Query Optimization: Chap. 15

CS634
Lecture 12

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

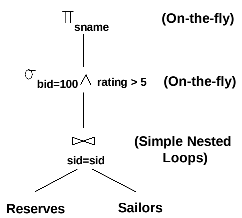
Query Evaluation Overview

- SQL query first translated to relational algebra (RA)
  - Actually, some additional operators needed for SQL
  - Tree of RA operators, with choice of algorithm among available implementations for each operator
- Main issues in query optimization
  - For a given query, what plans are considered?
  - Algorithm to search plan space for cheapest (estimated) plan
  - How is the cost of a plan estimated?
- Objective
  - Ideally: Find best plan
  - Practically: Avoid worst plans!

Evaluation Example

```
SELECT S.sname
FROM Reserves R, Sailors S
WHERE R.sid=S.sid AND
   R.bid=100 AND S.rating>5
```

Annotated Tree



Cost Estimation

For each plan considered, must estimate:

- Cost of each operator in plan tree
  - Depends on input cardinalities
  - Operation and access type: sequential scan, index scan, joins
- Size of result for each operation in tree
  - Use information about the input relations
  - For selections and joins, assume independence of predicates

Query Blocks

- SQL query parsed into a collection of *query blocks*
  - Blocks are optimized one at a time
- Nested blocks can be treated as calls to a subroutine
  - One call made once per outer tuple
  - In some cases cross-block optimization is possible
  - A good query optimizer can unnest queries

```
SELECT S.sname
FROM Sailors S
WHERE S.age IN
   (SELECT MAX (S2.age)
    FROM Sailors S2)
```

Outer block

Nested block

Query Blocks

```
SELECT S.sname
FROM Sailors S
WHERE S.age IN
   (SELECT MAX (S2.age)
    FROM Sailors S2)
```

- In fact this is an uncorrelated subquery: The inner block can be evaluated once!

Query Blocks

```
SELECT  S.sname
FROM  Sailors S
WHERE  S.age IN
    (SELECT  MAX (S2.age)
     FROM  Sailors S2
        WHERE S2.rating = S.rating)
```

- Looking for sailors who are of max age in their own rating group.
- Correlated subquery: each row in S needs its own execution of the inner block

Block Optimization

- Block = Unit of optimization
- For each block, consider:
  1. All available access methods, for each relation in FROM clause
  2. All **left-deep join trees**
     - Left-deep defined pg. 415: right child of each join is a base table
     - Start with all ways to join the relations one-at-a-time
     - Consider all relation permutations and join methods
- Recall:
- Left table = outer table of a nested loop join
- Left table of NLJ can be pipelined: rows used one at a time in order
- But need to consider other join methods too, giving up pipelining in many cases

$\sigma\pi\times$ Expressions

- Query is simplified to a selection-projection-cross product expression
  - Aggregation and grouping can be done afterwards
- Optimization with respect to such expressions
- Cross-product includes conceptually joins
  - Will talk about equivalences in a bit

Statistics and Catalogs

- To choose an efficient plan, we need information about the relations and indexes involved
- ***Catalogs*** contain information such as:
  - Tuple count (NTuples) and page count (NPages) for each relation
  - Distinct key value count (NKeys) for each index, INPages
  - Index height, low/high key values (Low/High) for each tree index
  - Histograms of the values in some fields (optional)
- Catalogs updated periodically
  - Approximate information used, slight inconsistency is ok
  - Databases provide tools for updating stats on demand

Size Estimation and Reduction Factors

SELECT attribute list
FROM relation list
WHERE term_1 AND … AND term_k

- Maximum number of tuples is cardinality of cross product
- Reduction factor (RF) associated with each *term* reflects its impact in reducing result size
  - Implicit assumption that *terms* are independent!
  - *col = value* has RF =1/NKeys(*I*), given index *I* on *col*
  - *col1 = col2* has RF = 1/max(NKeys(*I1*), NKeys(*I2*))
  - *col > value* has RF = (High(*I*)-value)/(High(*I*)-Low(*I*))
    - Example: rating > 6 has RF = 4/10 = 0.4

Histograms

- Most often, data values are not uniformly distributed within domain
  - Skewed distributions result in inaccurate cost estimations
- Histograms
  - More accurate statistics
  - Break up the domain into buckets
  - Store the count of records that fall in each bucket
- Tradeoff
  - Histograms are accurate, but take some space
  - The more fine-grained the partition, the better accuracy
    - But more space required

