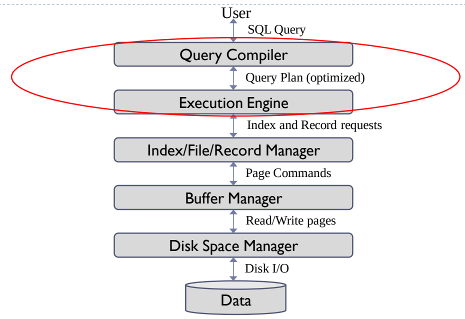
# Evaluation of Relational Operators: Chap. 14

CS634
Lecture 11

Slides based on "Database Management Systems" 3rd ed, Ramakrishnan and Gehrke

## Architecture of a DBMS




A first course in database systems, 3rd ed, Ullman and Widom



## Relational Algebra

- Relational operators:
  - Selection $\sigma$
  - Projection $\pi$
  - Join $\bowtie$ Combines several relations using conditions
  - Set-difference $-$ Union $\cup$ Intersection $\cap$
  - Aggregation and Grouping

## Example Schema

Sailors (<u>*sid*: integer</u>, *sname*: string, *rating*: integer, *age*: real)
Reserves (<u>*sid*: integer, *bid*: integer, *day*: dates</u>, *rname*: string)

- Similar to old schema; *rname* added
- Reserves:
  - 40 bytes long tuple, 100K records, 100 tuples per page, 1000 pages
- Sailors:
  - 50 bytes long tuple, 40K tuples, 80 tuples per page, 500 pages

## Selections with Simple Condition

$$\sigma_{attrOPval}(R)$$

- Case 1: No index, Unsorted data
  - Do scan
- Case 2: No Index, Sorted Data
  - Perform binary search on file (exact match or ranges)
  - O(log M), M = number of pages in file
- Case 3: Index Available
  - Is the index B+-Tree or Hash?
  - Is it clustered or not?

## Using an Index for Selections

- Cost depends on
  - Number of qualifying tuples
  - Clustering
- Cost has two components:
  - Finding qualifying data entries (typically small)
  - Retrieving records (could be large w/o clustering)
- Consider Reserves, assume 10% of tuples satisfy condition
  - Result has 10K tuples, 100 pages
  - With clustered index, cost is little more than 100 I/Os
  - If unclustered, up to 10000 I/Os!

## For Unclustered Indexes

- *Important refinement:*
  1. Find qualifying data entries
  2. Sort the rid's of the data records to be retrieved
  3. Fetch rids *in order*

- Ensures that each data page is looked at just once
  - although number of I/Os still higher than with clustering

## Example from Oracle: unclustered index on K500K (added to table bench)

```
SQL> select k500k, rowid from bench where k500k>=400 and k500k<403;
 K500K ROWID
---------- ------------------
       400 AAA8A4AACAAADZqAAU  }
       400 AAA8A4AACAAAGuHAAW  }  k500k = 400: 2 data entrie
       401 AAA8A4AACAAAFVzAAY  }
       401 AAA8A4AACAAAGRVAAC  }  k500k = 401: 2 data entries
       402 AAA8A4AACAAAEiLAAA
       402 AAA8A4AACAAAGWmAAB
       402 AAA8A4AACAAAGkWAAW     k500k=402:4 data entries
       402 AAA8A4AACAAAHpnAAE
```

- RIDs for a certain key are in sorted order in index.
- With 3 keys, the whole set of RIDs is not in RID order.
- This is an index-only query, no need to access heap table.

