# Relational Query Optimization

courtesy of Joe Hellerstein for some slides

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# Review

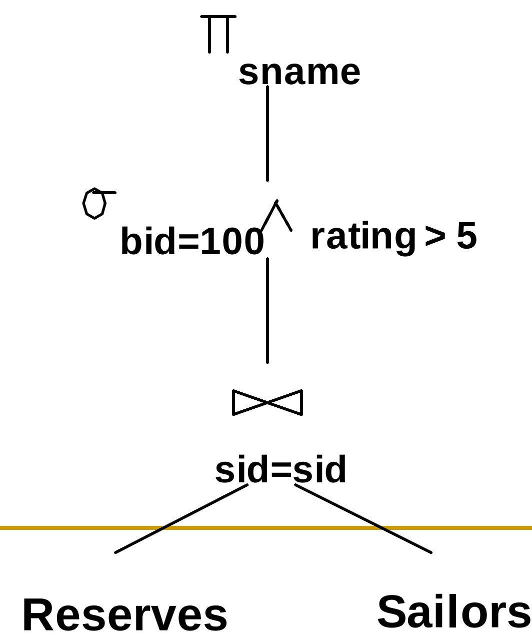
- Choice of single-table operations
  - Depends on indexes, memory, stats,…
- Joins
  - Blocked nested loops:
    - simple, exploits extra memory
  - Indexed nested loops:
    - best if 1 rel small and one indexed
  - Sort/Merge Join
    - good with small amount of memory, bad with duplicates
  - Hash Join
    - fast (enough memory), bad with skewed data
- These are “rules of thumb”
  - On their way to a more principled approach…

