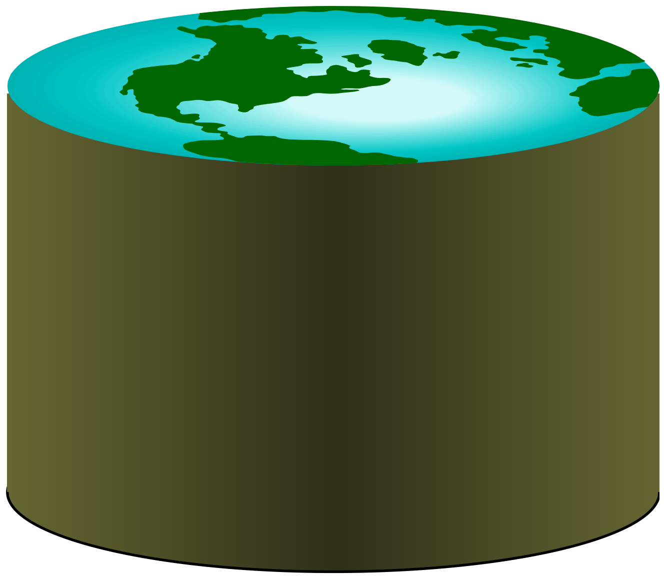
Relational Query Optimization

R & G Chapters 12/15



Review

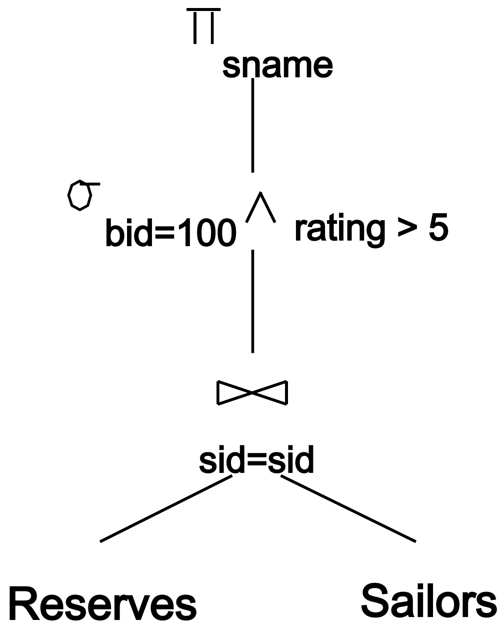
- Implementation of single Relational Operations
- Choices depend on indexes, memory, stats,…
- Joins
  - Blocked nested loops:
    - simple, exploits extra memory
  - Indexed nested loops:
    - best if 1 rel small and one indexed
  - Sort/Merge Join
    - good with small amount of memory, bad with duplicates
  - Hash Join
    - fast (enough memory), bad with skewed data

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
```

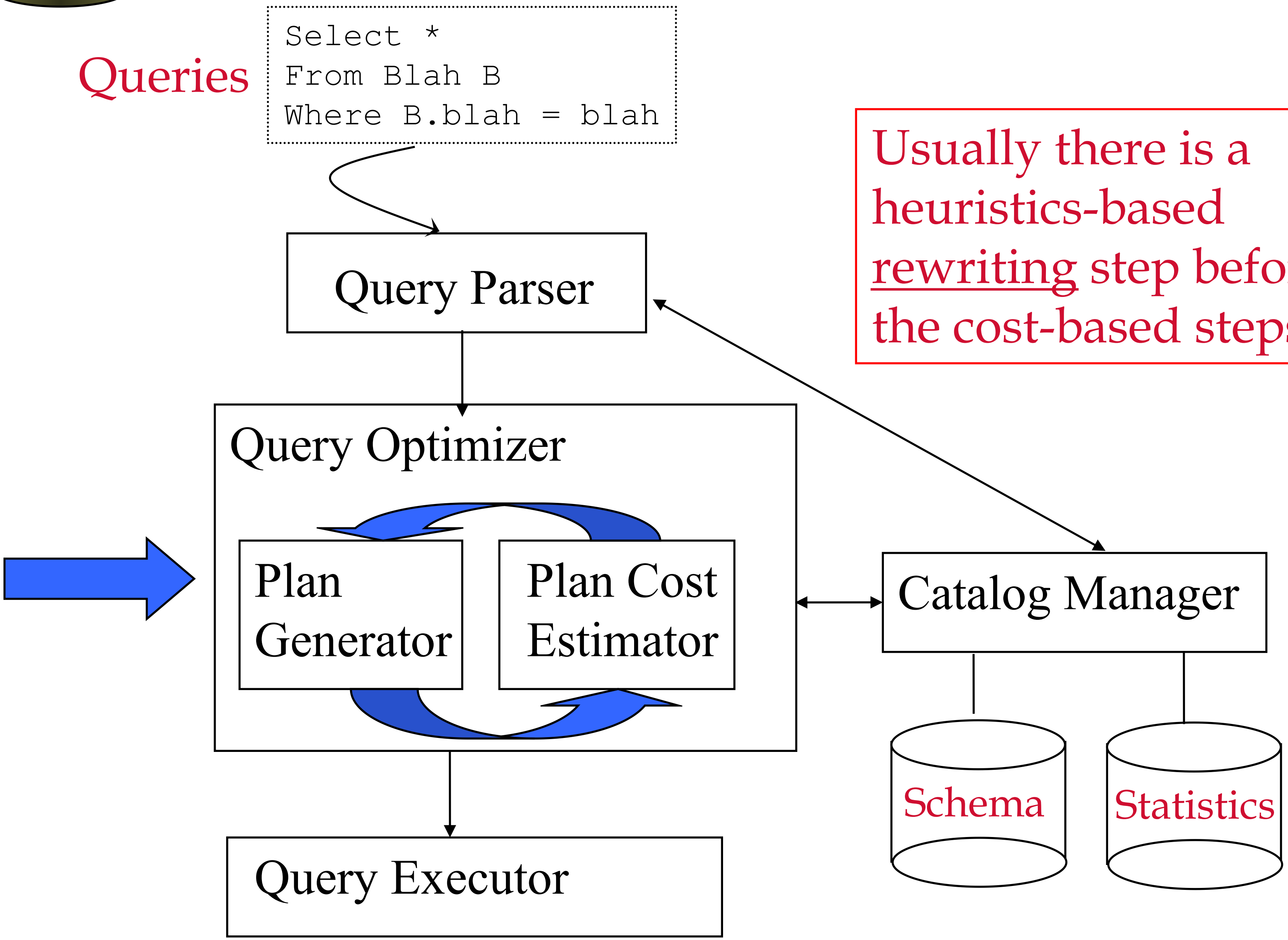
$$\pi_{(sname)}\sigma_{(bid=100 \wedge rating > 5)} (\text{Reserves} \bowtie \text{Sailors})$$



Query Optimization Overview (cont.)

