CAS CS 460/660
Introduction to Database Systems

Query Optimization II

Review

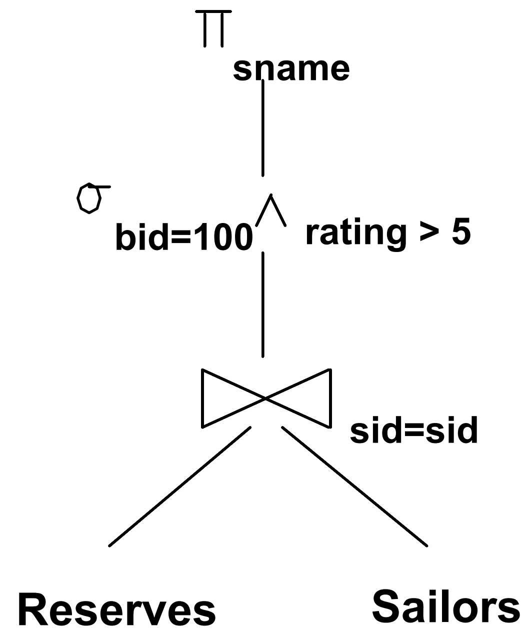
- Implementation of Relational Operations as Iterators
  - Focus largely on External algorithms (sorting/hashing)
- Choices depend on indexes, memory, stats,…
- Joins
  - Blocked nested loops:
    - simple, exploits extra memory
  - Indexed nested loops:
    - best if 1 rel small and one indexed
  - Sort/Merge Join
    - good with small amount of memory, bad with duplicates
  - Hash Join
    - fast (enough memory), bad with skewed data
    - Relatively easy to parallelize
- Sort and Hash-Based Aggs and DupElim

Query Optimization Overview

- Query can be converted to relational algebra
- Rel. Algebra converted to tree, joins as branches
- Each operator has implementation choices
- Operators can also be applied in different order!

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

$\pi_{(sname)}(\sigma_{(bid=100 \wedge rating > 5)} (Reserves \bowtie Sailors))$



Relational Algebra Equivalences

- Allow us to choose different operator orders and to `push' selections and projections ahead of joins.
- *Selections*:

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

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

- *Projections:*

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

(if an includes an-1 includes… a1)

- *Joins:*

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

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

These two mean we can do joins in any order.

More Equivalences

- A projection commutes with a selection that only uses attributes retained by the projection.

- Selection between attributes of the two arguments of a cross-product converts cross-product to a join.

- Selection Push: selection on R attrs commutes with

$R \bowtie S$: $\sigma(R \bowtie S) \equiv \sigma(R) \bowtie S$

- Projection Push: A projection applied to $R \bowtie S$ can be pushed before the join by retaining only attributes of R (and S) that are needed for the join or are kept by the projection.

The “System R” Query Optimizer

- Impact:
  - Inspired most optimizers in use today
  - Works well for small-med complexity queries (< 10 joins)
- Cost estimation:
  - Very inexact, but works ok in practice.
  - Statistics, maintained in system catalogs, used to estimate cost of operations and result sizes.
  - Considers a simple combination of CPU and I/O costs.
  - More sophisticated techniques known now.
- Plan Space: Too large, must be pruned.
  - Only the space of *left-deep plans* is considered.
  - Cartesian products avoided.

Cost Estimation

- To estimate cost of a plan:
  - Must *estimate cost* of each operation in plan tree and sum them up.
    - Depends on input cardinalities.
  - So, must *estimate size of result* for each operation in tree!
    - Use information about the input relations.
    - For selections and joins, assume independence of predicates.
- In System R, cost is boiled down to a single number consisting of

  #I/O ops + *factor* * #CPU instructions

Statistics and Catalogs

- Need information about the relations and indexes involved.

  Catalogs typically contain at least:
  - # tuples (**NTuples**) and # pages (**NPages**) per rel'n.
  - # distinct key values (**NValues**) for each index.
  - low/high key values (**Low/High**) for each index.
  - Index height (**IHeight**) for each tree index.
  - # index pages (**INPages**) for each index.

