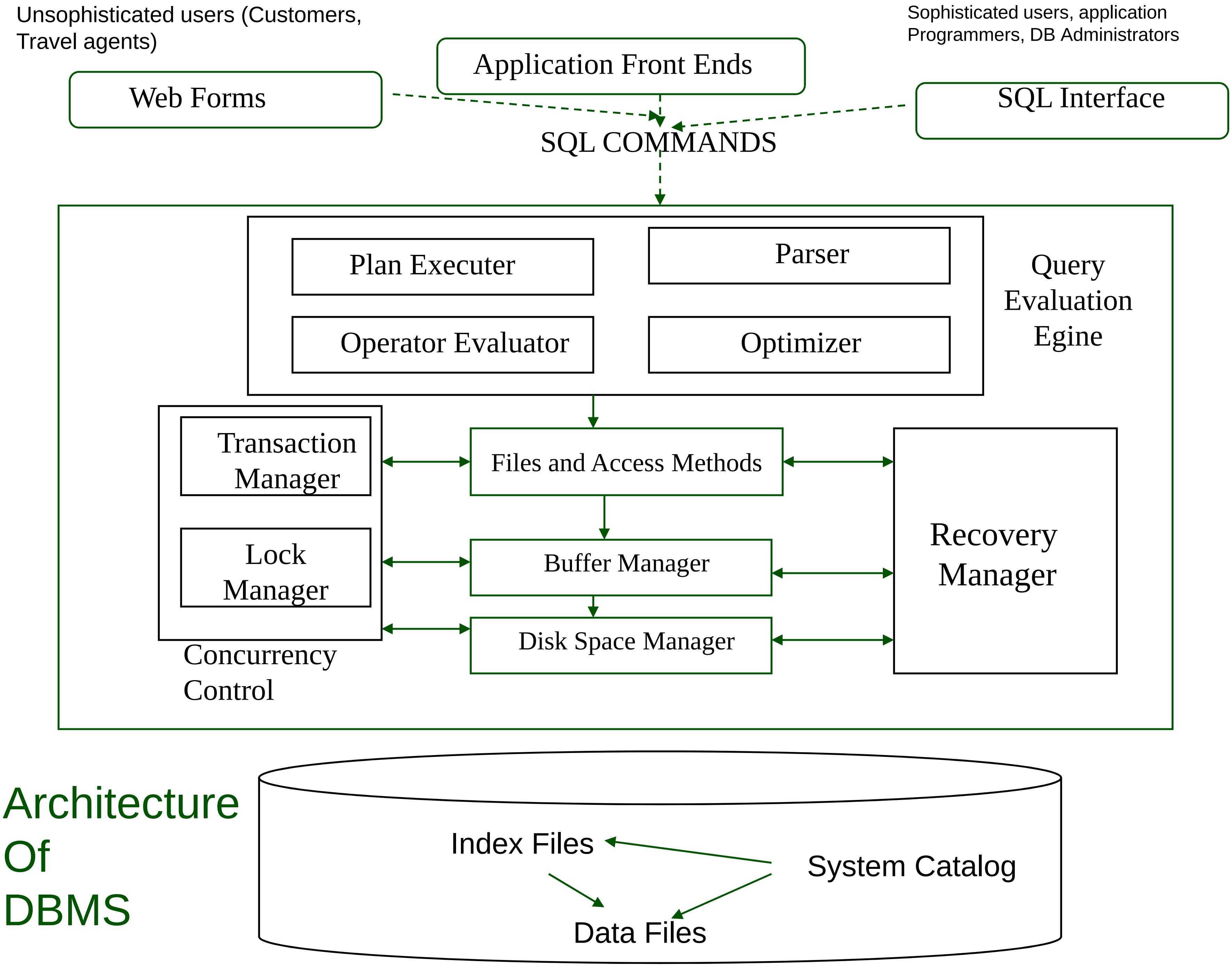
# Overview of Query Evaluation

Chapter 12




# Architecture Of DBMS

# Introduction

- We present an overview of how queries are evaluated in DBMS
- SQL queries are translated into an extended form of relational algebra
- Query evaluation plans are represented as trees of relational operators along with labels that identify the algorithm to use at each node.
- Relational operators are building blocks for evaluating queries.
- Algorithms for individual operators can be combined in several ways to evaluate a query

# Introduction

- Example queries
  - Sailors(sid:integer, sname: string, rating:integer, age: real)
  - Reserves(sid: integer, bid:integer, day:dates, rname:string)
- Statistics
  - Each tuple of reserves is 40 bytes long, a page can hold 100 Reserves tuples and we have 1000 pages of such tuples.
  - Each tuple of Sailors is 50 bytes long, and a page can hold 80 Sailors tuples and we have 500 pages of such tuples.