## Example from Oracle: unclustered index on K500K

```
SQL> select kseq from bench250 where k500k>=400 and k500k<403;
 KSEQ
----------
    432909
    894121
   1226517
...
 247946329
 248832188
 249145270
 249135567
1517 rows selected.
```

- Note that the RIDs were sorted before the KSEQ values were obtained from the heap table.
- For the smaller bench table, rid sort isn't done for this query.
- Mysql also sorts RIDs before at least some lookups, starting with v. 5.6 ("MRR" Multi Range Read, new feature)
- Rid sort works for RAID set too: each disk is given a sorted set of its

## General Conditions Selections

- Condition may be composite
  - In conjunctive form: easier to deal with
  - At least one disjunction: less favorable case

- Disjunctive form
  - Only one of the conditions, if met, qualifies tuple
  - Even if some disjunct is optimized, the other(s) may require scan
  - In general, this case dealt with using set union
  - Most DBMS optimizers focus on conjunctive forms

## Evaluating Conjunctive Forms (1/2)

- Find the *most selective access path*, retrieve tuples using it, and apply any remaining terms that don't match the index
  - *Most selective access path:* An index or file scan that we estimate will require the fewest page I/Os
  - Example: *day<8/9/94 AND bid=5 AND sid=3*
  - B+ tree index on *day* can be used; then, *bid=5* and *sid=3* must be checked for each retrieved tuple
  - Similarly, a hash index on *<bid, sid>* could be used; *day<8/9/94* must then be checked.

## Evaluating Conjunctive Forms (2/2)

- Intersect rid's
- If we have two or more matching indexes that use Alternatives (2) or (3) for data entries:
  - Get sets of rids of data records using each matching index
  - Then *intersect* these sets of rids (we'll discuss intersection soon!)
  - Retrieve the records and apply any remaining terms
  - Example: *day<8/9/94 AND bid=5 AND sid=3*
  - B+ tree index on *day* and a hash index on *sid*, both using Alt. (2)
  - Retrieve rids satisfying *day<8/9/94* using the B+ tree, rids satisfying *sid=3* using the hash, intersect, retrieve records and check *bid=5*

## Intersecting RIDs via Index JOIN

- Example: *day<8/9/94 AND bid=5 AND sid=3*
- B+ tree index on *day* and a hash index on *sid*, both using Alt. (2)
- Retrieve rids satisfying *day<8/9/94* using the B+ tree, rids satisfying *sid=3* using the hash, intersect, retrieve records and check *bid=5*
- Here the intersection is hopefully pipelined
- Another way to achieve this: Join the two indexes as files
  - As tables, indexes are I1 = (rid, day) and I2 = (rid, sid)
  - Join them: I1 where day<8/9/94 JOIN I2 where sid = 3
  - Obtain (rid, day, sid) satisfying the two conditions and providing rids
  - Pg. 446: Oracle does this.

## Projection

- Remove unwanted attributes
- Eliminate any duplicate tuples produced (the hard part)

## Projection with Sorting

- Modify Pass 0 of external sort to eliminate unwanted fields
  - Produce runs of about 2B pages are produced
  - Tuples in runs are smaller than input tuples
  - Size ratio depends on number and size of fields that are dropped
- Modify merging passes to eliminate duplicates
  - Thus, number of result tuples smaller than input
  - Difference depends on number of duplicates
- Cost
  - In Pass 0, read original relation (size M), write out same number of smaller tuples
  - In merging passes, fewer tuples written out in each pass. Using Reserves example, 1000 input pages reduced to 250 in Pass 0 if size ratio is 0.25

## Projection with Sorting

- Can be done without modifying sort:

1. Do attribute-dropping before feeding data (pipelined) to sort, end up with T pages.
2. Sort result
3. Post-process by watching for new row-values as data is produced.

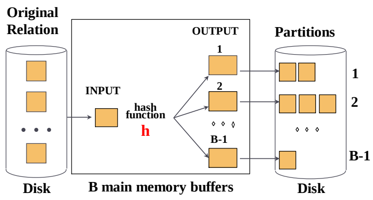
- Cost
  - In step 1, read original relation (size M), write out same number of smaller tuples
  - In merging passes, same number of tuples written out in each pass. Use normal sort cost for M pages, 2M * (# of passes)