- ***Plan*:** ***Tree of R.A. ops (and some others) with choice of algorithm for each op.***
- **Three main issues:**
  - **For a given query, what plans are considered?**
  - **How is the cost of a plan estimated?**
  - **How do we "search" in the "plan space"?**
- **Ideally: Want to find best plan.**
- **Reality: Avoid worst plans!**

Cost-based Query Sub-System



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

Schema for Examples

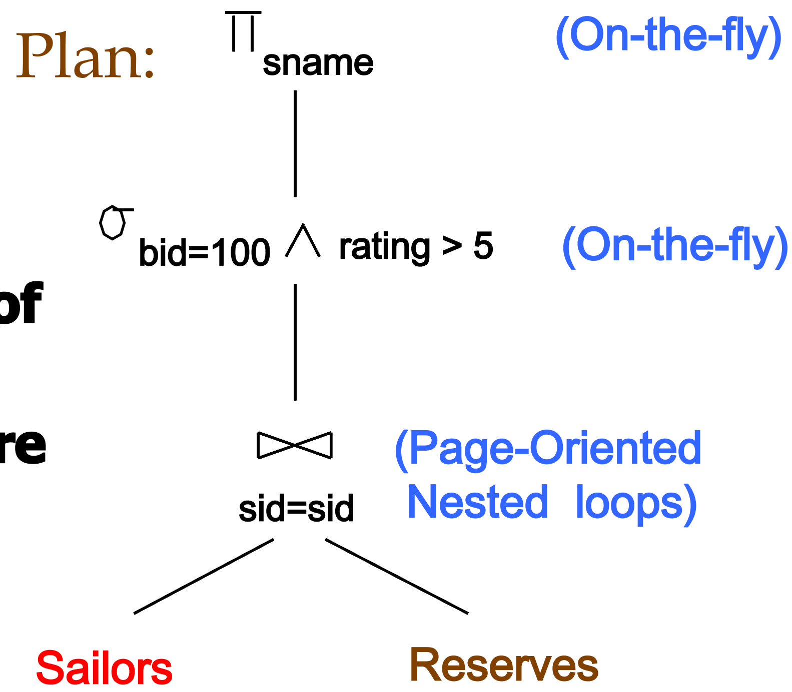
Sailors (*sid*: integer, *sname*: string, *rating*: integer, *age*: real)
Reserves (*sid*: integer, *bid*: integer, *day*: dates, *rname*: string)

- **As seen in previous lectures…**
- **Reserves:**
  - **Each tuple is 40 bytes long, 100 tuples per page, 1000 pages.**
  - **Assume there are 100 boats**
