block from each run: $M > B(R) / M + B(S) / M$
  - $M > \text{sqrt}(B(R) + B(S))$

Other sort-based algorithms

- Union (set), difference, intersection
  - More or less like SMJ
- Duplication elimination
  - External merge sort
    - Eliminate duplicates in sort and merge
- `GROUP BY` and aggregation
  - External merge sort
    - Produce partial aggregate values in each run
    - Combine partial aggregate values during merge
    - Partial aggregate values don't always work though
      - Examples: `SUM(DISTINCT …)`, `MEDIAN(…)`

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

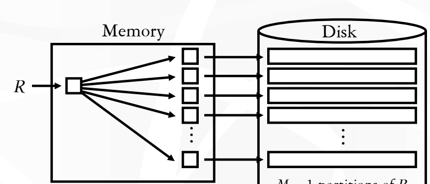


Nested-loop join considers all slots

Hash join considers only those along the diagonal

Partitioning phase

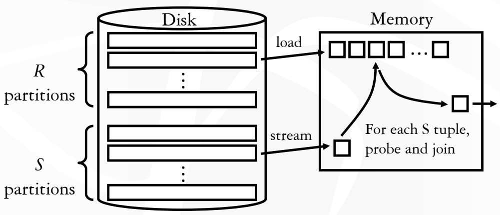
- Partition R and S according to the same hash function on their join attributes



Same for S

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!

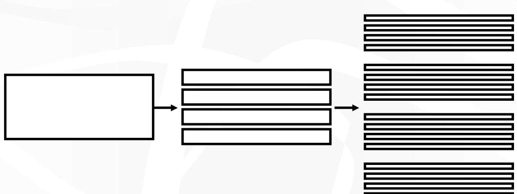


Performance of hash join

- 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: $M - 1 \geq B(R) / (M - 1)$
  - $M >$ sqrt($B(R)$)
  - We can always pick R to be the smaller relation, so: $M >$ sqrt(min($B(R)$, $B(S)$))

Hash join tricks

- 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($B(R)$, $B(S)$)) < 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
- `GROUP BY` and aggregation
  - Apply the hash functions to `GROUP BY` attributes
  - Tuples in the same group must end up in the same partition/bucket
  - Keep a running aggregate value for each group

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)

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(!):

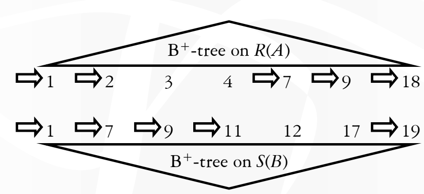
- Consider $\sigma_{A>v}(R)$ and a secondary, non-clustered index on $R(A)$
  - Need to follow pointers to get the actual result tuples
  - Say that 20% of R satisfies $A > v$
    - Could happen even for equality predicates
  - I/O's for index-based selection: lookup + 20% $|R|$
  - I/O's for scan-based 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

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



Summary of tricks

- Scan
  - Selection, duplicate-preserving projection, nested-loop join
- Sort
  - External merge sort, sort-merge join, union (set), difference, intersection, duplicate elimination, GROUP BY and aggregation
- Hash
  - Hash join, union (set), difference, intersection, duplicate elimination, GROUP BY and aggregation
- Index
  - Selection, index nested-loop join, zig-zag join