- Stats in catalogs updated periodically.
  - Updating whenever data changes is too expensive; lots of approximation anyway, so slight inconsistency ok.

- More detailed information (e.g., histograms of the values in some field) are sometimes stored.

Size Estimation and Reduction Factors

- Consider a query block:

```
SELECT  attribute list
FROM  relation list
WHERE  term1 AND ... AND termk
```

- *Reduction factor (RF)* associated with each *term* reflects the impact of the *term* in reducing result size.
- *RF is usually called "selectivity".*
- How to predict size of output?
  - Need to know/estimate input size
  - Need to know/estimate RFs
  - Need to know/assume how terms are related

Result Size Estimation for Selections

- *Result cardinality (for conjunctive terms)* =
  \# input tuples * product of all RF's.

  Assumptions:

  1. Values are uniformly distributed and *terms* are independent!
  2. In System R, stats only tracked for indexed columns

     (modern systems have removed this restriction)

- Term *col=value*

  RF = *1/NValues(I) (e.g. rating=5, RF = 1/10 (assume rating:[1,10])*

- Term *col1=col2* (This is handy for joins too…)

  RF = *1/MAX(NValues(I1), NValues(I2))*

- Term *col>value*

  RF = *(High(I)-value)/(High(I)-Low(I))*

- *Note, In System R, if missing indexes, assume 1/10!!!*

Reduction Factors & Histograms

- For better RF estimation, many systems use histograms:

No. of Values	2	3	3	1	8	2	1
Value	0-.99	1-1.99	2-2.99	3-3.99	4-4.99	5-5.99	6-6.99

equiwidth

No. of Values	3	3	3	3	3	3	3
Value	0-.99	1-1.99	2-2.99	3-4.05	4.06-4.67	4.68-4.99	5-6.99

equidepth

Histograms and other Stats

- Postgres uses equidepth histograms (need to store just the boundaries) and Most Common Values (MCV).

- Example:

most_common_vals | {EJAAAA,BBAAAA,CRAAAA,FCAAAA,FEAAAA,GSAAAA,JOAAAA,MCAAAA,NAAAAA}

most_common_freqs | {0.00333333,0.003,0.003,0.003,0.003,0.003,0.003,0.003,0.003}

The estimator uses both histograms (for range queries) and MCVs for exact match queries (equality).

Sometimes, we use both to estimate range queries and join results.

See more:

http://www.postgresql.org/docs/9.2/interactive/row-estimation-examples.html

Result Size estimation for joins

- Q: Given a join of R and S, what is the range of possible result sizes (in #of tuples)?
  - Hint: what if R and S have no attributes in common?
  - Join attributes are a key for R (and a Foreign Key in S)?
- General case: join attributes in common but a key for neither:
  - estimate each tuple r of R generates NTuples(S)/NKeys(A,S) result tuples, so result size estimate:

    (NTuples(R) * NTuples(S)) / NValues(A,**S**)

  - but can also can estimate each tuple s of S generates NTuples(R)/ NKeys(A,R) result tuples, so:

    (NTuples(R) * NTuples(S)) / NValues(A,**R**)

  - If these two estimates differ, take the lower one!

Enumeration of Alternative Plans

- There are two main cases:
  - Single-relation plans (unary ops) and Multiple-relation plans

- For unary operators:
  - For a scan, each available access path (file scan / index) is considered, and the one with the least estimated cost is chosen.

  - consecutive **Scan, Select, Project** and **Aggregate** operations can be essentially carried out together

  (e.g., if an index is used for a selection, projection is done for each retrieved tuple, and the resulting tuples are *pipelined* into the aggregate computation).

I/O Cost Estimates for Single-Relation Plans

- Index I on primary key matches selection:
  - *Cost is Height(I)+1 for a B+ tree, about 1.2 for hash index (or 2.2)*
- Clustered index I matching one or more selects:
  - *(NPages(I)+NPages(R)) * product of RF’s of matching selects.*
- Non-clustered index I matching one or more selects:
  - *(NPages(I)+NTuples(R)) * product of RF’s of matching selects.*
- Sequential scan of file:
  - *NPages(R).*

  - ***Note:*** *Must also charge for duplicate elimination if required*

Schema for Examples

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

- Reserves:
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages. 100 distinct bids.
- Sailors:
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages. 10 Ratings, 40,000 sids.