Histogram Classification

- **Equiwidth**
  - Domain split into equal-length partitions
  - Large difference between counts in different buckets
  - Dense areas not sufficiently characterized
- **Equidepth**
  - Histograms "adapts" to data distribution
  - Fewer buckets in sparse areas, more buckets in dense areas
  - Used by Oracle (pg. 485)

Relational Algebra Equivalences

- Why are they important?
- They allow us to:
  - Convert cross-products to joins
    - Cross products should always be avoided (when possible)
  - Choose different join orders
    - Recall that choice of outer/inner influences cost
  - "Push-down" selections and projections ahead of joins
    - When doing so decreases cost

Relational Algebra Equivalences

Selections:

$$\sigma_{c1 \wedge \ldots \wedge cn}(R) \equiv \sigma_{c1}(\ \ldots\ \sigma_{cn}(R)) \qquad \textit{Cascade}$$

$$\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c2}(\sigma_{c1}(R)) \qquad \textit{Commute}$$

- Cascade property:
  - Allows us to check multiple conditions in same pass
  - Allows us to "push down" only partial conditions (when not possible/advantageous to push entire condition)

Relational Algebra Equivalences

Projections:

$$\pi_{a1}(R) \equiv \pi_{a1}(\ \ldots(\pi_{an}(R))) \qquad \textit{Cascade}$$

If every a_i set is included in $a_{i+1,}$
Example:
a1 = {a,b}, a2 = {a,b,c}
$\pi_{a2}(T)$ has (a, b, c) columns
$\pi_{a1}(\pi_{a2}(T))$ has (a,b) columns, same as $\pi_{a1}(T)$

Relational Algebra Equivalences

Joins:

$$(R \bowtie S) \equiv (S \bowtie R) \qquad \textit{Commute}$$

$$R \bowtie (S \bowtie T) \equiv (R \bowtie S) \bowtie T \qquad \textit{Associative}$$

Sketch of proof:
- Show for cross product
- Add join conditions as selection operators
- Use cascading selections in associative case

Relational Algebra Equivalences

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$$(R \bowtie S) \equiv (S \bowtie R) \qquad \textit{Commute}$$

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- Commutative property:
  - Allows us to choose which relation is inner/outer
- Associative property:
  - Allows us to restrict plans to left-deep only, i.e., any query tree can be turned into a left-deep tree.

Relational Algebra Equivalences

Commuting selections with projections

- Projection can be done before selection if all attributes in the condition evaluation are retained by the projection

$$\pi_a(\sigma_c(R)) \equiv \sigma_c(\pi_a(R))$$

Relational Algebra Equivalences

Commute selection with join

- Only if all attributes in condition appear in one relation and not in the other: ***c*** includes only attributes from ***R***

$$\sigma_c(R \bowtie S) \equiv \sigma_c(R) \bowtie S$$

- Condition can be decomposed and "pushed" down before joins

$$\sigma_{c1 \wedge c2}(R \bowtie S) \equiv \sigma_{c1}(R) \bowtie \sigma_{c2} S$$

- Here, ***c1*** includes only attributes from ***R*** and ***c2*** only attributes from ***S***

Relational Algebra Equivalences

Commute projection with join

- Only if attributes in join condition appear in the corresponding projection lists (so they aren't "projected out")

$$\pi_a(R \bowtie_c S) \equiv \pi_{a1}(R) \bowtie_c \pi_{a2}(S)$$

System R Optimizer

- Developed at IBM starting in the 1970's
  - Most widely used currently; works well for up to 10 joins
- Cost estimation
  - Statistics maintained in system catalogs
  - Used to estimate cost of operations and result sizes
- Query Plan Space
  - Only the space of left-deep plans is considered
  - Left-deep plans allow output of each operator to be pipelined into the next operator without storing it in a temporary relation
  - Cartesian products avoided

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SQL Query Semantics (pg. 136, 156)

1. compute the cross product of tables in FROM
2. delete rows that fail the WHERE clause
3. project out columns not mentioned in select list or group by or having clauses
4. group rows by GROUP BY
5. apply HAVING to the groups, dropping some out
6. if necessary, apply DISTINCT
7. if necessary, apply ORDER BY

Note this all follows the order of the SELECT clauses, except for projection and DISTINCT, so it's not hard to remember.