# Query Optimization Overview

- Query can be converted to relational algebra
- Relational Algebra converts to tree, joins form 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
```

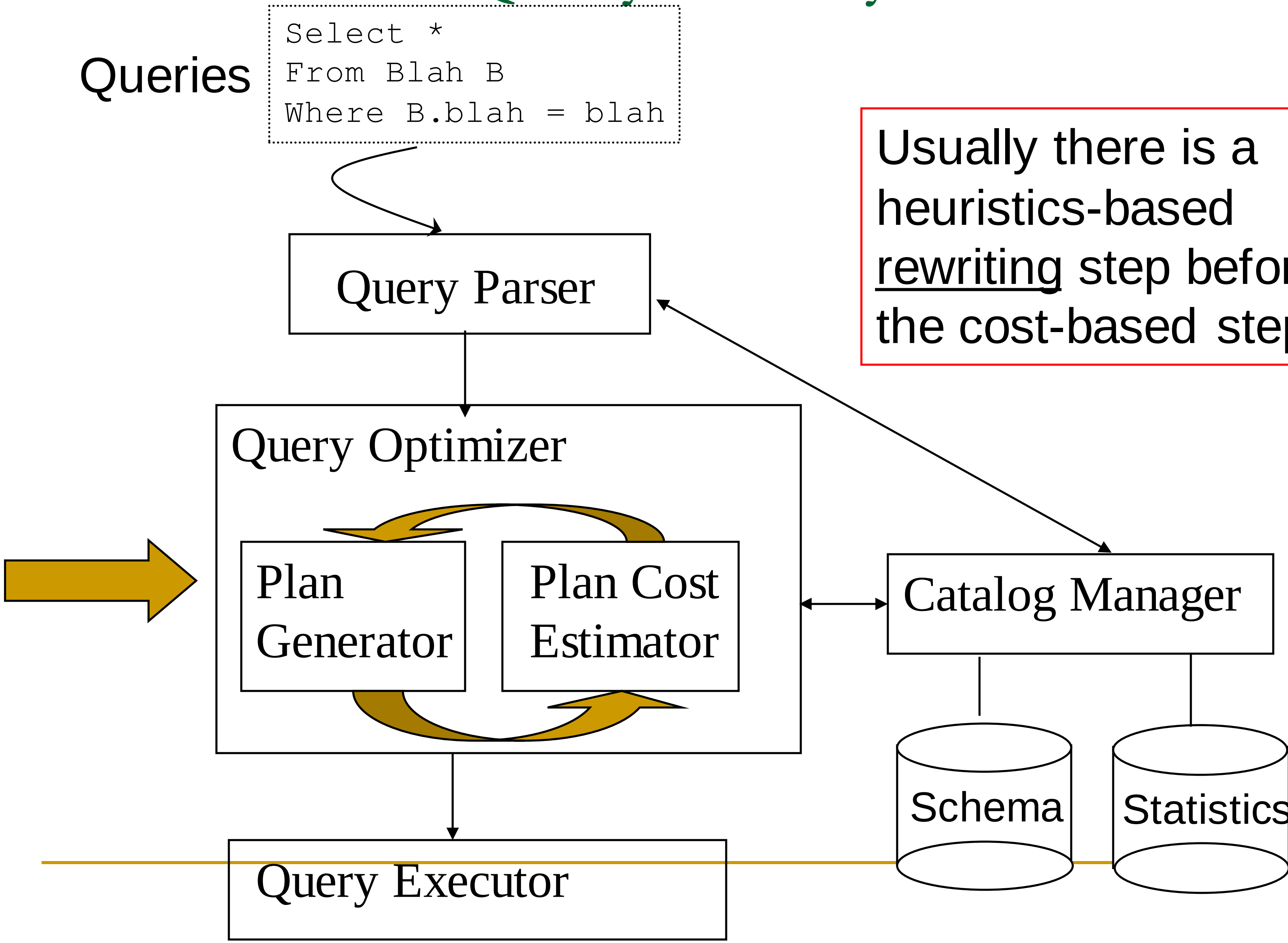
$$\pi_{(sname)}\sigma_{(bid=100\ \wedge\ rating\ >\ 5)}\ (\text{Reserves} \bowtie \text{Sailors})$$



# Query Optimization Overview (cont.)

- *Plan*: *Tree of Relation Algebra operations (and some others) with choice of algorithm for each operation.*
- 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 <u>rewriting</u> step before the cost-based steps.

# Schema for Examples

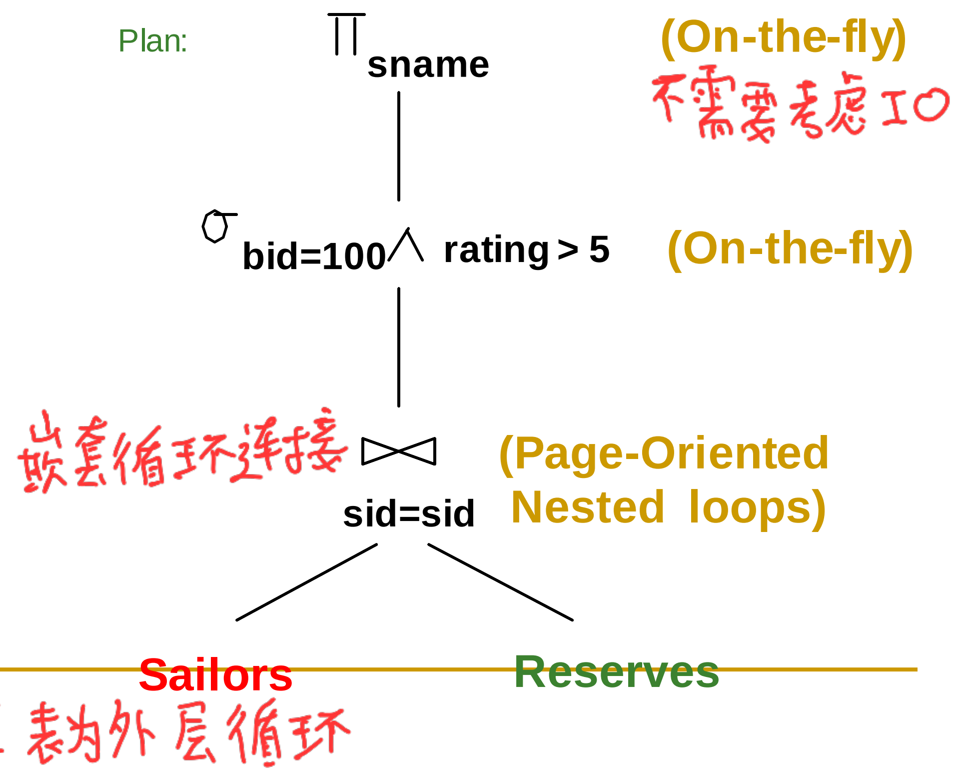
Sailors (*sid*: integer, *sname*: string, *rating*: integer, *age*: real)
Reserves (*sid*: integer, *bid*: integer, *day*: dates, *rname*: string)

- 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!

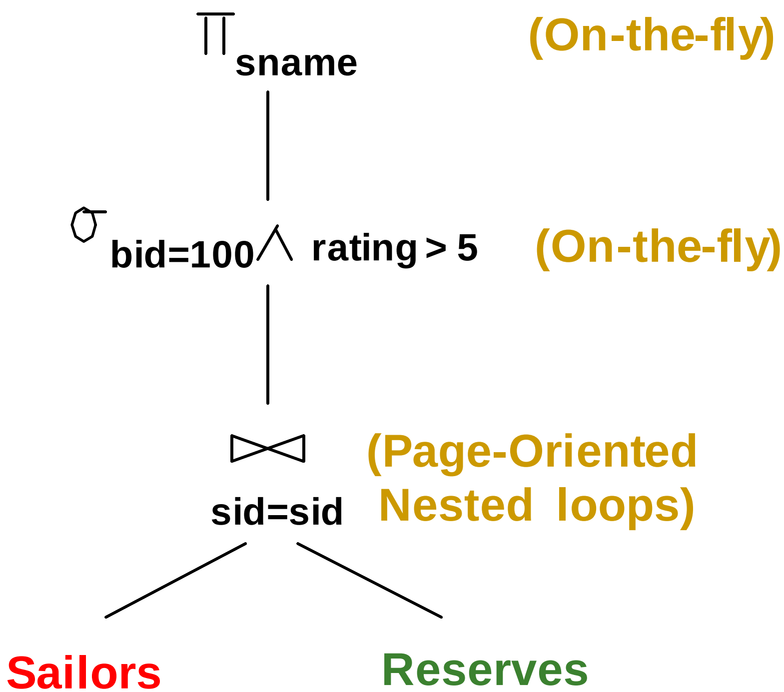
# Motivating Example

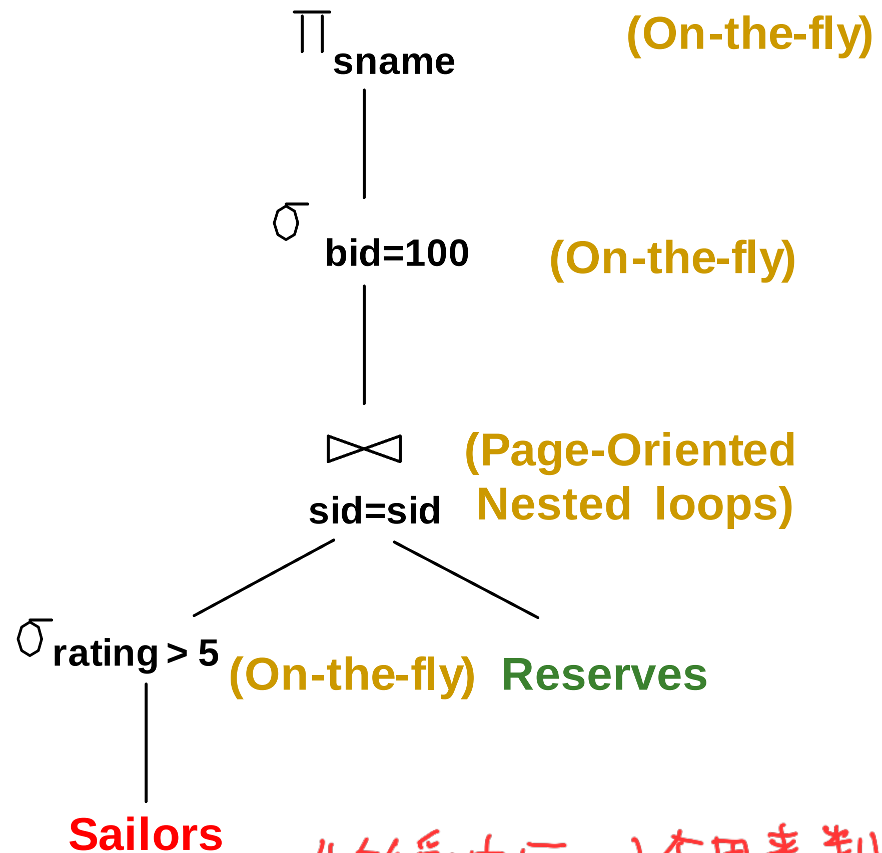