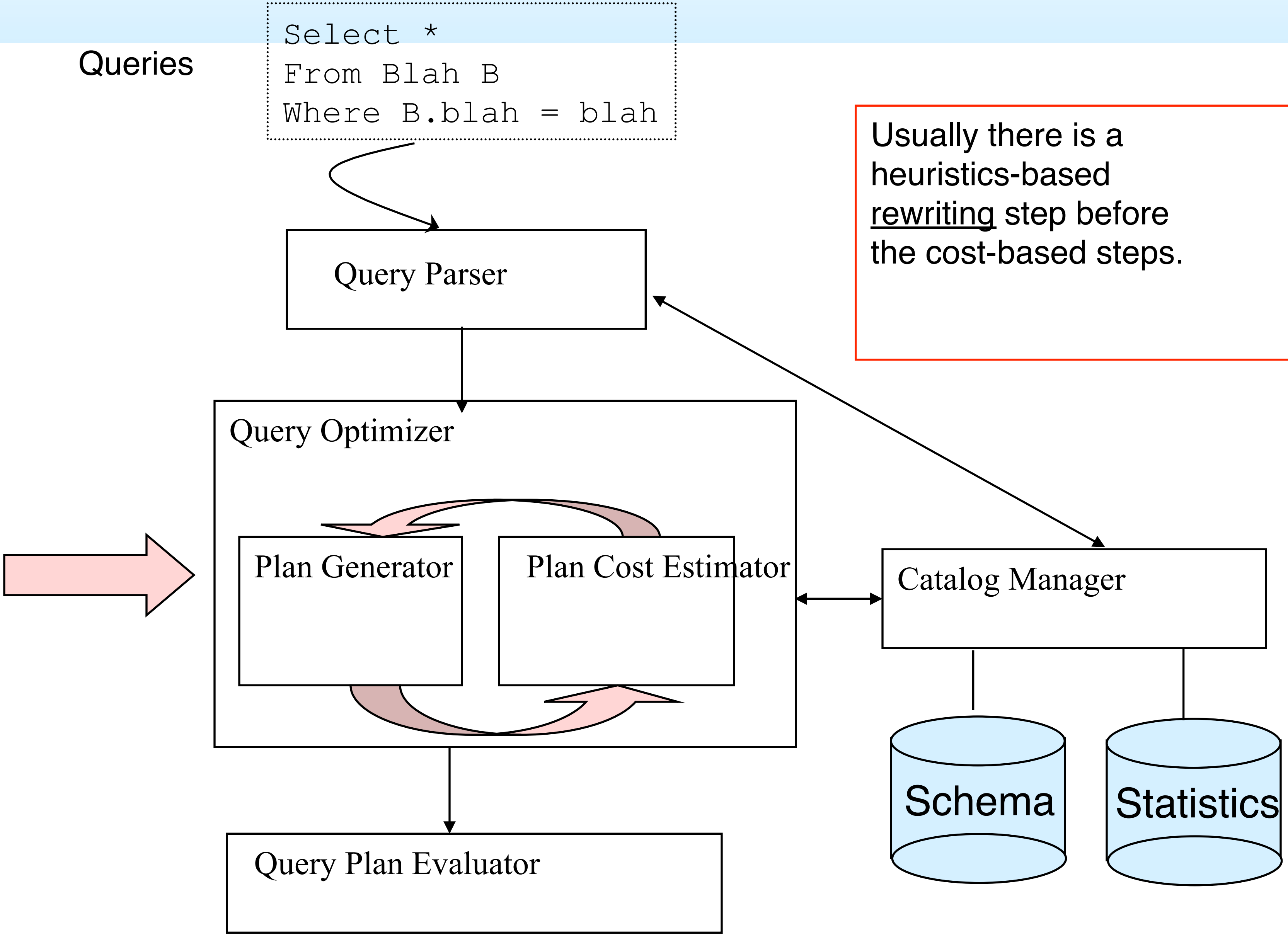
Example

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

- If we have an index on *rating*:
  - Cardinality: (1/NKeys(I)) * NTuples(S) = (1/10) * 40000 tuples retrieved.
  - Clustered index: (1/NKeys(I)) * (NPages(I)+NPages(S)) = (1/10) * (50+500) = 55 pages are retrieved. Another estimate is (1/NKeys(I)) * NPages(S)
  - Unclustered index: (1/NKeys(I)) * (NPages(I)+NTuples(S)) = (1/10) * (50+40000) = 4005 pages are retrieved.
  - Plus of course *Height(I). Usually, 2-4 pages.*
- If we have an index on *sid*:
  - Would have to retrieve all tuples/pages. With a clustered index, the cost is 50+500, with unclustered index, 50+40000. No reason to use this index! (see below)
- Doing a file scan:
  - We retrieve all file pages (500).

Cost-based Query Sub-System

Usually there is a heuristics-based rewriting step before the cost-based steps.



System R - Plans to Consider