# *Outline*

- **The System Catalog**
- Introduction to Operator Evaluation
- Algorithms for Relational Operators
- Introduction to Query Optimization
- Alternative plans
- What a typical optimizer does

# System Catalogs

- For each relation:
  - Table name, file name, file structure (e.g., Heap file)
  - attribute name and type, for each attribute
  - index name, for each index on the table
  - integrity constraints (primary and foreign key constraints on the table)
  - Cardinality: # tuples for each relation: NTuples(R)
  - # pages for each relation: NPages(R)
- For each index:
  - Name and structure (e.g., B+ tree) and search key attributes
  - Index cardinality: # distinct key values: NKeys(R)
  - Index size: NPages for each index: NPages(I)
    - For a B+tree index, we take NPages to be the number of leaf pages.
  - Index height: The number of non-leaf levels: IHight(I)
  - Index range: low/high key values (ILow(I)/IHigh(I)) for each tree index.
- For each view:
  - view name and definition
- Additional statistics, accounting information, authorization, buffer pool size, etc.

# Statistics and Catalogs

- 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.

*Catalogs are themselves stored as relations!*

# Attr_Cat(attr_name, rel_name, type, position)

| attr_name | rel_name | type | position |
|---|---|---|---|
| attr_name | Attribute_Cat | string | 1 |
| rel_name | Attribute_Cat | string | 2 |
| type | Attribute_Cat | string | 3 |
| position | Attribute_Cat | integer | 4 |
| sid | Students | string | 1 |
| name | Students | string | 2 |
| login | Students | string | 3 |
| age | Students | integer | 4 |
| gpa | Students | real | 5 |
| fid | Faculty | string | 1 |
| fname | Faculty | string | 2 |
| sal | Faculty | real | 3 |

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# Overview of Query Evaluation

- *Plan:* *Tree of R.A. ops, with choice of alg for each op.*
  - Each operator typically implemented using a \`pull' interface: when an operator is \`pulled' for the next output tuples, it \`pulls' on its inputs and computes them.
- Two 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?
- Ideally: Want to find best plan. Practically: Avoid worst plans!
- We will study the System R approach.

# Some Common Techniques

- Algorithms for evaluating relational operators use some simple ideas extensively:
  - Indexing: Can use WHERE conditions to retrieve small set of tuples (selections, joins)
  - Iteration: Sometimes, faster to scan all tuples even if there is an index. (And sometimes, we can scan the data entries in an index instead of the table itself.)
  - Partitioning: By using sorting or hashing, we can partition the input tuples and replace an expensive operation by similar operations on smaller inputs.

* *Watch for these techniques as we discuss query evaluation!*

# Access Paths

- An access path is a method of retrieving tuples:
  - File scan, or index that matches a selection (in the query)
- A tree index *matches* (a conjunction of) terms that involve only attributes in a *prefix* of the search key.
  - E.g., Tree index on <*a, b, c*> matches the selection *a*=5 *AND b*=3, and *a*=5 *AND b*>6, but not *b*=3.
- A hash index *matches* (a conjunction of) terms that has a term *attribute = value* for every attribute in the search key of the index.
  - E.g., Hash index on <*a, b, c*> matches *a*=5 *AND b*=3 *AND c*=5; but it does not match *b*=3, *or a*=5 *AND b*=3, *or a*>5 *AND b*=3 *AND c*=5.