```
SELECT  S.sname
FROM  Reserves R, Sailors S
WHERE  R.sid=S.sid AND
   R.bid=100 AND S.rating>5
```

- Cost:  500+500*1000 I/Os
- By no means the worst plan!
- Misses several opportunities:
  - selections could be `pushed' down
  - no use made of indexes
- *Goal of optimization:* Find faster plans that compute the same answer.



# Alternative Plans – Push Selects (No Indexes)




3个缓冲区

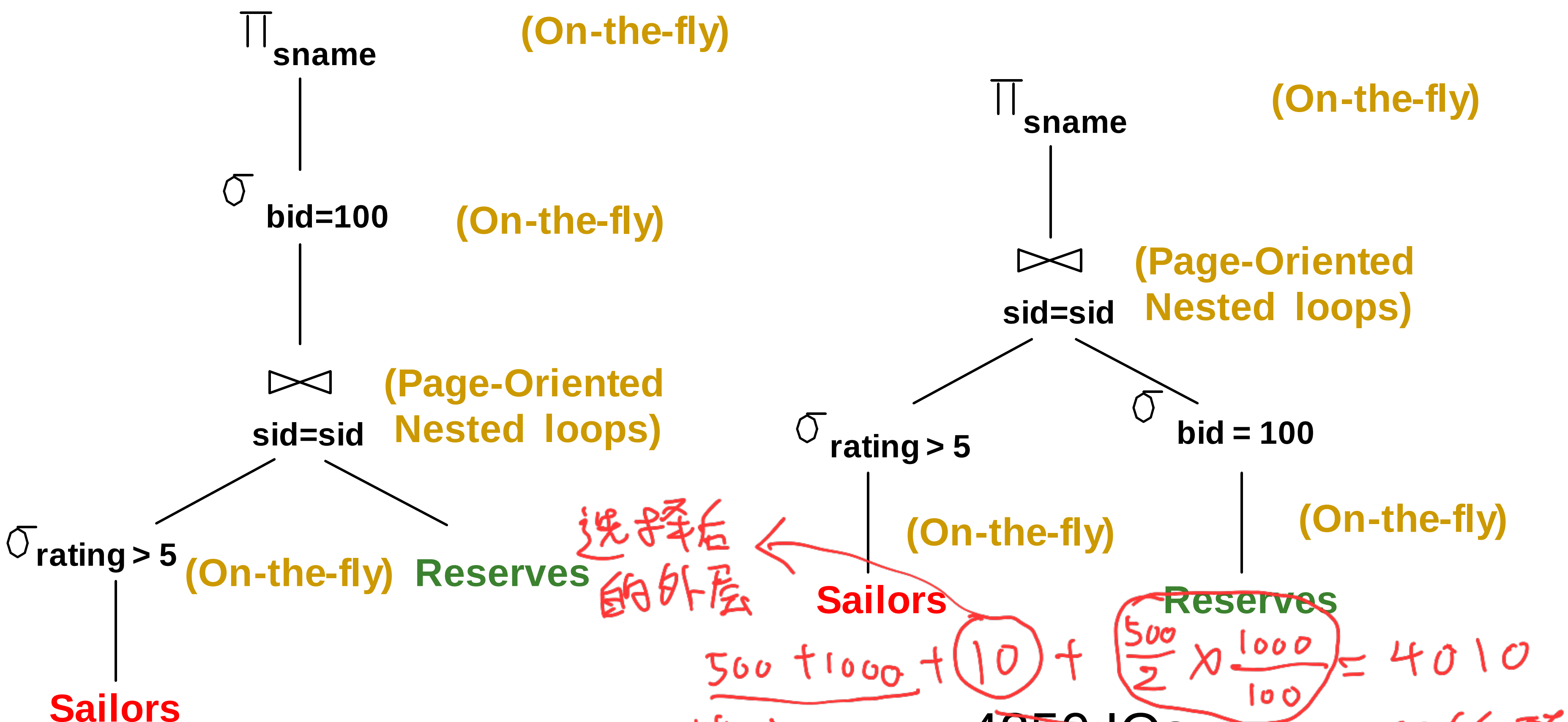
4个缓冲区，1个用来判断 rating>5

500,500 IOs

250,500 IOs

$500 + \frac{500}{2} \times 1000 = 250500$

# Alternative Plans – Push Selects (No Indexes)

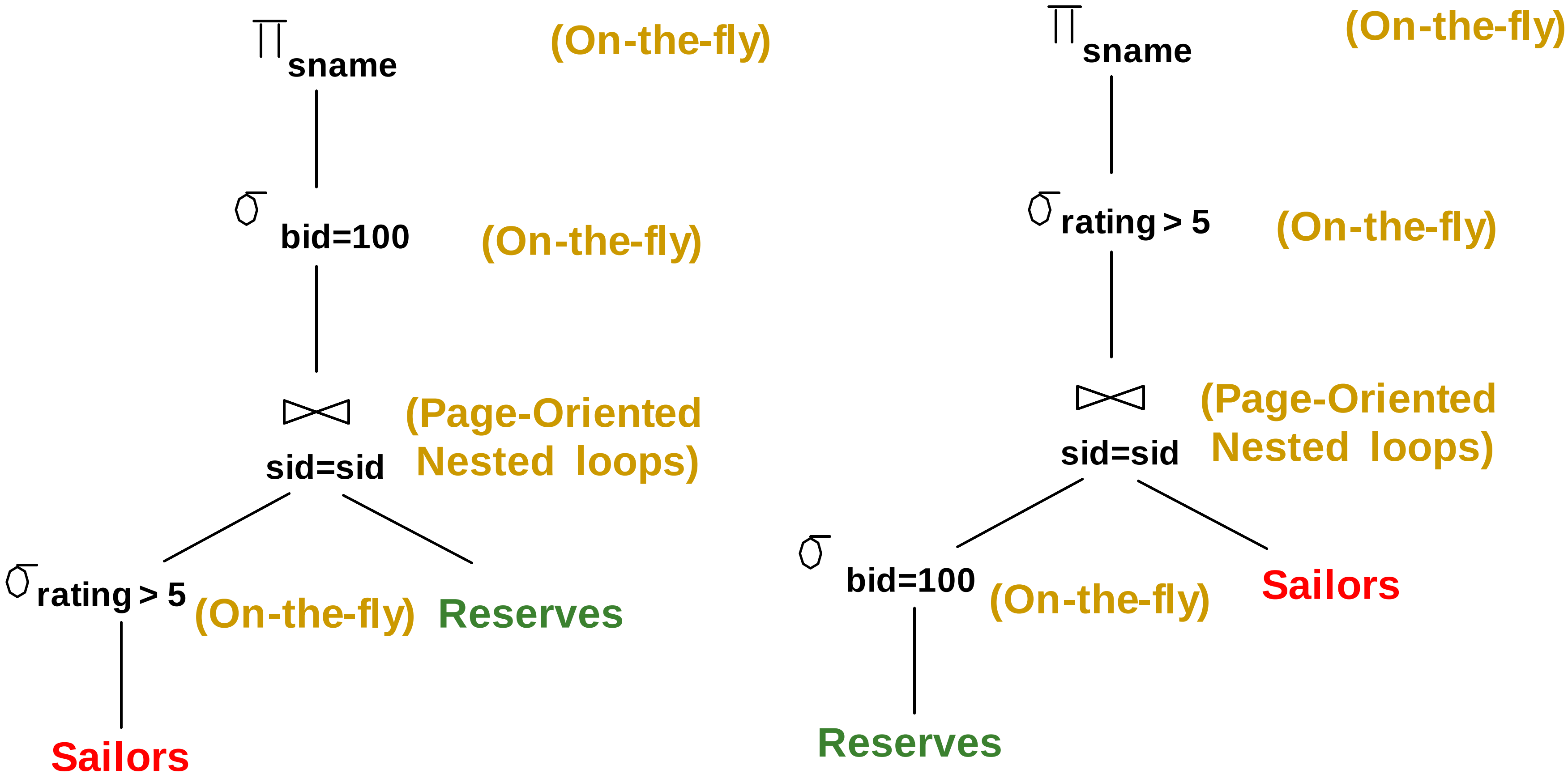



250,500 IOs

~~4250~~ 4010 IOs

~~500 + 1000 + 250 + 250*10~~

# Alternative Plans – Push Selects (No Indexes)

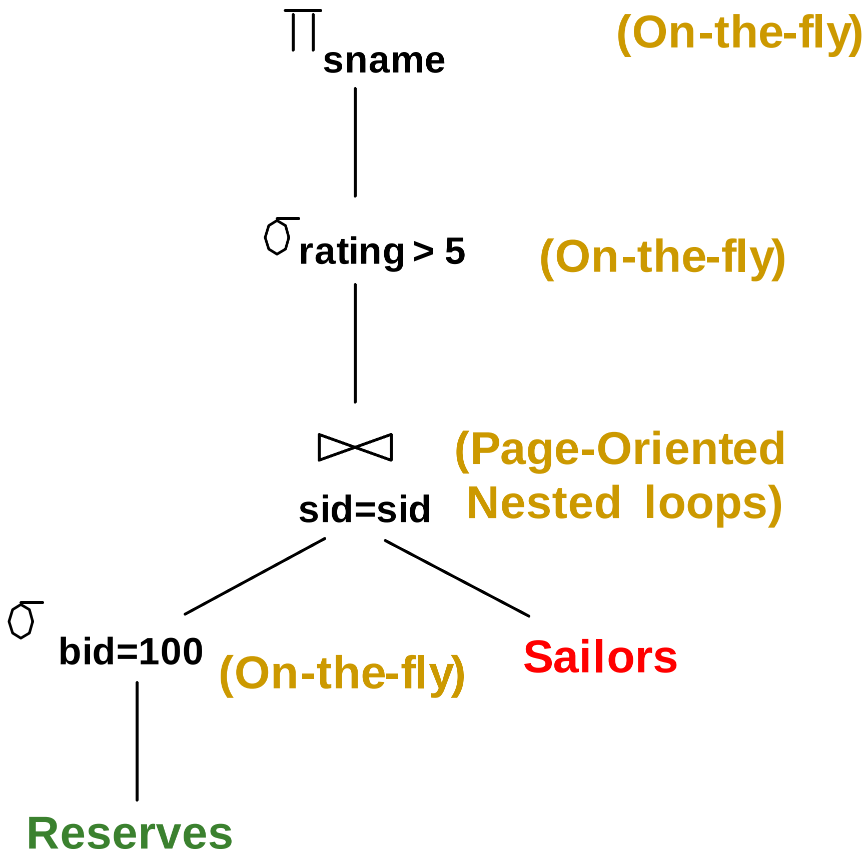


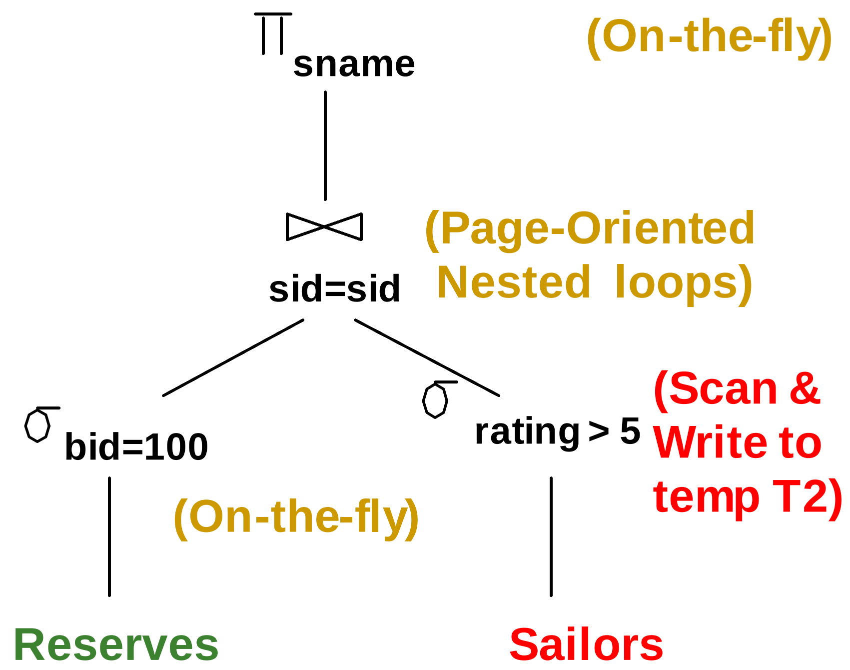

250,500 IOs

6000 IOs

$$1000 + \frac{1000}{100} \times 500 = 6000$$

