Query Processing

CPS 216
Advanced Database Systems

Announcements (February 17)

- Reading assignment for this week
  - Variant indexes (due Wednesday)
- Homework #1 is being graded
  - Sample solution available outside my office
- Homework #2 due February 26
- Midterm and course project proposal in 2½ weeks

Overview

- Many different ways of processing the same query
  - Scan? Sort? Hash? Use an index?
  - All with different performance characteristics
- 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 (double buffering)
- Not counting the cost of writing the result out
  - Same for any algorithm!
  - Maybe not needed—results may be pipelined directly 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: 4 (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

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- Stop early
  - If the key of the inner table is being matched
  - May reduce half of the I/O's (less for block-based)
- 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)

External merge sort

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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

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- Input: 1, 7, 4, 5, 2, 8, 9, 6, 3, 0
- Each block holds one number, and memory has 3 blocks
- Pass 0
  - 1, 7, 4 → 1, 4, 7
  - 5, 2, 8 → 2, 5, 8
  - 9, 6, 3 → 3, 6, 9
  - 0 → 0
- Pass 1
  - 1, 4, 7 + 2, 5, 8 → 1, 2, 4, 5, 7, 8
  - 3, 6, 9 + 0 → 0, 3, 6, 9
- Pass 2 (final)
  - 1, 2, 4, 5, 7, 8 + 0, 3, 6, 9 → 0, 1, 2, 3, 4, 5, 6, 7, 8, 9

Performance of external merge sort

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- 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

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- 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")
  - Trade-off: more sequential I/O's ↔ smaller fan-in (more passes)
- Dealing with input whose size is not an exact power of fan-in

Internal sort algorithm

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- Quicksort
  - ☞Fast
- Replacement selection
  - One block for input, one for output, rest for a heap
  - Fill the heap with input records
  - Find the smallest record in the heap that is no less than the largest record in the current run
    - If that exists, move it to the output buffer, and move a new record from input buffer into the heap
    - If that does not exist, flush output and start a new run
  - ☞Slower than quicksort, but produces longer runs (twice the size of memory if records are in random order)

Sort-merge join

- $R \bowtie_{R.A = S.B} S$
- Sort R and S by their join attributes, and then merge

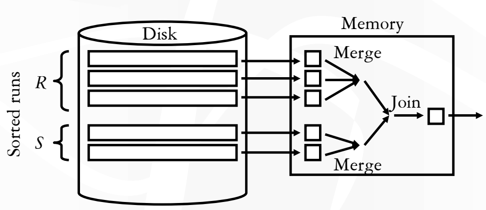
  r, s = the first tuples in sorted R and S
  Repeat until one of R and S is exhausted:
  If $r.A > s.B$ then s = next tuple in S
  else if $r.A < s.B$ then r = next tuple in R
  else output all matching tuples, and
  r, s = next in R and S
- I/O's: sorting + 2 $B(R)$ + 2 $B(S)$
  - In most cases (e.g.,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

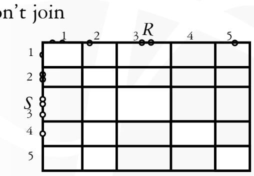
- I/O's: $3 \cdot (B(R) + B(S))$
- Memory requirement
  - To be able to merge in one pass, we should have enough memory to accommodate one block from each run: $M > B(R) / M + B(S) / M$
  - $M > \text{sqrt}(B(R) + B(S))$

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

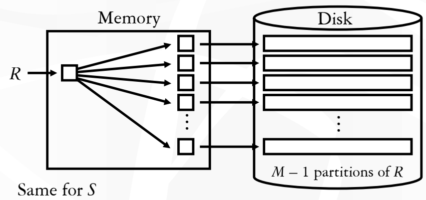
- $R \bowtie_{R.A = S.B} S$
- Main idea
  - Partition R and S by hashing their join attributes, and then consider corresponding partitions of R and S
  - If $r.A$ and $s.B$ get hashed to different partitions, they don't join



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

Partitioning phase

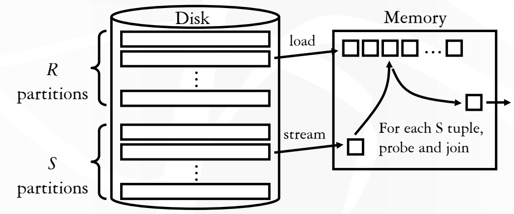
- ❖ Partition *R* and *S* according to the same hash function on their join attributes



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!

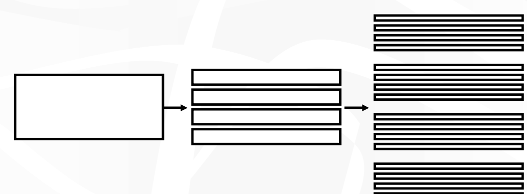


Performance of hash join

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

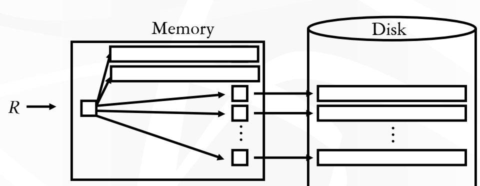
Hash join tricks

- ❖ What if a partition is too large for memory?
  - Read it back in and partition it further!
    - See the duality in multi-pass merge sort here?



Hybrid hash join

- ❖ What if there is extra memory available?
  - Use it to avoid writing/re-reading partitions
    - Of both *R* and *S*!



A generalization of the idea is described in the survey paper by Graefe

Hash join versus SMJ

(Assuming two-pass)

- ❖ I/O's: same
- ❖ Memory requirement: hash join is lower
  - $\text{sqrt}(\min(B(R), B(S))) < \text{sqrt}(B(R) + B(S))$
  - Hash join wins big 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)