- **Sailors:**
  - **Each tuple is 50 bytes long, 80 tuples per page, 500 pages.**
  - **Assume there are 10 different ratings**
- **Assume we have 5 pages in our buffer pool!**

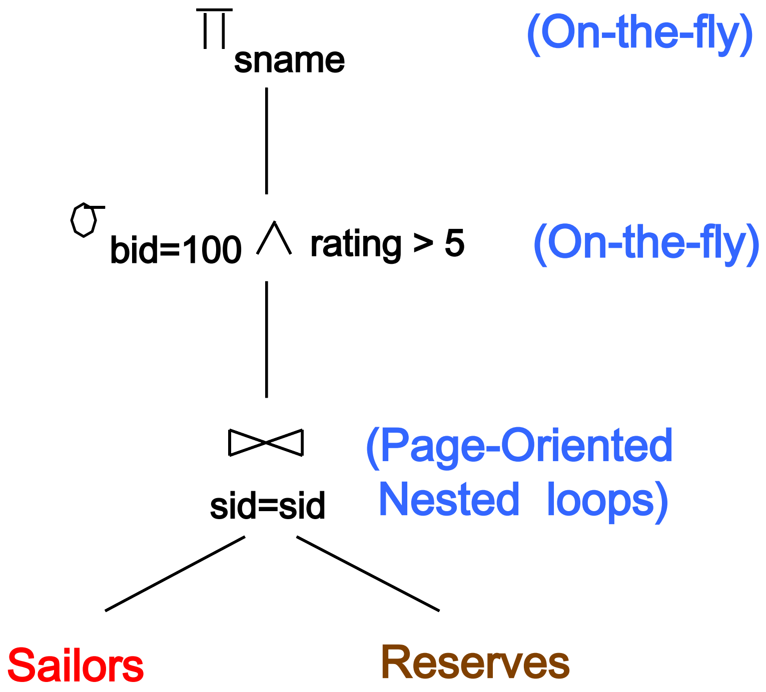
Motivating Example

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

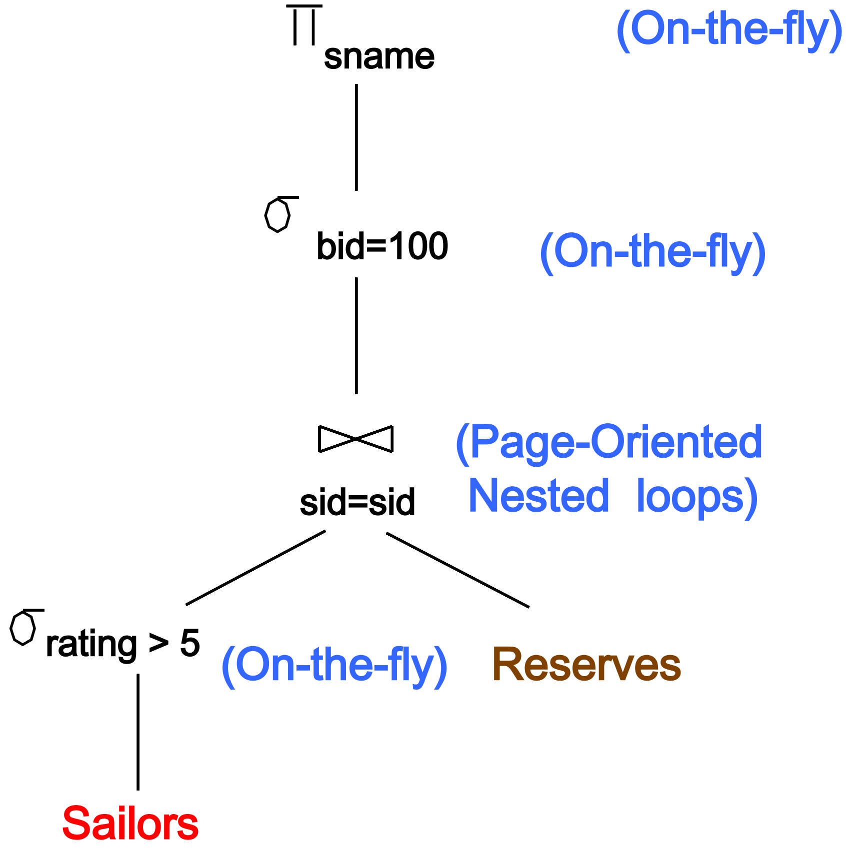
- **Cost: 500+500*1000 I/Os**
- **By no means the worst plan!**
- **Misses several opportunities: selections could have been `pushed' earlier, no use is made of any available indexes, etc.**
- ***Goal of optimization:* To find more efficient plans that compute the same answer.**



Alternative Plans – Push Selects (No Indexes)

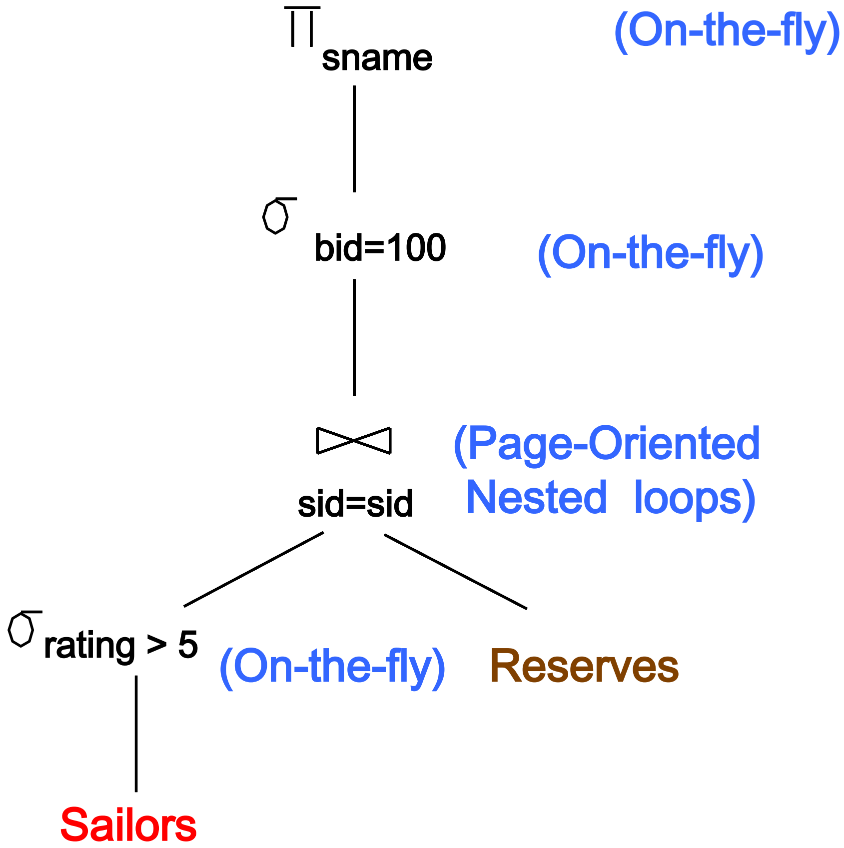


500,500 IOs

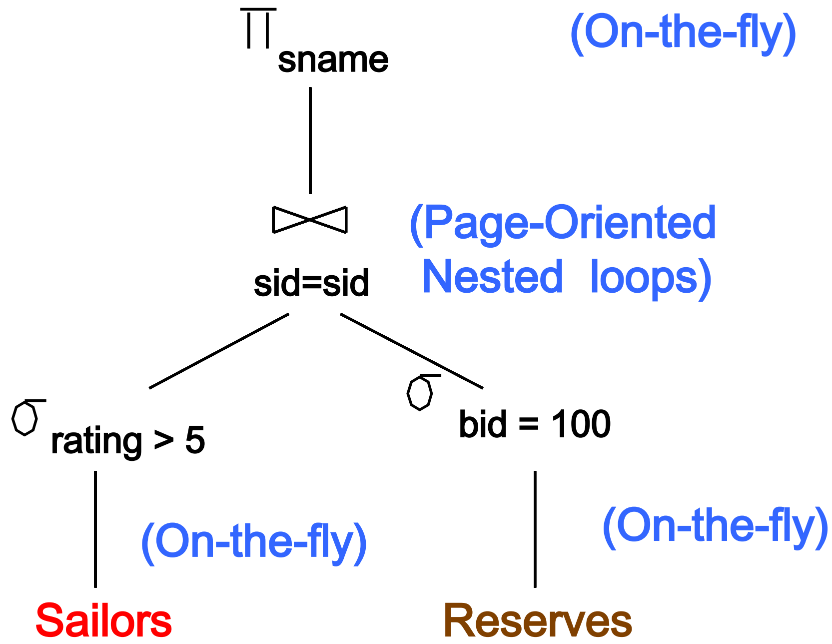


250,500 IOs