# Alternative Plans – Push Selects (No Indexes)



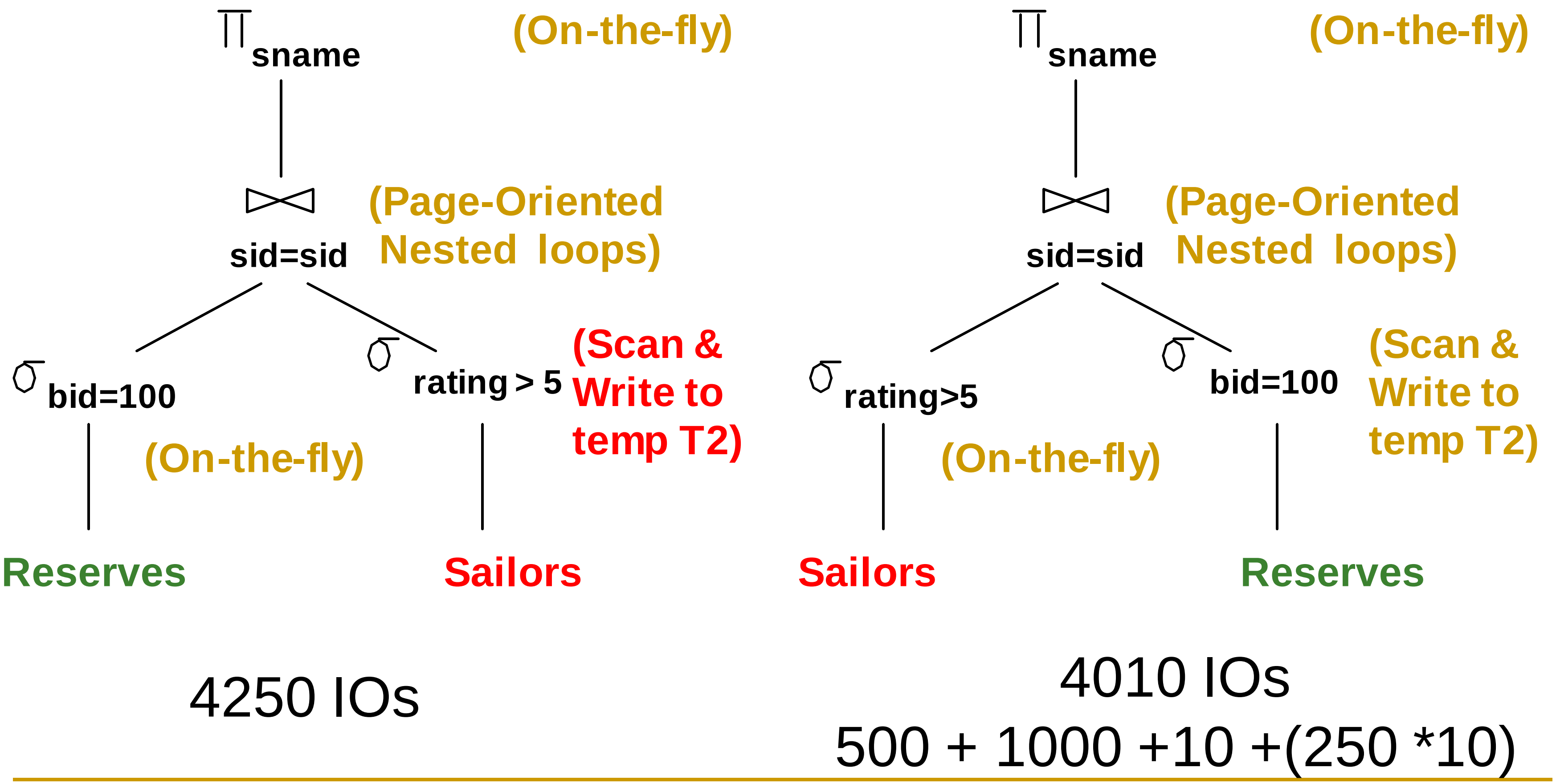




4250 IOs

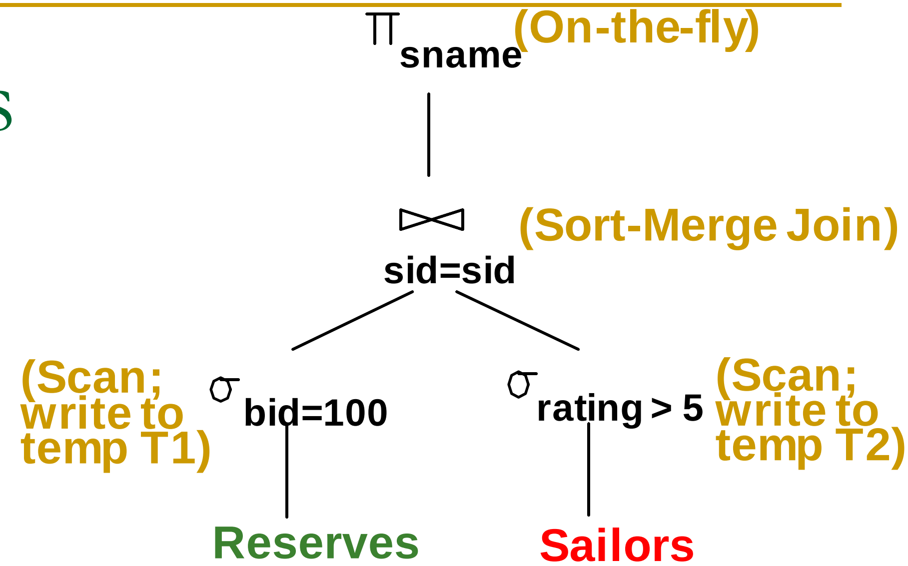
6000 IOs

1000 + 500+ 250 + (10 * 250)

# Alternative Plans – Push Selects (No Indexes)



# More Alternative Plans (No Indexes)




- <u>*Sort Merge Join*</u>

- With 5 buffers, cost of plan:
  - Scan Reserves (1000) + write temp T1 (10 pages) = 1010.
  - Scan Sailors (500) + write temp T2 (250 pages) = 750.
  - Sort T1 (2*2*10) + sort T2 (2*4*250) + merge (10+250) = 2300
  - Total: 4060 page I/Os. $\left\lceil \frac{250}{5} \right\rceil = 50$ $\quad \lceil \log_4 50 \rceil = 3$ $\quad 3+1 = 4$ 趟
- If use <u>BNL join</u>, join = 10+4*250, total cost = 2770.
- Can also 块 'push' projections, but must be careful! $10 + \left\lceil \frac{10}{3} \right\rceil \times 250$
  - T1 has only *sid*, T2 only *sid*, *sname*:
  - T1 fits in 3 pgs, cost of BNL under 250 pgs, total < 2000.

# Summing up

- There are *lots* of plans