## Projection with Hashing

- *Partitioning phase*:
  - Read R using one input buffer. For each tuple, discard unwanted fields, apply hash function *h1* to choose one of B-1output buffers
  - Each output buffer is feeding a run on disk
  - Result is B-1 partitions (of tuples with no unwanted fields), tuples from different partitions guaranteed to be distinct
  - See next slide for diagram
- *Duplicate elimination phase*: process runs from partitioning phase. Each run forms a partition of the data

## Hash Projection: Partitioning Phase

- Partition R using hash function **h**
- Duplicates will hash to the same partition

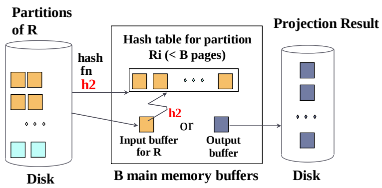


## Hash Projection: Second Phase

Read in a partition of R, hash it using **h2 (<> h!)**

Discard duplicates as go along.

When partition is all read in, scan the hash table and write it out as part of the projection result




## Projection with Hashing

- *Partitioning phase*: ends up with partitions of data, each held in a run on disk
- *Duplicate elimination phase*:
  - For each partition, read it and build an in-memory hash table, using hash *h2* on all fields, while discarding duplicates
  - If partition does not fit in memory, can apply hash-based projection algorithm recursively to this partition
- Cost
  - Read R, write out each tuple, but fewer fields, size T <= M. Result read in next phase. Total i/o cost: M + 2T<= 3M, similar to sort if it can be done in 2 passes and has pipelined output.

## Discussion of Projection

- Sort-based approach is the standard
  - better handling of skew and result is sorted.
  - Hashing is more parallelizable
- If index on relation contains all wanted attributes in its search key, do *index-only* scan
  - Apply projection techniques to data entries (much smaller!)
- If an ordered (i.e., tree) index contains all wanted attributes as *prefix* of search key, can do even better:
  - Retrieve data entries in order (index-only scan)
  - Discard unwanted fields, compare adjacent tuples to check for duplicates

## Equality Joins With One Join Column

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

- Most frequently occurring in practice
- We will consider more complex join conditions later
- *Cost metric*: number of I/Os
  - Ignore output costs

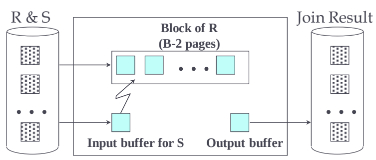
## Simple Nested Loops Join

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

- For each tuple in the *outer* relation R, we scan the entire *inner* relation S.
  - Cost: M + $p_R$ * M * N = 1000 + 100*1000*500 I/Os
- Page-oriented Nested Loops join:
  - For each *page* of R, get each *page* of S, and write out matching pairs
  - Cost: M + M*N = 1000 + 1000*500
  - If smaller relation (S) is outer, cost = 500 + 500*1000

## Block Nested Loops Join

- one page input buffer for scanning the inner S
- one page as the output buffer
- 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.



## Examples of Block Nested Loops

- Cost: Scan of outer + #outer blocks * scan of inner
  - #outer blocks = $\lceil \# \text{ of pages of outer} / \text{blocksize} \rceil$
- With Reserves (R) as outer, and 100 pages per block:
  - 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.
  - Total 1000 + 10*500 = 6000 i/os.
  - Need 101 buffer pages for this.
- 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.
  - Total 500 + 5*1000 = 5500 i/os. Same ballpark as above.
- Compare these to page-oriented NLJ: 500,000 i/o or worse!
- SSD: is equally helped by this kind of "block" algorithm

## Executing Joins: Index Nested Loops

```
foreach tuple r in R do
    foreach tuple s in S where ri == sj do
        add <r, s> to result
```

- Cost = M + ($M*p_R$) * (cost of finding matching S tuples)
- M = number of pages of R, $p_R$ = number of R tuples per page
- If relation has index on join attribute, make it inner relation
  - For each outer tuple, cost of probing inner index is 1.2 for hash index, 2-4 for B+, plus cost to retrieve matching S tuples
  - Clustered index typically single I/O (Alt 2) or none (Alt. 1)
  - Unclustered index 1 I/O per matching S tuple