Alternative Plans – Push Selects (No Indexes)



250,500 IOs



250,500 IOs

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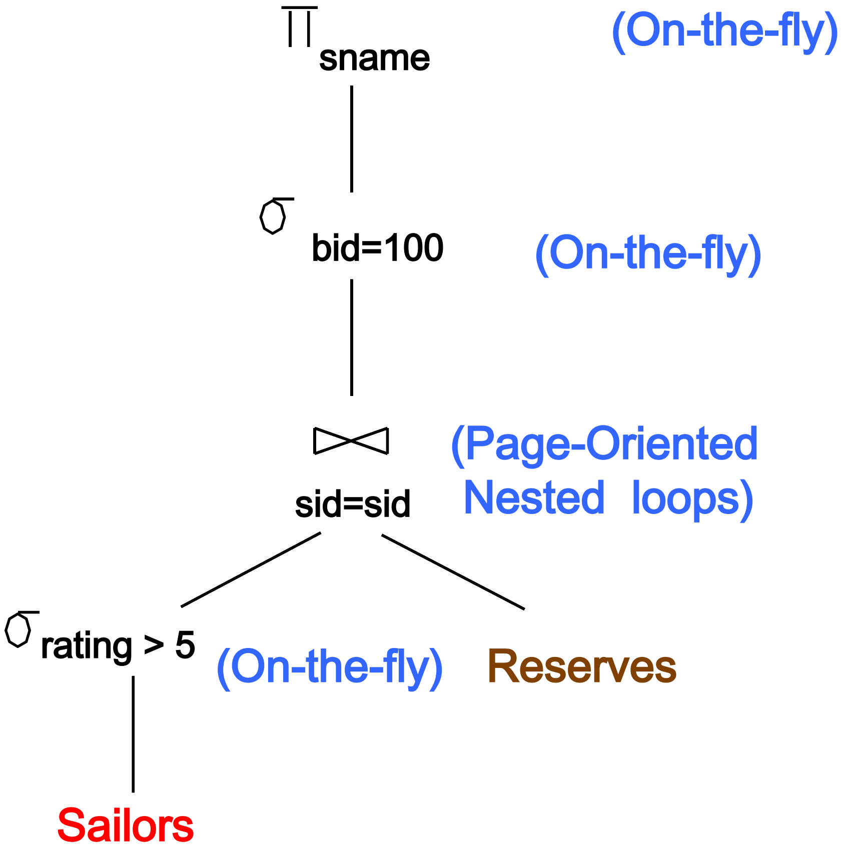
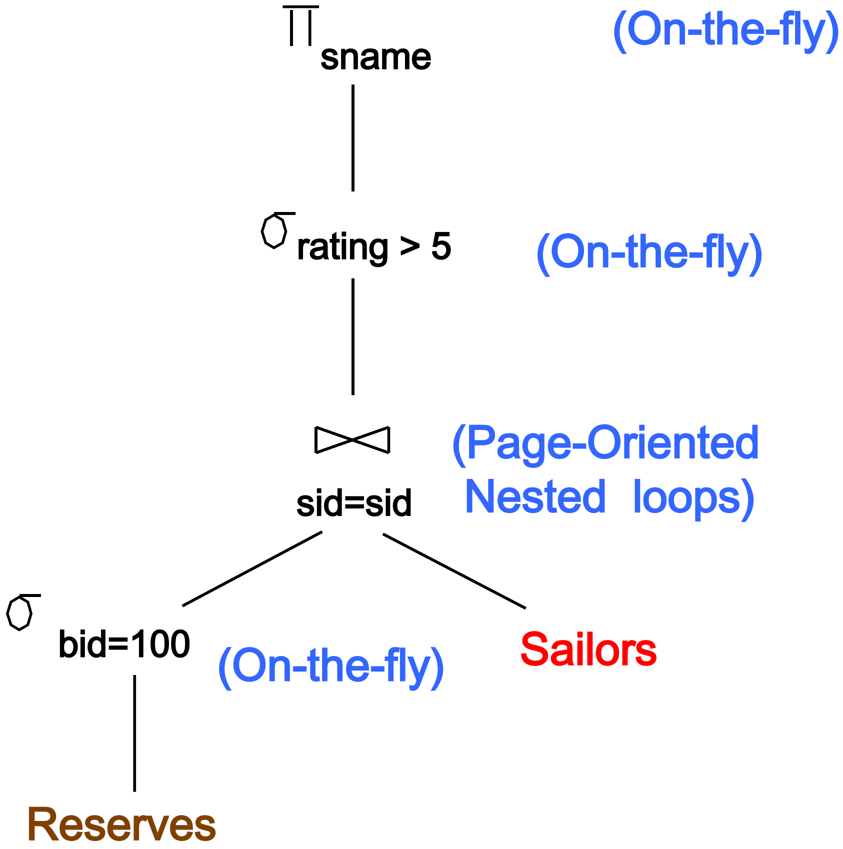
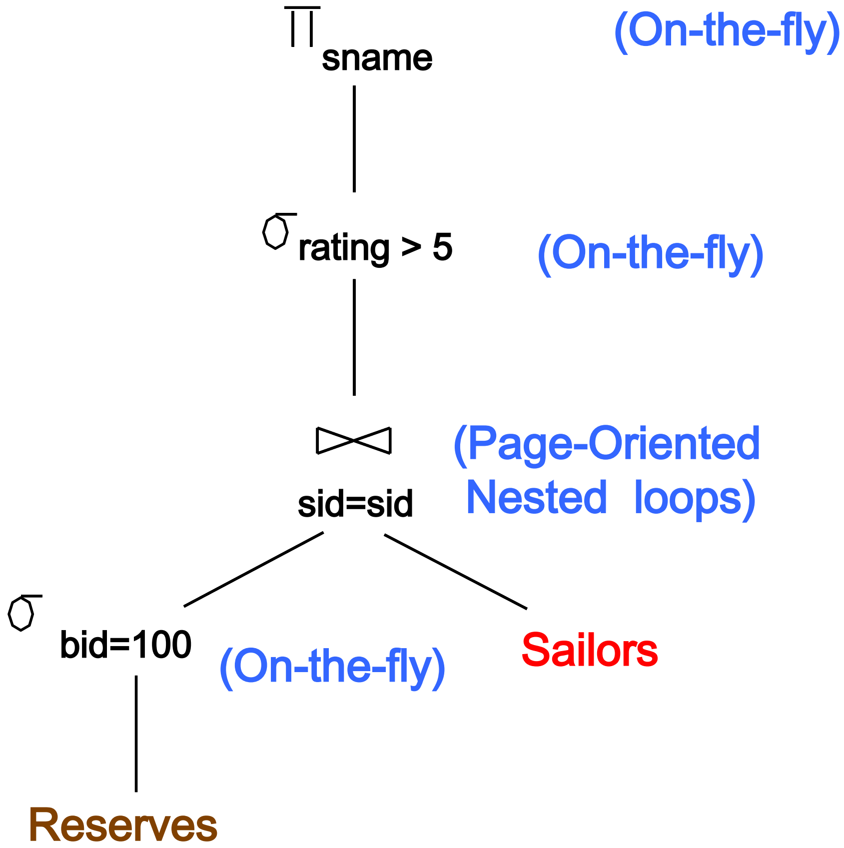


250,500 IOs

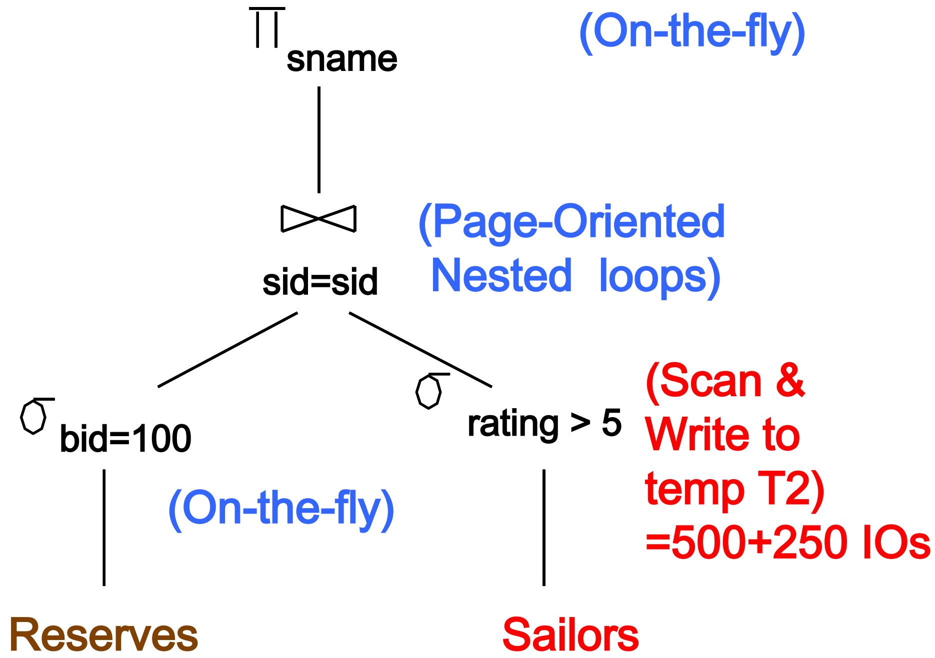


6000 IOs

Alternative Plans – Push Selects (No Indexes)

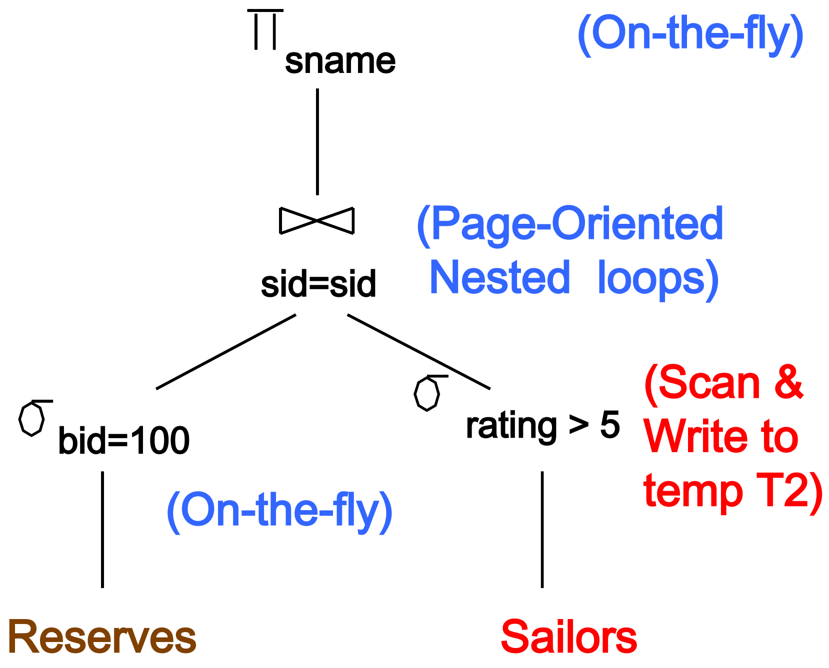


6000 IOs



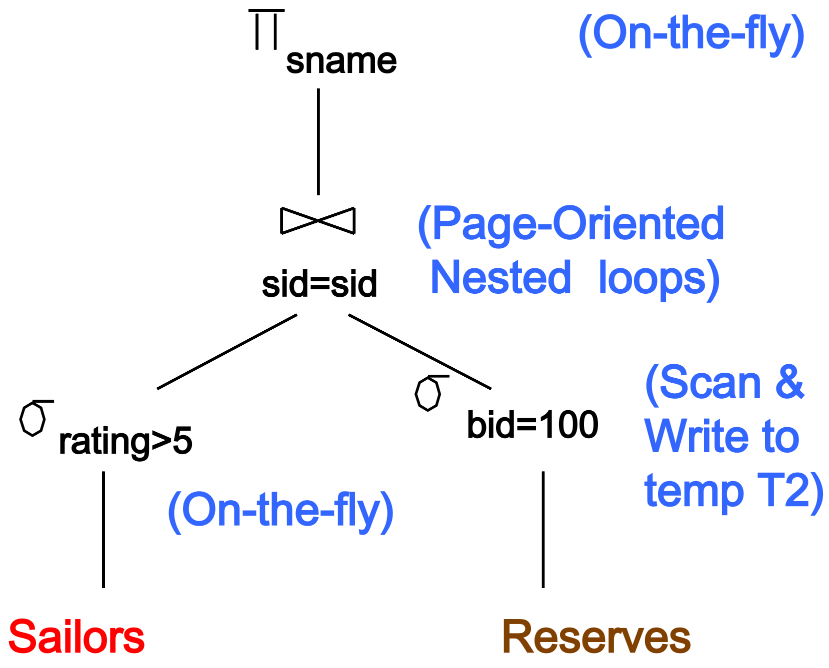
4250 IOs

Alternative Plans – Push Selects (No Indexes)



4250 IOs

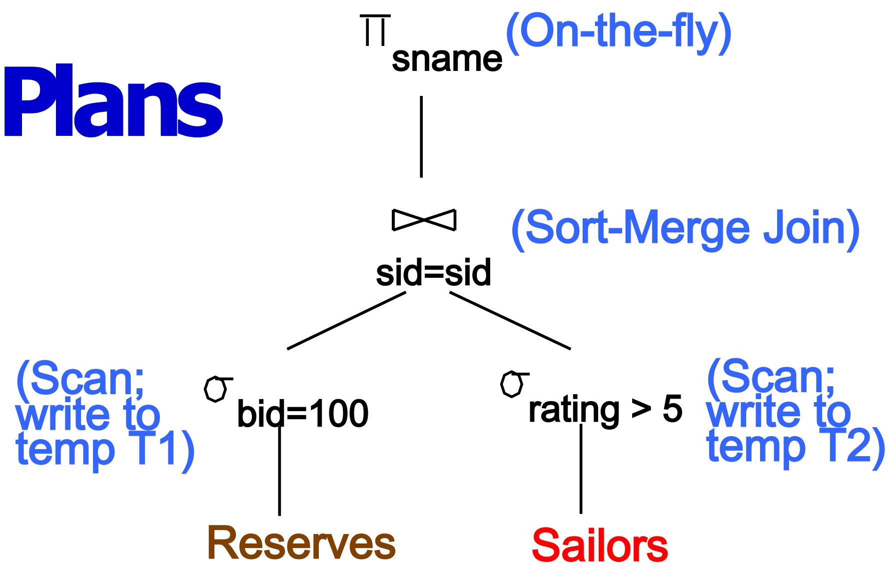
=1000 + 500+ 250 + (10 * 250)



4010 IOs

=500 + 1000 +10 +(250 *10)

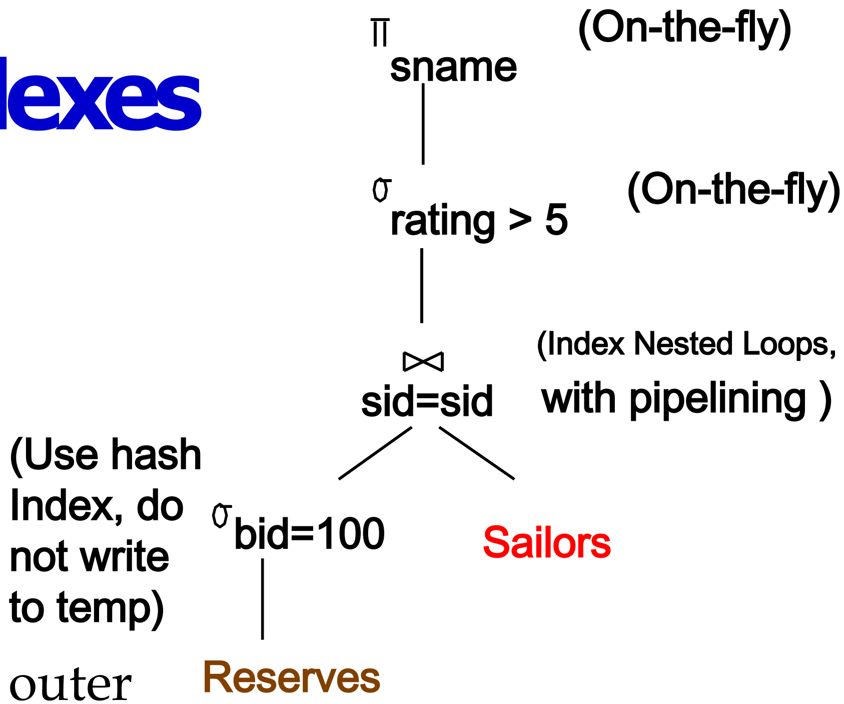
More Alternative Plans (No Indexes)



- ***Main difference:*** ***<u>Sort Merge Join</u>***
- **With 5 buffers, cost of plan:**
  - Scan Reserves (1000) + write temp T1 (10 pages, if we have 100 boats, uniform distribution) = 1010.
  - Scan Sailors (500) + write temp T2 (250 pages, if have 10 ratings) = 750.
  - Sort T1 (2*2*10) + sort T2 (2*4*250) + merge (10+250) = 2300
  - **Total: 4060 page I/Os.**
- **If use <u>BNL join</u>, join = 10+4*250, total cost = 2770.**
- **Can also `push' projections, but must be careful!**
  - T1 has only *sid*, T2 only *sid*, *sname*:
  - T1 fits in 3 pgs, cost of BNL under 250 pgs, total < 2000.

More Alt Plans: Indexes

- **With clustered index on *bid* of Reserves, we get 100,000/100 = 1000 tuples on 1000/100 = 10 pages.**
- **INL with outer not materialized.**
  - Projecting out unnecessary fields from outer doesn't help.