  - Even for a relatively simple query
- People tend to think they can pick good ones by hand
  - MapReduce is based on that assumption
- Not so clear that's true!
  - Machines are better at enumerating options than people
  - But we will see soon how optimizers make simplifying assumptions

# 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, in turn based on
    - Catalog information on base tables
    - Selectivity (Reduction Factor) estimation
- A search algorithm: To sift through the plan space and find lowest cost option!

# Query Optimization

- Will focus on "System R" (Selinger) style optimizers

Access Path Selection
in a Relational Database Management System

P. Griffiths Selinger
M. M. Astrahan
D. D. Chamberlin
R. A. Lorie
T. G. Price

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ABSTRACT: In a high level query and data manipulation language such as SQL, requests are stated non-procedurally, without reference to access paths. This paper describes how System R chooses access paths retrieval. Nor does a user specify in what order joins are to be performed. The System R optimizer chooses both join order and an access path for each table in the SQL statement. Of the many possible

# Highlights of System R Optimizer

- Impact:
  - Most widely used currently; works well for 10-15 joins.
- Cost estimation:
  - Very inexact, but works OK in practice.
  - Statistics in system catalogs used to estimate cost of operations and result sizes.
  - Considers combination of CPU and I/O costs.
  - System R's scheme has been improved since that time.

# Highlights of System R Optimizer (Contd)

- 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.

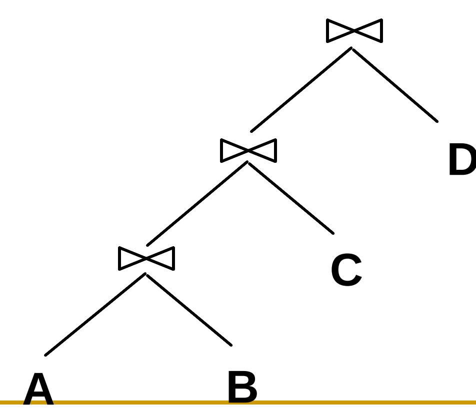
# Query Blocks: Units of Optimization

- 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*
    – 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
```