## Example of Index Nested Loops (1/2)

Case 1: Hash-index (Alternative 2) on *sid* of Sailors

- Choose Sailors as inner relation
- Scan Reserves: 100K tuples, 1000 page I/Os
- For each Reserves tuple
  - 1.2 I/Os to get data entry in index
  - 1 I/O to get (the exactly one) matching Sailors tuple (primary key)
- Total: 221,000 I/Os
- Most of these i/o's are random (within tablespace), so SSD would be about 25x faster than HDD.

## Example of Index Nested Loops (2/2)

Case 2: Hash-index (Alternative 2) on *sid* of Reserves

- Choose Reserves as inner
- Scan Sailors: 40K tuples, 500 page I/Os
- For each Sailors tuple
  - 1.2 I/Os to find index page with data entries
  - Assuming uniform distribution, 2.5 matching records per sailor
  - Cost of retrieving records is nothing (Alt 1 clustered), single I/O (Alt. 2 clustered index) or 2.5 I/Os (unclustered index)
- Total: 48,500 I/Os (clustered Alt 1), 88,500 I/Os (clustered Alt 2) or 148,500 I/Os (unclustered)
- Most of these i/o's are random (within tablespace), so SSD would be about 25x faster than HDD.

## Sort-Merge Join

- Sort R and S on the join column (book assumes file-to-file sort, no pipelining)
- Then scan them to do a merge on join column:
  - Advance scan of R until current R-tuple >= current S tuple
  - Then, advance scan of S until current S-tuple >= current R tuple
  - Repeat 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
    - May have to rescan part of one of the input files if have pages of duplicate join keys vs. multiple matching join keys
  - Resume scanning R and S

## Sort-Merge Join Cost

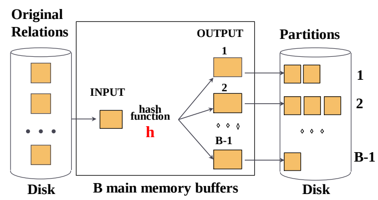
- R is scanned once
- Each S group is scanned once per matching R tuple
  - Multiple input-file scans per group needed only if S records with same join attribute value span multiple pages
  - Multiple such scans of an S group are likely to find needed pages in buffer
- Cost: (assume B buffers)
  - Sort(R) + Sort(S) + merge
  - $2M\ (1+\log_{B-1}(M/B)) + 2N\ (1+\log_{B-1}(N/B)) + (M+N)$
  - The cost of scanning, M+N, could be M*N worst case (very unlikely!)
  - In many cases, the join attribute is primary key in one of the tables, which means no duplicates in one merge stream.
  - Since both sort and merge use sequential i/o, SSD is "only" 5x faster than HDD here.

## 2-Pass Sort-Merge Join

- With enough buffers, sort can be done in 2 passes
  - First pass generates N/B sorted runs of B pages each
  - If one page from each run + output buffer fits in memory, then merge can be done in one pass; denote larger relation by L
  - $L/B + 1 <= B$, holds if (approx) $B > \sqrt{L}$ $L < B^2$
- One optimization of sort allows runs of 2B on average
  - First pass generates N/2B sorted runs of 2B pages each
  - Another optimization (pg, 462) runs the two sorts side-by-side and pipelines their results into the final merge, avoiding intermediate files. **(But we're not officially covering these optimizations)**
- Merge can be combined with filtering of matching tuples
- The cost of sort-merge join becomes 3(M+N), assuming both M and N are < $B^2$ and the sorts-to-merge are pipelined.

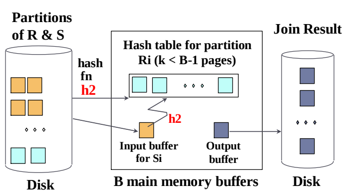
## Hash-Join: Partitioning Phase

- Partition both relations using hash function **h**
- R tuples in partition *i* will only match S tuples in partition *I*
- This is the similar to the partitioning phase of Projection by Hashing




## Hash-Join: Probing Phase

Read in a partition of R, hash it using **h2 (<> h!)**
Scan matching partition of S, search for matches.