- Join column *sid* is a key for Sailors.
  - At most one matching tuple, unclustered index on *sid* OK.
- Decision not to push *rating>5* before the join is based on availability of *sid* index on Sailors.
- Cost: Selection of Reserves tuples (10 I/Os); then, for each, must get matching Sailors tuple (1000*1.2); total 1210 I/Os.

What is needed for optimization?

- A closed set of operators
  - Relational ops (table in, table out)
  - Encapsulation (e.g. based on iterators)
- Plan space
  - Based on relational equivalences, different implementations
- Cost Estimation, based on
  - Cost formulas
  - Size estimation, based on
    - Catalog information on base tables
    - Selectivity (Reduction Factor) estimation
- A search algorithm
  - To sift through the plan space based on cost!

Summary

- **Query optimization is an important task in a relational DBMS.**
- **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.**

Query Optimization

- Query 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
- Will focus on “System R”-style optimizers

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.
  - More sophisticated techniques known now.
- **Plan Space:** Too large, must be pruned.
  - Many plans share common, "overpriced" subtrees
    - ignore them all!
  - In some implementations, only the space of *left-deep plans* is considered.
  - Cartesian products avoided in some implementations.

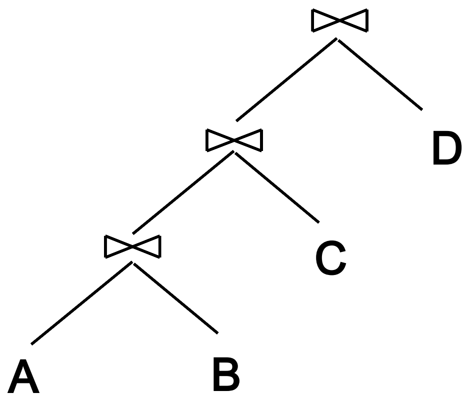
Query Blocks: Units of Optimization

- **Break query into *query blocks***
- **Optimized one block at a time**
- **Uncorrelated nested blocks computed once**
- **Correlated nested blocks like function calls**
  - **But sometimes can be "decorrelated"**
  - **Beyond the scope of introductory course!**

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

Outer block *Nested block*

- For each block, the plans considered are:
  - All available access methods, for each relation in FROM clause.
  - All *left-deep join trees* (i.e., right branch always a base table, consider all join orders and join methods.)



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.**

Translating SQL to Relational Algebra

```
SELECT  S.sid, MIN (R.day)
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
HAVING COUNT (*) >= 2
```

For each sailor with at least two reservations for red boats, find the sailor id and the earliest date on which the sailor has a reservation for a red boat.

Translating SQL to Relational Algebra

```
SELECT  S.sid, MIN (R.day)
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
HAVING COUNT (*) >= 2
```

$$\pi_{\text{S.sid, MIN(R.day)}} \left(\text{HAVING}_{\text{COUNT}(*)>2} \left(\text{GROUP BY}_{\text{S.Sid}} \left(\sigma_{\text{B.color = "red"}} \left(\text{Sailors} \bowtie \text{Reserves} \bowtie \text{Boats} \right) \right) \right) \right)$$

Relational Algebra Equivalences

- **Allow us to choose different join orders and to `push' selections and projections ahead of joins.**
- **Selections:**
  - $\sigma_{c1 \wedge \ldots \wedge cn}(R) \equiv \sigma_{c1}(\ldots(\sigma_{cn}(R))\ldots)$ (*cascade*)
  - $\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c1}(\sigma_{c1}(R))$ (*commute*)
- **Projections:**
  - $\pi_{a1}(R) \equiv \pi_{a1}(\ldots(\pi_{a1, \ldots, an}(R))\ldots)$ (*cascade*)
- **Cartesian Product**
  - $R \times (S \times T) \equiv (R \times S) \times T$ (associative)
  - $R \times S \equiv S \times R$ (commutative)
  - *This means we can do joins in any order.*
    - **But…beware of cartesian product!**

More Equivalences

- Eager projection
  - Can cascade and "push" some projections thru selection
  - Can cascade and "push" some projections below one side of a join
  - Rule of thumb: can project anything not needed "downstream"
- Selection between attributes of the two arguments of a cross-product converts cross-product to a join.
- A selection on just attributes of R commutes with $R \bowtie S$. (i.e., $\sigma(R \bowtie S) \equiv \sigma(R) \bowtie S$)

Cost Estimation

- **For each plan considered, must estimate total cost:**
  - **Must estimate *cost* of each operation in plan tree.**
    - **Depends on input cardinalities.**
    - **We've already discussed how to estimate the cost of operations (sequential scan, index scan, joins, etc.)**
  - **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 + *factor* * #CPU instructions**
  - **Q: Is "cost" the same as estimated "run time"?**

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 (NKeys) 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.
- 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

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

- **Consider a query block:**
- **Maximum # tuples in result is the product of the cardinalities of relations in the FROM clause.**
- ***Reduction factor (RF)*** **associated with each *term* reflects the impact of the *term* in reducing result size.** ***Result cardinality*** **= Max # tuples * product of all RF's. (RF = |output| / |input|)**
- ***RF usually called "selectivity"***
  - only R&G seem to call it Reduction Factor
  - beware of confusion between "high selectivity" as defined here and "highly selective" in common English!

Result Size Estimation

A
1
2
3
4

- *Result cardinality* =
  Max # tuples * product of all RF's.
- Term *col=value* (given index I on *col*)
  RF = *1/NKeys(I)*
- Term *col1=col2* (This is handy for joins too…)
  RF = *1/MAX(NKeys(I1), NKeys(I2))*
- Term *col>value*
  RF = *(High(I)-value)/(High(I)-Low(I))*

(Implicit assumptions: values are uniformly distributed and *terms* are independent!)

