Implementation of Relational Operations

Module 4, Lecture 1
Relational Operations

We will consider how to implement:

- **Selection** (\(\sigma\)) Selects a subset of rows from relation.
- **Projection** (\(\pi\)) Deletes unwanted columns from relation.
- **Join** (\(\bowtie\)) Allows us to combine two relations.
- **Set-difference** (\(-\)) Tuples in reln. 1, but not in reln. 2.
- **Union** (\(\cup\)) Tuples in reln. 1 and in reln. 2.
- **Aggregation** (SUM, MIN, etc.) and GROUP BY

Since each op returns a relation, ops can be *composed*! After we cover the operations, we will discuss how to optimize queries formed by composing them.
Schema for Examples

Sailors \((\text{sid}: \text{integer}, \text{sname}: \text{string}, \text{rating}: \text{integer}, \text{age}: \text{real})\)
Reserves \((\text{sid}: \text{integer}, \text{bid}: \text{integer}, \text{day}: \text{dates}, \text{rname}: \text{string})\)

- Similar to old schema; \textit{rname} added for variations.
- Reserves:
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages.
- Sailors:
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages.
Equality Joins With One Join Column

SELECT  *
FROM    Reserves R1, Sailors S1
WHERE   R1.sid=S1.sid

- In algebra: R ∞ S. Common! Must be carefully optimized. R × S is large; so, R × S followed by a selection is inefficient.

- Assume: M pages in R, \( p_R \) tuples per page, N pages in S, \( p_S \) tuples per page.
  - In our examples, R is Reserves and S is Sailors.

- We will consider more complex join conditions later.

- Cost metric: # of I/Os. We will ignore output costs.
**Simple Nested Loops Join**

For each tuple in the outer relation R, we scan the entire inner relation S.
- Cost: \( M + p_R \cdot M \cdot N = 1000 + 100 \cdot 1000 \cdot 500 \) I/Os.

Page-oriented Nested Loops join: For each page of R, get each page of S, and write out matching pairs of tuples \(<r, s>\), where r is in R-page and S is in S-page.
- Cost: \( M + M \cdot N = 1000 + 1000 \cdot 500 \)
- If smaller relation (S) is outer, cost = 500 + 500 \( \cdot 1000 \)

foreach tuple \( r \) in R do
  foreach tuple \( s \) in S do
    if \( r_i = s_j \) then add \(<r, s>\) to result
Index Nested Loops Join

foreach tuple r in R do
  foreach tuple s in S where r_i == s_j do
    add <r, s> to result

- If there is an index on the join column of one relation (say S), can make it the inner and exploit the index.
  - Cost: \( M + (M \times p_R) \times \text{cost of finding matching S tuples} \)

- For each R tuple, cost of probing S index is about 1.2 for hash index, 2-4 for B+ tree. Cost of then finding S tuples (assuming Alt. (2) or (3) for data entries) depends on clustering.
  - Clustered index: 1 I/O (typical), unclustered: upto 1 I/O per matching S tuple.
Examples of Index Nested Loops

- Hash-index (Alt. 2) on \textit{sid} of Sailors (as inner):
  - Scan Reserves: 1000 page I/Os, 100*1000 tuples.
  - For each Reserves tuple: 1.2 I/Os to get data entry in index, plus 1 I/O to get (the exactly one) matching Sailors tuple. Total: 220,000 I/Os.

- Hash-index (Alt. 2) on \textit{sid} of Reserves (as inner):
  - Scan Sailors: 500 page I/Os, 80*500 tuples.
  - For each Sailors tuple: 1.2 I/Os to find index page with data entries, plus cost of retrieving matching Reserves tuples. Assuming uniform distribution, 2.5 reservations per sailor (100,000 / 40,000). Cost of retrieving them is 1 or 2.5 I/Os depending on whether the index is clustered.
Block Nested Loops Join

- Use one page as an input buffer for scanning the inner S, one page as the output buffer, and use all remaining pages to hold ``block'' of outer R.
  - For each matching tuple r in R-block, s in S-page, add <r, s> to result. Then read next R-block, scan S, etc.

Diagram:

- R & S
- Hash table for block of R (k < B-1 pages)
- Input buffer for S
- Output buffer
- Join Result
Examples of Block Nested Loops

- Cost: Scan of outer + #outer blocks * scan of inner
  - #outer blocks = ⌈# of pages of outer / blocksize⌉

- With Reserves (R) as outer, and 100 pages of R:
  - Cost of scanning R is 1000 I/Os; a total of 10 blocks.
  - Per block of R, we scan Sailors (S); 10*500 I/Os.
  - If space for just 90 pages of R, we would scan S 12 times.

- With 100-page block of Sailors as outer:
  - Cost of scanning S is 500 I/Os; a total of 5 blocks.
  - Per block of S, we scan Reserves; 5*1000 I/Os.