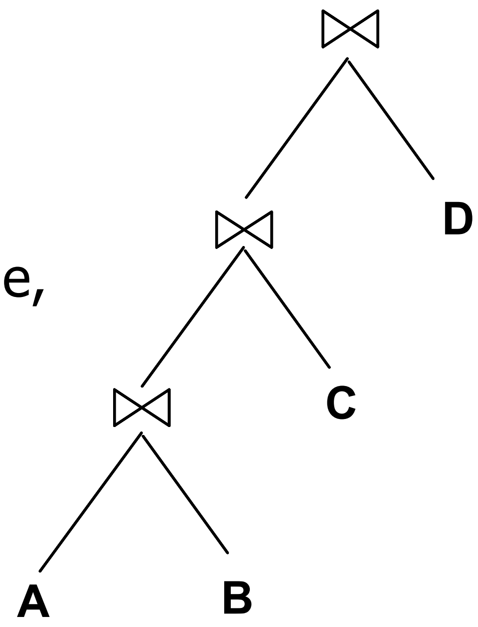
For each block, plans considered are:

- All available access methods, for each relation in FROM clause.

- All *left-deep join trees*
  - i.e., all ways to join the relations one-at-a-time, considering all relation permutations and join methods.

  (note: system R originally only

  had NL and Sort Merge)

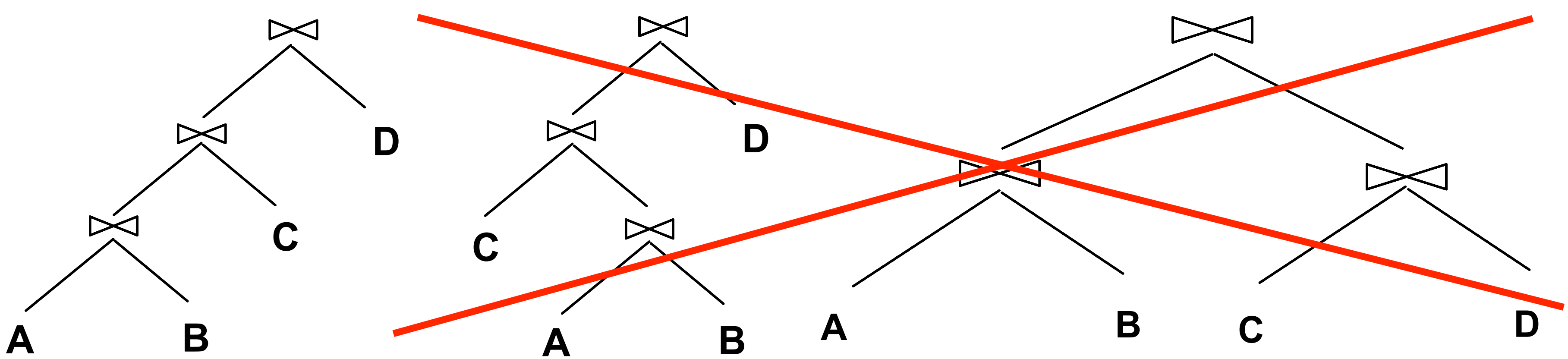


Highlights of System R Optimizer

- Impact:
  - Most widely used currently; works well for < 10 joins.
- Cost estimation:
  - Very inexact, but works ok in practice.
  - Statistics, maintained in system catalogs, used to estimate cost of operations and result sizes.
  - Considers combination of CPU and I/O costs.
    - For simplicity we ignore CPU costs in this discussion
  - More sophisticated techniques known now.
- Plan Space: Too large, must be pruned.
  - Only the space of *left-deep plans* is considered.
  - Cartesian products avoided.

