### Query Processing

CPS 116
Introduction to Database Systems

### Announcements (November 17)
- Makeup lecture in audio format?
- Homework #4 assigned last Thursday
  - Due December 1, but please start early!
- Project milestone #2 feedback emailed
- Project demo period December 1-8
  - An email about sign-up will go out 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

### 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
- \( R \bowtie S \)
- 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
- 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
  - $I/O \leq B(R) + \lceil B(R) / (M - 2) \rceil \cdot B(S)$
  - 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 $B(R) / M$ 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: $\lceil \log_{M-1} [B(R) / M] \rceil + 1$
- $I/O$'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 $O(B(R) \cdot \log \eta B(R))$
- 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, 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 $S$
- $I/O$: sorting + $2 \cdot B(R) + 2 \cdot B(S)$
  - In most cases (e.g., join of key and foreign key)
  - Worst case is $B(R) \cdot B(S)$: everything joins
Example

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>R:</th>
<th>S:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>r₁.A = 1</td>
<td>s₁.B = 1</td>
<td>r₁.s₁</td>
</tr>
<tr>
<td></td>
<td></td>
<td>r₂.A = 3</td>
<td>s₂.B = 2</td>
<td>r₂.s₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td>r₃.A = 3</td>
<td>s₃.B = 3</td>
<td>r₃.s₃</td>
</tr>
<tr>
<td></td>
<td></td>
<td>r₄.A = 5</td>
<td>s₄.B = 3</td>
<td>r₄.s₄</td>
</tr>
<tr>
<td></td>
<td></td>
<td>r₅.A = 7</td>
<td>s₅.B = 8</td>
<td>r₅.s₅</td>
</tr>
<tr>
<td></td>
<td></td>
<td>r₆.A = 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>r₇.A = 8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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: 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: \( M > B(R)/M + B(S)/M \)
  - \( M > \sqrt{B(R) + B(S)} \)

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
    - Tricks:
      - 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

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!

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

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
  - $\sqrt{\min(B(R), B(S))} + 1 < \sqrt{B(R) + B(S)}$
  - 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
- 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
    - 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)

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: $B(R) + |R| \cdot (\text{index lookup})$
  - 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
- 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