# A Note on Complex Selections

*(day<8/9/94* AND *rname='Paul')* OR *bid=5* OR *sid=3*

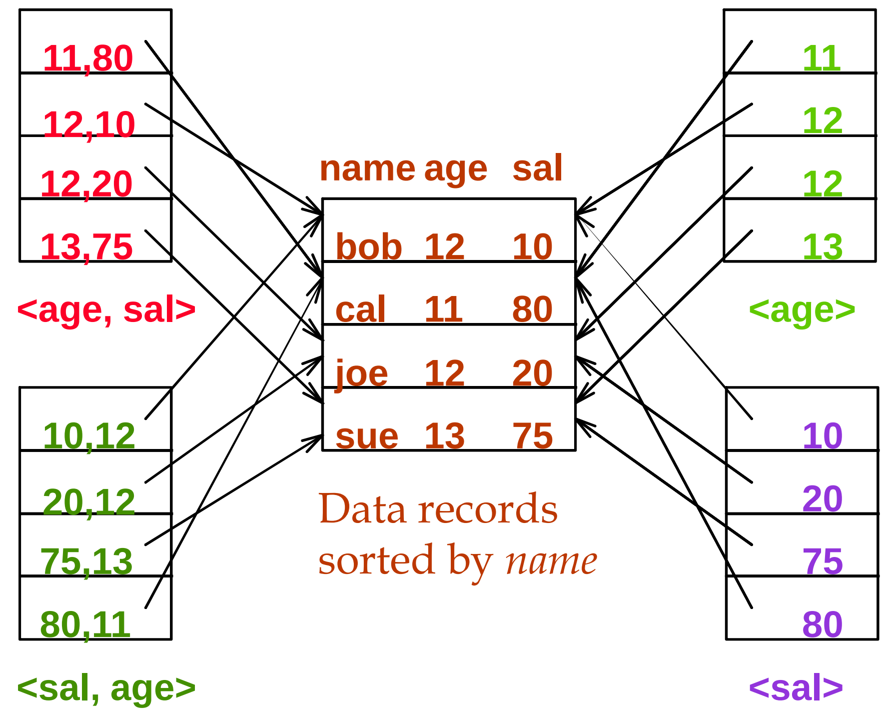
- Selection conditions are first converted to ***conjunctive normal form* (CNF)**:

  *(day<8/9/94* OR *bid=5* OR *sid=3 )* AND
  *(rname='Paul'* OR *bid=5* OR *sid=3)*
- We only discuss case with no ORs; see text if you are curious about the general case.

# Indexes with Composite Search Keys

- *Composite Search Keys:* Search on a combination of fields.
  - Equality query: Every field value is equal to a constant value. E.g. wrt <sal,age> index:
    - age=20 and sal =75
  - Range query: Some field value is not a constant. E.g.:
    - age =20; or age=20 and sal > 10
- Data entries in index sorted by search key to support range queries.
  - Lexicographic order, or
  - Spatial order.

Examples of composite key indexes using lexicographic order.




Data entries in index sorted by <*sal,age*>

Data entries sorted by <*sal*>

# One Approach to Selections

- 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.
  - Terms that match this index reduce the number of tuples *retrieved*; other terms are used to discard some retrieved tuples, but do not affect number of tuples/pages fetched.
  - Consider *day<8/9/94 AND bid=5 AND sid=3*. A 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.

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# Using an Index for Selections

- Cost depends on #qualifying tuples, and clustering.
  - Cost of finding qualifying data entries (typically small) plus cost of retrieving records (could be large w/o clustering).
  - In example, assuming uniform distribution of names, about 10% of tuples qualify (100 pages, 10000 tuples). With a clustered index, cost is little more than 100 I/Os; if unclustered, upto 10000 I/Os!

```
SELECT  *
FROM    Reserves R
WHERE   R.rname < 'C%'
```

# Projection

```
SELECT  DISTINCT
        R.sid, R.bid
FROM    Reserves R
```

- The expensive part is removing duplicates.
  - SQL systems don't remove duplicates unless the keyword DISTINCT is specified in a query.
- Sorting Approach: Sort on <sid, bid> and remove duplicates. (Can optimize this by dropping unwanted information while sorting.)
- Hashing Approach: Hash on <sid, bid> to create partitions. Load partitions into memory one at a time, build in-memory hash structure, and eliminate duplicates.
- If there is an index with both R.sid and R.bid in the search key, may be cheaper to sort data entries!

# Join: Index Nested Loops

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

- If there is an index on the join column of one relation (say S), can make it the inner and exploit the index.
  - Cost: M + ( (M*$p_R$) * cost of finding matching S tuples)
- For each R tuple, cost of probing S index is about 1.2 for hash index, 2-4 for B+ tree. Cost of then finding S tuples (assuming Alt. (2) or (3) for data entries) depends on clustering.
  - Clustered index: 1 I/O (typical), unclustered: upto 1 I/O per matching S tuple.