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

# Relational Algebra Equivalences (1)

- 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*)
  - $\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c2}(\sigma_{c1}(R))$ (*commute*) 缩少元组范围
- Projections:
  - $\pi_{a1}(R) \equiv \pi_{a1}(\ldots(\pi_{a1, \ldots, an}(R))\ldots)$ (*cascade*)

# Relational Algebra Equivalences (2)

- Cartesian Product
  - $R \times (S \times T) \equiv (R \times S) \times T$ (associative)
  - $R \times S \equiv S \times R$ (commutative)
- JOIN
  - $R \bowtie (S \bowtie T) \equiv (R \bowtie S) \bowtie T$ (associative)
  - $R \bowtie S \equiv S \bowtie R$ (commutative)

  - *This means we can do joins in any order.*
    - But…beware of cartesian product!

# 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.

- A selection on attributes of R commutes with R $\bowtie$ S.
  - i.e., $\sigma(R \bowtie S) \equiv \sigma(R) \bowtie S$
  - but only if the selection doesn't refer to 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 this for various operators
      - 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 + CPU-*factor* * #tuples
- Q: Is "cost" the same as estimated "run time"?

# Statistics and Catalogs

- Need infomation on relations and indexes involved.
- *Catalogs* typically contain at least:

| Statistic | Meaning |
|---|---|
| NTuples | # of tuples in a table (cardinality) |
| NPages | # of disk pages in a table |
| Low/High | min/max value in a column |
| Nkeys | # of distinct values in a column |
| IHeight | the height of an index |
| INPages | # of disk pages in an index |

- Catalogs updated periodically.
- Modern systems do more
  - keep more detailed information on data values, e.g., histograms

# Size Estimation and Selectivity

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

- Max output cardinality = product of input cardinalities
- *Selectivity (sel)* associated with each *term*
  - reflects the impact of the *term* in reducing result size.
  - |output| / |input|

  *Result cardinality* = Max # tuples * $\prod \text{sel}_i$

  - *Book calls selectivity "Reduction Factor" (RF)*
- Avoid confusion:
  - "highly selective" in common English is opposite of a high selectivity value (|output|/|input| high!)

# Result Size Estimation

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

Implicit <u>assumptions</u>: values are uniformly distributed and *terms* are independent!

- *Note, if missing the needed stats, assume 1/10!!!*

# Enumeration of Alternative Plans

- There are two main cases:
  - Single-relation plans (base case)
  - Multiple-relation plans (induction)
- Single-table queries include selects, projects, and grouping/aggregate operations:
  - Consider each available access path (file scan / index)
    - Choose the one with the least estimated cost
  - Selection/Projection done on the fly
  - Result pipelined into grouping/aggregation

# Cost Estimates for Single-Relation Plans

- Index I on primary key matches selection:
  - *Cost is Height(I)+1 for a B+ tree.* 聚簇索引
- 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: 文件顺序扫描
  - *NPages(R).*