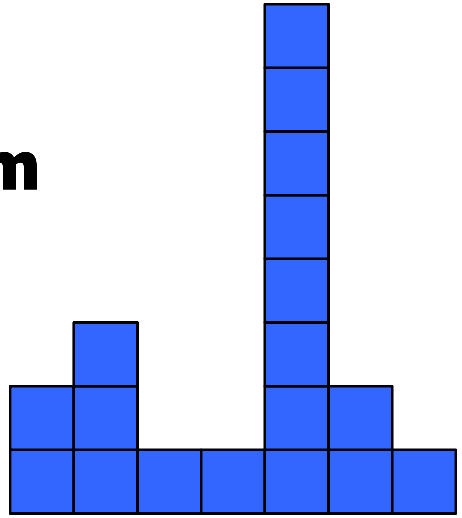
- ***Note, if missing indexes, assume 1/10!!!***

Reduction Factors & Histograms

- **For better estimation, use a histogram**

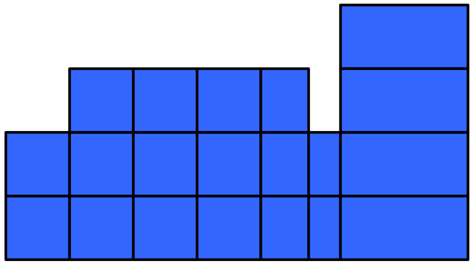
equiwidth

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



equidepth

No. of Values	2	3	3	3	3	2	4
Value	0-.99	1-1.99	2-2.99	3-4.05	4.06-4.67	4.68-4.99	5-6.99

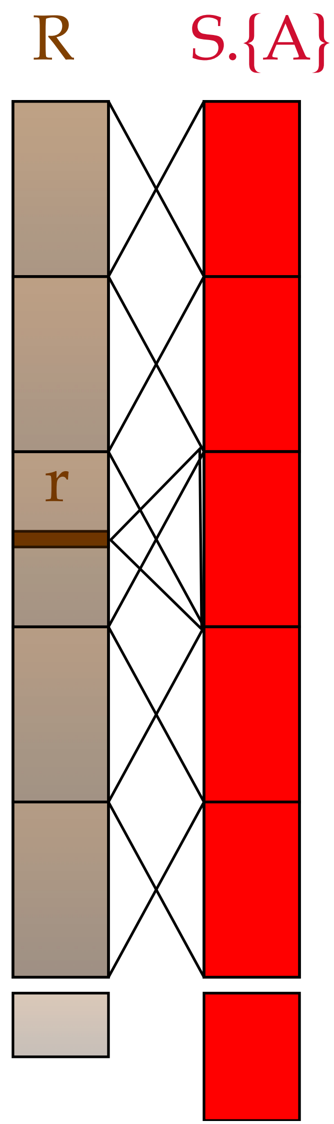


Think through estimation for joins

- Term *col1=col2*
  - RF = *1/MAX(NKeys(I1), NKeys(I2))*
- Q: Given a join of R and S, what is the range of possible result sizes (in #of tuples)?
  - If join is on a key for R (and a Foreign Key in S)?
    - A common case, can treat it specially
- General case: join on {A} ({A} is key for neither)
  - estimate each tuple r of R generates NTuples(S)/NKeys(A,S) result tuples, so…

    NTuples(R) * NTuples(S)/NKeys(A,S)
  - but can also consider it starting with S, yielding:

    NTuples(S) * NTuples(R)/NKeys(A,R)
  - If these two estimates differ, take the lower one!
    - Q: Why?



estimation for joins - example

- NTuples(R) * NTuples(S)/NKeys(A,S)
  - NTuples(R) = 4
    - R有4条记录
  - NTuples(S) = 9
    - S有9条记录
  - NKeys(A,S) = 3
    - S的A属性共有3种不同的聚值
  - NTuples(S)/NKeys(A,S) = 3
    - 取值1或2或3的记录估计平均有3条
  - Est #=4 * 9/3 = 12
  - Actual # = 14

R ⋈ S

R

A
1
2
3
2

S

A
1
2
3
2
3
3
2
2
2

Enumeration of Alternative Plans

- There are two main cases:
  - Single-relation plans
  - Multiple-relation plans
- For queries over a single relation, queries consist of a combination of selects, projects, and aggregate ops:
  - Each available access path (file scan / index) is considered, and the one with the least estimated cost is chosen.
  - The different operations are 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).

Cost Estimates for Single-Relation Plans

- **Index I on primary key matches selection:**
  - *Cost is Height(I)+1 for a B+ tree.*
- **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).*

Recall: Must also charge for duplicate elimination if required

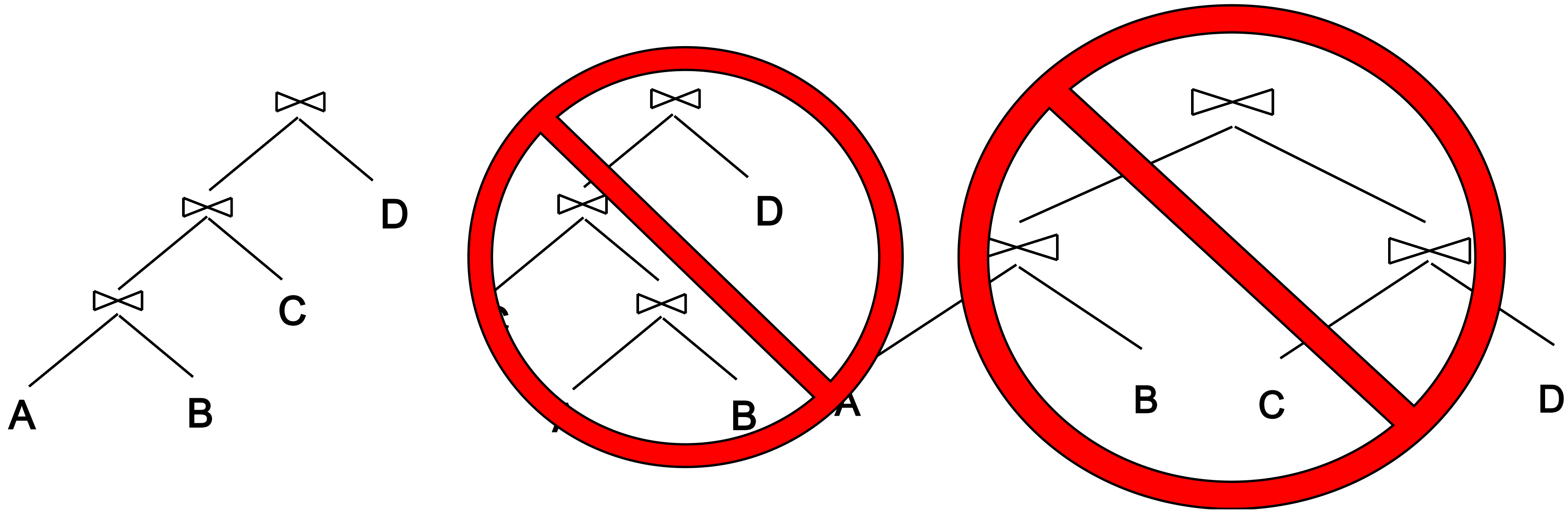
Example

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

- **If we have an index on *rating*:**
  - Cardinality = (1/NKeys(I)) * NTuples(R) = (1/10) * 40000 tuples
  - Clustered index: (1/NKeys(I)) * (NPages(I)+NPages(R)) = (1/10) * (50+500) = 55 pages are retrieved. (This is the *cost*.)
  - Unclustered index: (1/NKeys(I)) * (NPages(I)+NTuples(R)) = (1/10) * (50+40000) = 401 pages are retrieved.
- **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.
- **Doing a file scan:**
  - We retrieve all file pages (500).

Queries Over Multiple Relations

- **A heuristic 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 of Left-Deep Plans

- **Left-deep plans differ only in the order of relations, the access method for each relation, and the join method for each join.**
- **Enumerated using N passes (if N relations 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. *(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. *(All N-relation plans.)*
- **For each subset of relations, retain only:**
  - Cheapest plan overall, plus
  - Cheapest plan for each *interesting order* of the tuples.