Note: A smaller table has smaller partitions, so each of its partition hash tables will more easily fit in memory

## Hash-Join Properties

- #partitions k <= B-1 because one buffer is needed for scanning input
- Assuming uniformly sized partitions, and maximizing k:
  - k= B-1, and M/(B-1) = size of one partition <= B-2, i.e., $B > \sqrt{M}$
  - M is smaller of the two relations!
  - So best to use the smaller table's partitions for the second-phase hash tables.
  - i.e., we can take advantage of one table being small, unlike sort-merge.
- If the hash function does not partition uniformly, one or more second-phase 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 R and S: 2(M+N)
- In matching phase, read both R and S: M+N
  - (assumes hash tables fit in memory, $B > \sqrt{M}$ )
  - Note M can be size of the *smaller* table here.
- With sizes of 1000 and 500 pages, total is 4500 I/Os
- SSD: i/os are sequential, so "only" 5x faster.

## Hash-Join vs Sort-Merge Join

- Given sufficient amount of memory both have a cost of 3(M+N) I/Os
  - Assumes no pipelining *into* the whole operation, so both input tables need full scan, M+N i/os.
  - Ignores any cost of materializing the output of the operation.
- Hash Join superior on this count if relation sizes differ greatly
- Hash Join shown to be highly parallelizable, unlike sort.
- Sort-Merge less sensitive to data skew, and result is sorted

## General Join Conditions (1/2)

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

## General Join Conditions (2/2)

- Inequality conditions
  - e.g., *R.rname* < *S.sname*
  - For Index Nested Loop 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 Nested Loop quite likely to be the best join method here

## Set Operations

- Intersection and cross-product special cases of join
- Union and Except similar
- Both hashing and sorting are possible
  - Similar in concept with projection

## Union with Sorting

- Sort both relations (on combination of all attributes)
- Scan sorted relations and merge them
- *Alternative*: Merge runs from Pass 0 for *both* relations

## Union with Hashing

- Partition R and S using hash function *h*
- For each S-partition, build in-memory hash table (using *h2*)
  - scan corresponding R-partition and add tuples to table while discarding duplicates

## Aggregate Operations (sum, avg, count, min, max)

- Without grouping:
  - In general, requires scanning the relation
  - Given index whose search key includes all attributes in the SELECT or WHERE clauses, can do **index-only scan**
  - Example: select avg(s.age) from sailors s
    - With index on age, just scan it for age values, take avg on the fly.
  - Select max(s.age) from sailors s where age < 50;
    - Still index-only
  - Select max(s.age) from sailors s where rating = 5;
    - Uses table scan unless there is an index on rating.
    - With index, need to cost table scan vs. many index lookups

## Aggregate Operations

- With grouping:
  - Sort on group-by attributes, then scan relation and compute aggregate for each group
  - Similar approach based on hashing on group-by attributes
  - Given tree index whose search key includes all attributes in SELECT, WHERE and GROUP BY clauses, can do index-only scan
    - Ex: select age, count(*) from sailors
      group by age
      With B+-tree index on age
  - If group-by attributes form prefix of search key, can retrieve data entries/tuples in group-by order

## Impact of Buffering

- Repeated access patterns interact with buffer replacement policy
  - Inner relation is scanned repeatedly in no-index Nested Loop Joins
  - With enough buffer pages to hold inner, replacement policy does not matter. Otherwise, MRU is best, LRU is worst (*sequential flooding*)
  - What about Index Nested Loops? Sort-Merge Join?

## Summary

- Queries are composed of a few basic operators
  - The implementation of these operators can be carefully tuned
- Many alternative implementation techniques for each operator
- No universally superior technique for most operators
- Must consider available alternatives for each operation in a query and choose best one based on system statistics