Queries Over Multiple Relations

- Fundamental decision in System R: *only left-deep join trees* are considered.
  - As the number of joins increases, the number of alternative plans grows rapidly; *we need 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., SM join).



Enumeration: Dynamic Programming

- Plans differ by: order of the N relations, access method for each relation, and the join method for each join.
  - maximum possible orderings = N! (but delay X-products)

- Enumerated using N passes

- For each subset of relations, retain only:
  - Cheapest plan overall (possibly unordered), plus
  - Cheapest plan for each *interesting order* of the tuples.

Enumeration: Dynamic Programming

- Pass 1: Find best 1-relation plans for each relation.
- Pass 2: Find best ways to join result of each 1-relation plan as outer to another relation. *(All 2-relation plans.)*

  consider all possible join methods & inner access paths

- Pass N: Find best ways to join result of a (N-1)-rel'n plan as outer to the N'th relation. *(All N-relation plans.)*

  consider all possible join methods & inner access paths

Interesting Orders

- An intermediate result has an “interesting order” if it is returned in order of any of:
  - ORDER BY attributes
  - GROUP BY attributes
  - Join attributes of other joins

System R Plan Enumeration (Contd.)

- An N-1 way plan is not combined with an additional relation unless there is a join condition between them, unless all predicates in WHERE have been used up.
  - i.e., avoid Cartesian products if possible.
- ORDER BY, GROUP BY, aggregates etc. handled as a final step, using either an `<u>interestingly ordered</u>' plan or an additional sorting operator.
- In spite of pruning plan space, this approach is still exponential in the # of tables.
- COST = #IOs + (inst_per_IO * *CPU Inst)*

Example (modified from book ch 15)

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

Indexes

<u>Reserves:</u>
Clustered B+ tree on *bid*
<u>Sailors:</u>
Unclust B+ tree on *rating*

Pass1:

Reserves: Clustered B+ tree on *bid* matches *bid=100*, and is cheaper than file scan

Sailors: B+ tree matches *rating>5*, not very selective, and index is unclustered, so <u>file scan w/ select is likely cheaper</u>. Also, Sailors.rating is not an interesting order.

Pass 2:We consider each Pass 1 plan as the outer:

Reserves as outer (B+Tree selection on bid):

Use Sort Merge to join with Sailors as inner

Sailors as outer (File Scan w/select on rating):

Use BNL on result of selection on Reserves.bid

Example (modified from book ch 15)

Select S.sid, COUNT(*) AS numredres
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
AND B.color = "red"
GROUP BY S.sid

<u>Sailors:</u>
B+ on *sid*
<u>Reserves:</u>
Clustered B+ tree on *bid*
B+ on *sid*
<u>Boats</u>
Clustered Hash on *color*

- **Pass1: Best plan(s) for accessing each relation**
  - Sailors: File Scan; B+ on sid
  - Reserves: File Scan; B+ on bid, B+ on sid
  - Boats: Hash on color

    (note: given selection on color, clustered Hash is likely to be cheaper than file scan, so only it is retained)

Pass 2

- For each of the plans in pass 1, generate plans joining another relation as the inner (avoiding cross products).

- Consider all join methods and every access path for the inner.
  - File Scan Reserves (outer) with Boats (inner)
  - File Scan Reserves (outer) with Sailors (inner)
  - B+ on Reserves.bid (outer) with Boats (inner)
  - B+ on Reserves.bid (outer) with Sailors (inner)
  - B+ on Reserves.sid (outer) with Boats (inner)
  - B+ on Reserves.sid (outer) with Sailors (inner)
  - File Scan Sailors (outer) with Reserves (inner)
  - B+Tree Sailors.sid (outer) with Reserves (inner)
  - Hash on Boats.color (outer) with Reserves (inner)

- Retain cheapest plan for each pair of relations plus cheapest plan for each interesting order.