The Dynamic Programming Table

Subset of tables in FROM clause	Interesting-order columns	Best plan	Cost
{R, S}	<none>	hashjoin(R, S)	1000
{R, S}	<R.a, S.b>	sortmerge(R,S)	1500

A Note on "Interesting Orders"

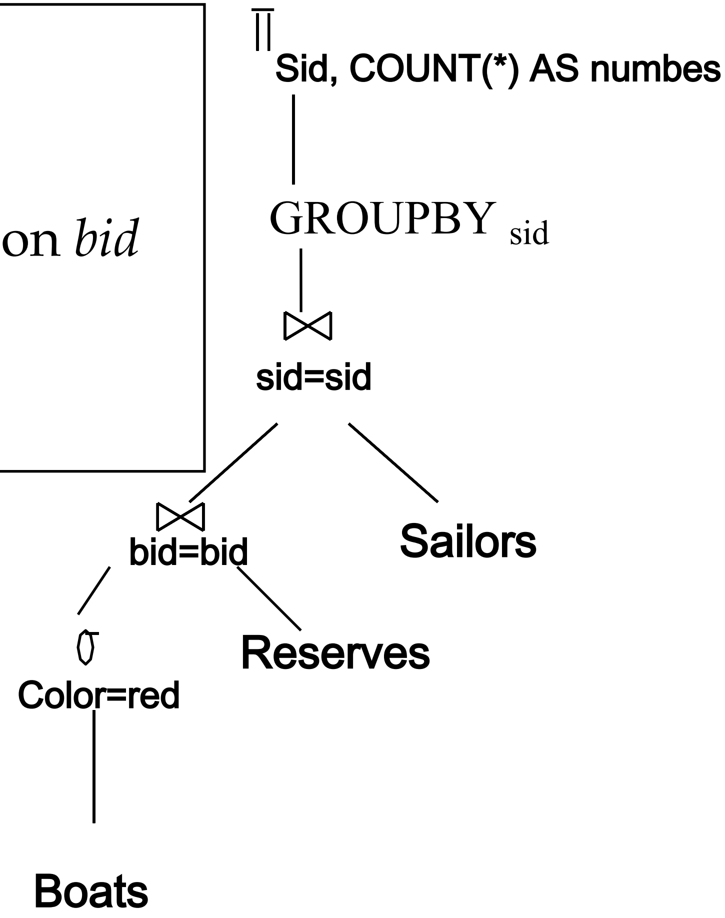
- An intermediate result has an "interesting order" if it is sorted by any of:
  - ORDER BY attributes
  - GROUP BY attributes
  - Join attributes of *yet-to-be-added* (downstream) joins

Enumeration of Plans (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 `interestingly ordered' plan or an additonal sort/hash operator.
- In spite of pruning plan space, this approach is still exponential in the # of tables.
- Recall that in practice, COST considered is #IOs + *factor * CPU Inst*

Example

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



Select S.sid, COUNT(*) AS number
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

- **Pass1: Best plan(s) for accessing each relation**
  - **Reserves, Sailors: File Scan**
  - **Q: What about Clustered B+ on Reserves.bid???**
  - **Boats: B+ tree & Hash on color**

Pass 1

- Best plan for accessing each relation regarded as the first relation in an execution plan
  - Reserves, Sailors: File Scan
  - Boats: B+ tree & Hash on color

Pass 2

- For each of the plans in pass 1, generate plans joining another relation as the inner, using all join methods (and matching inner access methods)
  - File Scan Reserves (outer) with Boats (inner)
  - File Scan Reserves (outer) with Sailors (inner)
  - File Scan Sailors (outer) with Boats (inner)
  - File Scan Sailors (outer) with Reserves (inner)
  - Boats hash on color with Sailors (inner)
  - Boats Btree on color with Sailors (inner)
  - Boats hash on color with Reserves (inner) (sort-merge)
  - Boats Btree on color with Reserves (inner) (BNL)
- Retain cheapest plan for each pair of relations

Pass 3 and beyond

- **For each of the plans retained from Pass 2, taken as the outer, generate plans for the next join**
  - **eg Boats hash on color with Reserves (bid) (inner) (sortmerge))**

    inner Sailors (B-tree sid) sort-merge
- **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**

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.
    - Good to prune search space; e.g., left-deep plans only, avoid Cartesian products.
  - Must estimate cost of each plan that is considered.
    - Output cardinality 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'.

Physical DB Design

- Query optimizer does what it can to use indices, clustering etc.
- DataBase Administrator (DBA) is expected to set up physical design well.
- Good DBAs understand query optimizers very well.

One Key Decision: Indexes

- Which tables
- Which field(s) should be the search key?
- Multiple indexes?
- Clustering?

Index Selection

- One approach:
  - Consider most important queries in turn.
  - Consider best plan using the current indexes
  - See if better plan is possible with an additional index.
  - If so, create it.
- But consider impact on updates!
  - Indexes can make queries go faster, updates slower.
  - Require disk space, too.

Issues to Consider in Index Selection

- Attributes mentioned in a WHERE clause are candidates for index search keys.
  - Range conditions are sensitive to clustering
  - Exact match conditions don't require clustering
    - Or do they???? :-)
- Choose indexes that benefit many queries
- NOTE: only one index can be clustered per relation!
  - So choose it wisely!

Example 1

```
SELECT  E.ename, D.mgr
FROM  Emp E, Dept D
WHERE  E.dno=D.dno AND D.dname='Toy'
```

- **B+ tree index on *D.dname* supports 'Toy' selection.**
  - Given this, index on D.dno is not needed.
- **B+ tree on *E.dno* allows us to get matching (inner) Emp tuples for each selected (outer) Dept tuple.**
- **What if WHERE included: `` ... AND E.age=25" ?**
  - Could retrieve Emp tuples using index on *E.age*, then join with Dept tuples satisfying *dname* selection.
    - Comparable to strategy that used *E.dno* index.
  - So, if *E.age* index is already created, this query provides much less motivation for adding an *E.dno* index.

Example 2

```
SELECT  E.ename, D.mgr
FROM  Emp E, Dept D
WHERE  E.sal BETWEEN 10000 AND 20000
  AND E.hobby='Stamps' AND E.dno=D.dno
```

- **All selections are on Emp so it should be the outer relation in any Index NL join.**
  - Suggests that we build a B+ tree index on *D.dno.*
- **What index should we build on Emp?**
  - B+ tree on *E.sal* could be used, OR an index on *E.hobby* could be used.
  - Only one of these is needed, and which is better depends upon the selectivity of the conditions.
    - As a rule of thumb, equality selections more selective than range selections.
- ***Have to understand optimizers to get this right!***

Examples of Clustering

- **B+ tree index on E.age can be used to get qualifying tuples.**
  - How selective is the condition?
  - Is the index clustered?

```
SELECT  E.dno
FROM  Emp E
WHERE  E.age>40
```

- **Consider the GROUP BY query.**
  - If many tuples have *E.age* > 10, using *E.age* index and sorting the retrieved tuples may be costly.
  - Clustered *E.dno* index may be better!

```
SELECT  E.dno,  COUNT (*)
FROM  Emp E
WHERE  E.age>10
GROUP BY E.dno
```

- **Equality queries and duplicates:**
  - Clustering on *E.hobby* helps!

```
SELECT  E.dno
FROM  Emp E
WHERE  E.hobby=Stamps
```

Summary

- Optimization is the reason for the lasting power of the relational system
- But it is primitive in some ways
- New areas: Smarter summary statistics (fancy histograms and "sketches"), auto-tuning statistics, adaptive runtime re-optimization (e.g. *eddies*)