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

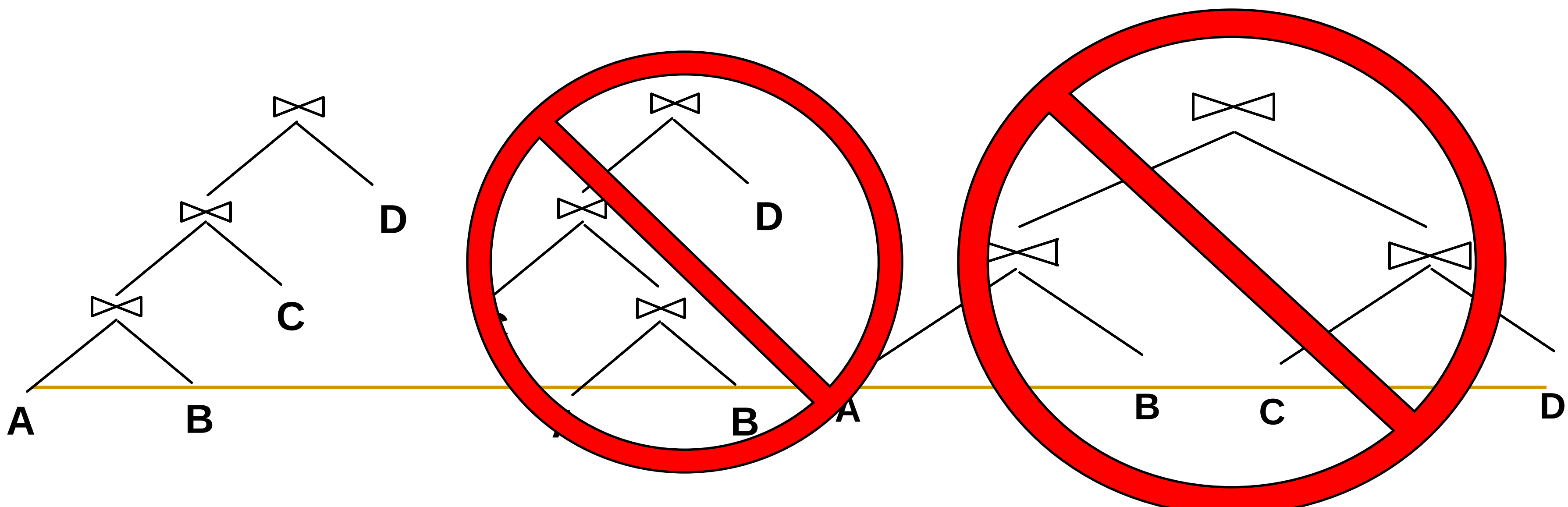
# Example

```
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) = 4005 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 System R heuristic: 左深树
  *only left-deep join trees* considered.
  - Restricts 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 in
  - the order of relations
  - the access method for each relation
  - 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 i: Find best way to join result of an ($i$ -1)-relation plan (as outer) to the $i$'th relation. ($i$ between 2 and N.)
- 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”

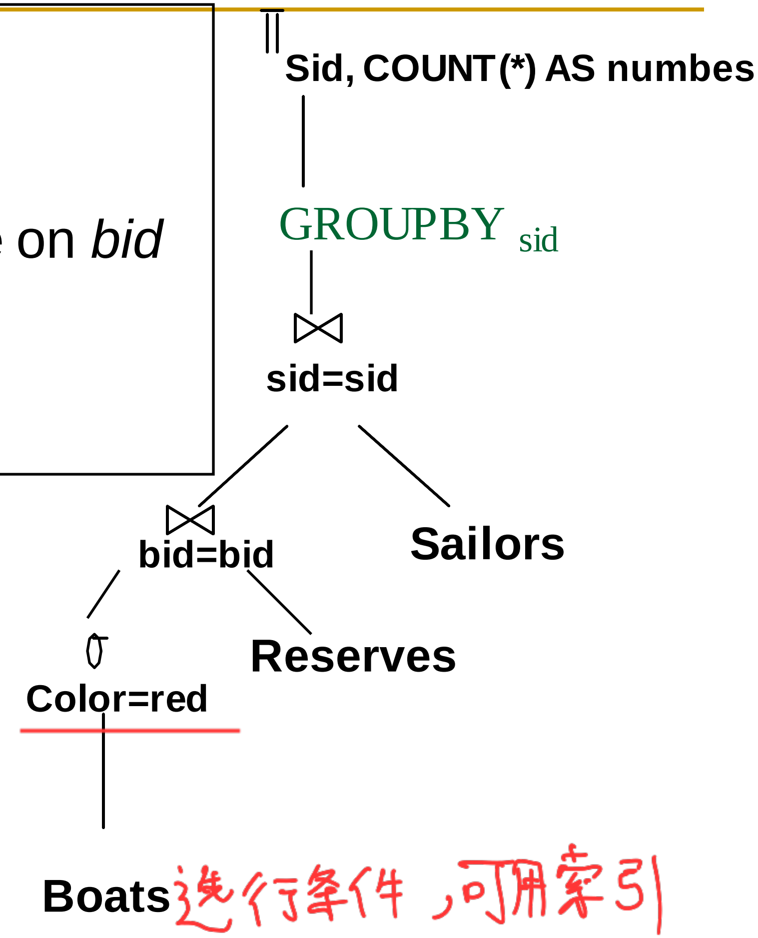
- An intermediate result has an “interesting order” if it is sorted by any of:
  - ORDER BY attributes
  - GROUP BY attributes
  - Join attributes of *yet-to-be-added* (downstream) joins

# Enumeration of Plans (Contd.)

- Match an $i$ -1 way plan with another table *only if*
  a) there is a join condition between them, *or*
  b) 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
  - via `interestingly ordered' plan if chosen (free!)
  - or via an additional sort/hash operator
- Despite pruning, this is exponential in #tables.

# Example

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

# Pass 1

- Find best plan for each relation in isolation:
  - Reserves, Sailors: File Scan
  - Boats: B+ tree on color

# Pass 2

- For each plan 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 Btree on color with Sailors (inner)
  - Boats Btree on color with Reserves (inner)
- Retain cheapest plan for each (pair of relations, order)

# Pass 3 and beyond

- Using Pass 2 plans as outer relations, generate plans for the next join
  - E.g. Boats B+-tree on color with Reserves (bid) (sortmerge)
    inner Sailors (B-tree sid) sort-merge
- Then, add cost for groupby/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

# Summary

- Optimization is the reason for the lasting power of the relational system
- But it is primitive in some ways
- New areas: many!
  - Smarter summary statistics (fancy histograms and "sketches")
  - Auto-tuning statistics,
  - Adaptive runtime re-optimization (e.g. *eddies*),
  - Multi-query optimization,
  - And parallel scheduling issues, etc.