Single-Relation Plans

Single-Relation Plans

- FROM clause contains single relation
- Query is combination of selection, projection, and aggregates (possibly GROUP BY and HAVING, but these come late in the logical progression, so usually less crucial to planning)
- Main issue is to select best from all available access paths (either file scan or index)
- Access path involves the table and the WHERE clause
- Another factor is whether the output must be sorted
  - E.g., GROUP BY requires sorting (or hashing)
  - Sorting may be done as separate step, or using an index if an indexed access path is available

Plans Without Indexes

- Only access path is file scan
- Apply selection and projection to each retrieved tuple
  - Projection may or may not use duplicate elimination, depending on whether there is a DISTINCT keyword present
- GROUP BY:
- Write out intermediate relation after selection/projection
- (or pipeline into sort)
- Sort intermediate relation to create groups

- Apply aggregates on-the-fly per each group
  - HAVING also performed on-the-fly, no additional I/O needed

Plans With Indexes

- There are four cases:

1. Single-index access path
   - Each index offers an alternative access path
   - Choose one with lowest I/O cost
   - Non-primary conjuncts, projection, aggregates/grouping applied next
2. Multiple-index access path
   - Each index used to retrieve set of rids
   - Rid sets intersected, result sorted by page id
   - (Alternatively, join indexes as tables)
   - Retrieve each page only once
   - Non-primary conjuncts, projection, aggregates/grouping applied next

Plans With Indexes (contd.)

3. Tree-index access path: extra possible use…
   - If GROUP BY attributes prefix of tree index, retrieve tuples in order required by GROUP BY
   - Apply selection, projection for each retrieved tuple, then aggregate
   - Works well for clustered indexes

   Example: With tree index on rating

```
SELECT count(*), max(age)
FROM Sailors S
GROUP BY rating
```

Plans With Indexes (contd.)

3. Index-only access path
   - If all attributes in query included in index, then there is no need to access data records: **index-only scan**
   - If index matches selection, even better: only part of index examined
   - Does not matter if index is clustered or not!
   - If GROUP BY attributes prefix of a tree index, no need to sort!
   - Example: With tree index on rating

```
SELECT max(rating),count(*)
FROM Sailors S
```

   - Note count(*) doesn't require access to row, just RID.

Example Schema

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

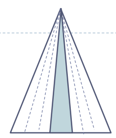
- Similar to old schema; *rname* added
- Reserves:
  - 40 bytes long tuple, 100K records, 100 tuples per page, 1000 pages
- Sailors:
  - 50 bytes long tuple, 40K tuples, 80 tuples per page, 500 pages
- Assume index entry size 10% of data record size

Cost Estimates for Single-Relation Plans

- Sequential scan of file:
  - *NPages(R)*
- Index *I* on primary key matches selection
  - *Cost is Height(I)+1 for a B+ tree, about 1.2 for hash index*
- Clustered index *I* matching one or more conjuncts:
  - *NPages(CI) * product of RF's of matching conjuncts*
    *Quick estimate: Npages(CI) = 1.1*NPages(TableData)*
    i.e. 10% more for needed keys
- Non-clustered index *I* matching one or more conjuncts:
  - *(NPages(I)+NTuples(R)) * product of RF's of matching conjuncts*
    *Quick estimate: Npages(I) = .1*Npages(R) (10% of data size)*
- *Note: these formulas are not in the text, but are consistent with the discussions and examples there.*

Example

```
SELECT S.sid
FROM Sailors S
WHERE S.rating=8
```



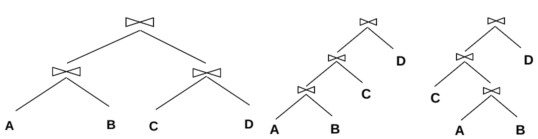
Note: One rating value owns a fraction (1/10) of the index at all levels, so #pages accessed = (1/10) Npages(CI) Or (1/10) Npages(I)

- File scan: retrieve all 500 pages
- Clustered Index *I* on *rating*
  (1/NKeys(I)) * (NPages(CI)) = (1/10) * (50+500) pages
- Unclustered Index *I* on *rating*
  (1/NKeys(I)) * (NPages(I)+NTuples(S)) = (1/10) * (50+40000) pages

Multiple-Relation Plans

Queries Over Multiple Relations

- In System R *only left-deep join trees* are considered
  - In order to restrict the search space
  - Left-deep trees allow us to generate all *fully pipelined* plans
    - Intermediate results not written to temporary files.
    - Not all left-deep trees are fully pipelined (e.g., sort-merge join)



Left-deep

Enumeration of Left-Deep Plans

- Among all left-deep plans, we need to determine:
  - the order of joining relations
  - the access method for each relation
  - the join method for each join
- Enumeration done in N passes (if N relations are joined):
  - Pass 1: Find best 1-relation plan for each relation
  - Pass 2: Find best way to join result of each 1-relation plan (as outer) to another relation - result is the set of all 2-relation plans
  - Pass N: Find best way to join result of a (N-1)-relation plan (as outer) to the N'th relation - result is the set of all N-relation plans
- Speed-up computation using dynamic programming (remember details of good plans to avoid recalc)

Enumeration of Left-Deep Plans (contd.)