Pass 3

- For each of the plans retained from Pass 2, taken as the outer, generate plans for the remaining join
  - e.g.

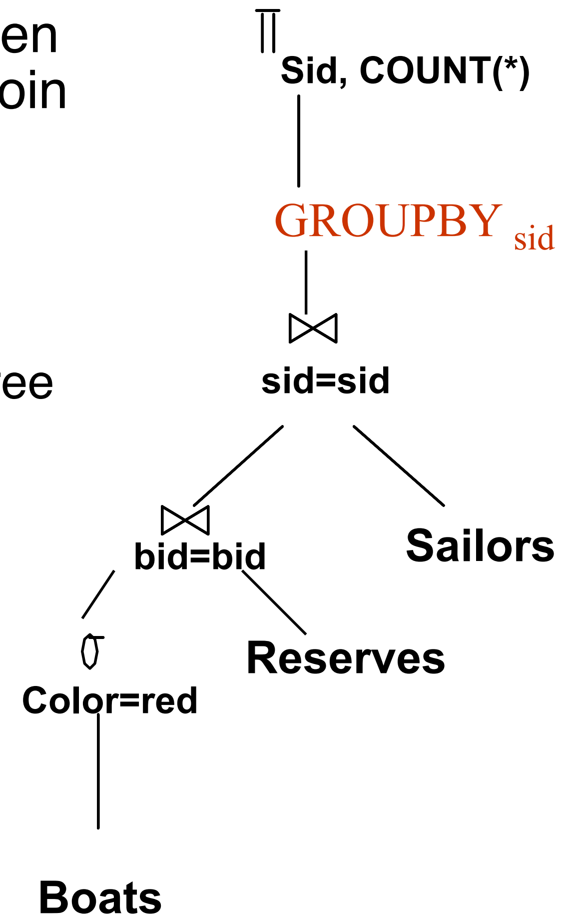
    Outer= Hash on Boats.color JOIN Reserves

    Inner = Sailors

    Join Method = Index NL using Sailors.sid B+Tree

- Then, add the cost for doing the group by and aggregate:
  - This is the cost to sort the result by sid, *unless it has already been sorted by a previous operator.*

- Then, choose the cheapest plan overall



Nested Queries

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

- 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 block to optimize:

```
SELECT  *
FROM  Reserves R
WHERE  R.bid=103
   AND  R.sid= outer value
```

Equivalent non-nested query:

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

Points to Remember

- Must understand optimization in order to understand the performance impact of a given database design (relations, indexes) on a workload (set of queries).
- Two parts to optimizing a query:
  - Consider a set of alternative plans.
    - Must prune search space; typically, left-deep plans only.
  - Must estimate cost of each plan that is considered.
    - Must estimate size of result and cost for each plan node.
    - *Key issues*: Statistics, indexes, operator implementations.

Points to Remember

- Single-relation queries:
  - All access paths considered, cheapest is chosen.
  - *Issues*: Selections that *match* index, whether index key has all needed fields and/or provides tuples in a desired order.

More Points to Remember

- Multiple-relation queries:
  - All single-relation plans are first enumerated.
    - Selections/projections considered as early as possible.
  - Next, for each 1-relation plan, all ways of joining another relation (as inner) are considered.
  - Next, for each 2-relation plan that is `retained', all ways of joining another relation (as inner) are considered, etc.
  - At each level, for each subset of relations, only best plan for each interesting order of tuples is `retained'.

Summary

- Performance can be dramatically improved by changing access methods, order of operators.
- Iterator interface
- Cost estimation
  - Size estimation and reduction factors
- Statistics and Catalogs
- Relational Algebra Equivalences
- Choosing alternate plans
- Multiple relation queries
- We focused on "System R"-style optimizers
  - New areas: Rule-based optimizers, random statistical approaches (*eg simulated annealing), adaptive/dynamic optimization.*