- With sequential reads considered, analysis changes: may be best to divide buffers evenly between R and S.
Sort-Merge Join \((R \bowtie S)_{i=j}\)

- Sort R and S on the join column, then scan them to do a ``merge'' (on join col.), and output result tuples.
  - Advance scan of R until current R-tuple \(\geq\) current S tuple, then advance scan of S until current S-tuple \(\geq\) current R tuple; do this until current R tuple = current S tuple.
  - At this point, all R tuples with same value in Ri (current R group) and all S tuples with same value in Sj (current S group) match; output \(<r, s>\) for all pairs of such tuples.
  - Then resume scanning R and S.

- R is scanned once; each S group is scanned once per matching R tuple. (Multiple scans of an S group are likely to find needed pages in buffer.)
Example of Sort-Merge Join

<table>
<thead>
<tr>
<th>sid</th>
<th>sname</th>
<th>rating</th>
<th>age</th>
<th>sid</th>
<th>bid</th>
<th>day</th>
<th>rname</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>dustin</td>
<td>7</td>
<td>45.0</td>
<td>28</td>
<td>103</td>
<td>12/4/96</td>
<td>guppy</td>
</tr>
<tr>
<td>28</td>
<td>yuppy</td>
<td>9</td>
<td>35.0</td>
<td>28</td>
<td>103</td>
<td>11/3/96</td>
<td>yuppy</td>
</tr>
<tr>
<td>31</td>
<td>lubber</td>
<td>8</td>
<td>55.5</td>
<td>31</td>
<td>101</td>
<td>10/10/96</td>
<td>dustin</td>
</tr>
<tr>
<td>31</td>
<td>lubber</td>
<td>8</td>
<td>55.5</td>
<td>31</td>
<td>102</td>
<td>10/12/96</td>
<td>lubber</td>
</tr>
<tr>
<td>44</td>
<td>guppy</td>
<td>5</td>
<td>35.0</td>
<td>31</td>
<td>101</td>
<td>10/11/96</td>
<td>lubber</td>
</tr>
<tr>
<td>58</td>
<td>rusty</td>
<td>10</td>
<td>35.0</td>
<td>58</td>
<td>103</td>
<td>11/12/96</td>
<td>dustin</td>
</tr>
</tbody>
</table>

- **Cost**: $M \log M + N \log N + (M+N)$
  - The cost of scanning, $M+N$, could be $M*N$ (very unlikely!)
- With 35, 100 or 300 buffer pages, both Reserves and Sailors can be sorted in 2 passes; total join cost: 7500.
  (BNL cost: 2500 to 15000 I/Os)
Refinement of Sort-Merge Join

- We can combine the merging phases in the sorting of R and S with the merging required for the join.
  - With $B > \sqrt{L}$, where $L$ is the size of the larger relation, using the sorting refinement that produces runs of length $2B$ in Pass 0, #runs of each relation is $< B/2$.
  - Allocate 1 page per run of each relation, and `merge` while checking the join condition.
  - 
    - Cost: read+write each relation in Pass 0 + read each relation in (only) merging pass (+ writing of result tuples).
    - In example, cost goes down from 7500 to 4500 I/Os.

- In practice, cost of sort-merge join, like the cost of external sorting, is linear.
**Hash-Join**

- Partition both relations using hash function $h$: R tuples in partition $i$ will only match S tuples in partition $i$.

- Read in a partition of R, hash it using $h_2$ ($<> h$). Scan matching partition of S, search for matches.
Observations on Hash-Join

- #partitions \( k < B-1 \) (why?), and \( B-2 > \) size of largest partition to be held in memory. Assuming uniformly sized partitions, and maximizing \( k \), we get:
  - \( k = B-1, \) and \( M/(B-1) < B-2, \) i.e., \( B \) must be \( > \sqrt{M} \)

- If we build an in-memory hash table to speed up the matching of tuples, a little more memory is needed.

- If the hash function does not partition uniformly, one or more \( R \) partitions may not fit in memory. Can apply hash-join technique recursively to do the join of this \( R \)-partition with corresponding \( S \)-partition.
Cost of Hash-Join

- In partitioning phase, read+write both relns; \( 2(M+N) \). In matching phase, read both relns; \( M+N \) I/Os.
- In our running example, this is a total of 4500 I/Os.
- Sort-Merge Join vs. Hash Join:
  - Given a minimum amount of memory (what is this, for each?) both have a cost of \( 3(M+N) \) I/Os. Hash Join superior on this count if relation sizes differ greatly. Also, Hash Join shown to be highly parallelizable.
  - Sort-Merge less sensitive to data skew; result is sorted.
General Join Conditions

- Equalities over several attributes (e.g., $R.sid=S.sid$ AND $R.rname=S.sname$):
  - For Index NL, build index on $<sid, sname>$ (if S is inner); or use existing indexes on sid or sname.
  - For Sort-Merge and Hash Join, sort/partition on combination of the two join columns.

- Inequality conditions (e.g., $R.rname < S.sname$):
  - For Index NL, need (clustered!) B+ tree index.
    - Range probes on inner; # matches likely to be much higher than for equality joins.
  - Hash Join, Sort Merge Join not applicable.
  - Block NL quite likely to be the best join method here.