- For each subset of relations, retain only:
  - Cheapest plan overall, plus
  - Cheapest plan for each *interesting order* of the tuples
- Interesting order: order that allows execution of GROUP BY without requiring an additional step of sorting, aggregates
- Avoid Cartesian products if possible
  - An N-1 way plan is not combined with an additional relation unless there is a join condition between them
  - Exception is case when all predicates in WHERE have been used up (i.e., query itself requires a cross-product)
    - Ex: select … from T1, T2, T3 where T1.x = T2.x
    - Only one join condition, 3 tables, so end up with cross product

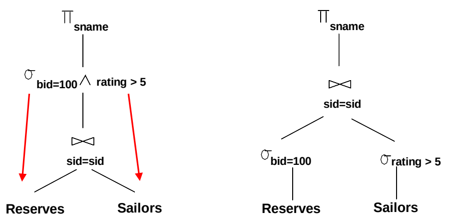
Cost Estimation for Multi-Relation Plans

- Two components:

1. Size of intermediate relations
   - Maximum tuple count is the product of the cardinalities of relations in the FROM clause
   - *Reduction factor (RF)* associated with each condition term
   - *Result cardinality* estimate = Max # tuples * product of all RF's
   - Example query on next slide:
     - Result cardinality estimate = (40K*100K) * ((1/100)*(5/10)*(1/40K)) = 500
     - This means we estimate the query returns 500 rows as its result
     - It is not a "cost" calculation
     - Here 1/40K = RF of join condition, 1/100 assumes 100 boats.
2. Cost of each join operator
   - Depends on join method

Example

SELECT S.sname
FROM Sailors S, Reserves R
WHERE S.sid=R.sid AND S.rating>5 AND R.bid=100



But this is not left-deep!

Example

Sailors:
Unclustered B+ tree on *rating*
Unclustered Hash on *sid*
Reserves:
Unclustered B+ tree on *bid*

Pass 1 Single-relation plans

- *Sailors*
  - B+ tree matches *rating>5*
  - Most selective access path
    - But index unclustered!
    - Sometimes may prefer scan
- *Reserves*
  - B+ tree on *bid* matches selection *bid=100*
  - Cheapest plan for this table

Note: Here we are evaluating plans as candidates for the leftmost spot in the final plan
Result of Pass 1: One plan for each table.

Example

Pass 2

- Consider each plan retained from Pass 1 as the outer, and how to join it with the (only) other relation
- *Sailors outer, Reserves inner*
  - No index matches join condition, this could be done as block nested loop
- *Reserves outer, Sailors inner*
  - Since we have hash index on sid for Sailors, this could be a cheap plan using an indexed nested loop
  - This would mean S.rating>5 is done after join.
  - Also see discussion of this on pg. 412, point 3
  - End up with left-deep plan.

Example, cont. (pipelining not in book)

- Also need to check sort-merge join
- But that requires materialization of input tables, an extra expense (or use pipelining into sort)
- Need to cost all three competing plans, choose least expensive
- Note that left-deep plans assume nested-loop joins are in use, so may miss good hash join plans
- Note on pg. 500: Oracle considers non-left-deep plans to better utilize hash joins.

Nested Queries

- Nested block is optimized independently, with the outer tuple considered as providing a selection condition
- Outer block is optimized with the cost of "calling" nested block computation taken into account
- Implicit ordering of these blocks means that some good strategies are not considered
- *The non-nested version of the query is typically optimized better*

Nested Queries

```
SELECT  S.sname
FROM  Sailors S
WHERE EXISTS
   (SELECT  *
    FROM  Reserves R
    WHERE  R.bid=103
    AND  R.sid=S.sid)
```

Equivalent non-nested query:

```
SELECT  S.sname
FROM Sailors S, Reserves R
WHERE  S.sid=R.sid
  AND R.bid=103
```