# Examples of Index Nested Loops

- Hash-index (Alt. 2) on *sid* of Sailors (as inner):
  - Scan Reserves: 1000 page I/Os, 100*1000 tuples.
  - For each Reserves tuple: 1.2 I/Os to get data entry in index, plus 1 I/O to get (the exactly one) matching Sailors tuple. Total: 220,000 I/Os.
- Hash-index (Alt. 2) on *sid* of Reserves (as inner):
  - Scan Sailors: 500 page I/Os, 80*500 tuples.
  - For each Sailors tuple: 1.2 I/Os to find index page with data entries, plus cost of retrieving matching Reserves tuples. Assuming uniform distribution, 2.5 reservations per sailor (100,000 / 40,000). Cost of retrieving them is 1 or 2.5 I/Os depending on whether the index is clustered.

# Join: Sort-Merge ($R \bowtie_{i=j} S$)

- Sort R and S on the join column, then scan them to do a ``merge'' (on join col.), and output result tuples.
  - Advance scan of R until current R-tuple >= current S tuple, then advance scan of S until current S-tuple >= current R tuple; do this 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.
  - Then resume scanning R and S.
- R is scanned once; each S group is scanned once per matching R tuple. (Multiple scans of an S group are likely to find needed pages in buffer.)

# Example of Sort-Merge Join

| sid | sname | rating | age |
|---|---|---|---|
| 22 | dustin | 7 | 45.0 |
| 28 | yuppy | 9 | 35.0 |
| 31 | lubber | 8 | 55.5 |
| 44 | guppy | 5 | 35.0 |
| 58 | rusty | 10 | 35.0 |

| sid | bid | day | rname |
|---|---|---|---|
| 28 | 103 | 12/4/96 | guppy |
| 28 | 103 | 11/3/96 | yuppy |
| 31 | 101 | 10/10/96 | dustin |
| 31 | 102 | 10/12/96 | lubber |
| 31 | 101 | 10/11/96 | lubber |
| 58 | 103 | 11/12/96 | dustin |

- Cost: M log M + N log N + (M+N)
  - The cost of scanning, M+N, could be M*N (very unlikely!)
- With 35, 100 or 300 buffer pages, both Reserves and Sailors can be sorted in 2 passes; total join cost: 7500.

# Indexed Nested Loops versus Sort-merge join

- Index nested loop is incremental
- If there are small set of  Reserve tuples, we can avoid computing the join.
- If we use sort-merge join, we have to scan entire Sailors table at least once. The cost of this is much higher.
- So the cost of nested loop depends on the selection.
- So, we have to find a process of  a good plan.

# Highlights of System R Optimizer

- Impact:
  - Most widely used currently; works well for < 10 joins.
- Cost estimation: Approximate art at best.
  - Statistics, maintained in system catalogs, used to estimate cost of operations and result sizes.
  - Considers combination of CPU and I/O costs.
- Plan Space: Too large, must be pruned.
  - 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.

# Cost Estimation

- For each plan considered, must estimate 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 also estimate *size of result* for each operation in tree!
    - Use information about the input relations.
    - For selections and joins, assume independence of predicates.

# 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.
  - Implicit assumption that *terms* are independent!
  - Term *col=value* has RF *1/NKeys(I),* given index I on *col*
  - Term *col1=col2* has RF *1/MAX(NKeys(I1), NKeys(I2))*
  - Term *col>value* has RF *(High(I)-value)/(High(I)-Low(I))*

# Schema for Examples

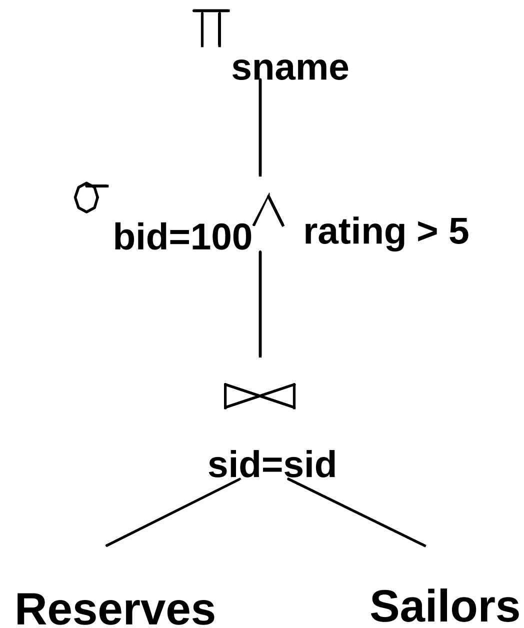
Sailors (*sid*: integer, *sname*: string, *rating*: integer, *age*: real)
Reserves (*sid*: integer, *bid*: integer, *day*: dates, *rname*: string)

- Similar to old schema; *rname* added for variations.
- Reserves:
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages.
- Sailors:
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages.

# Motivating Example

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

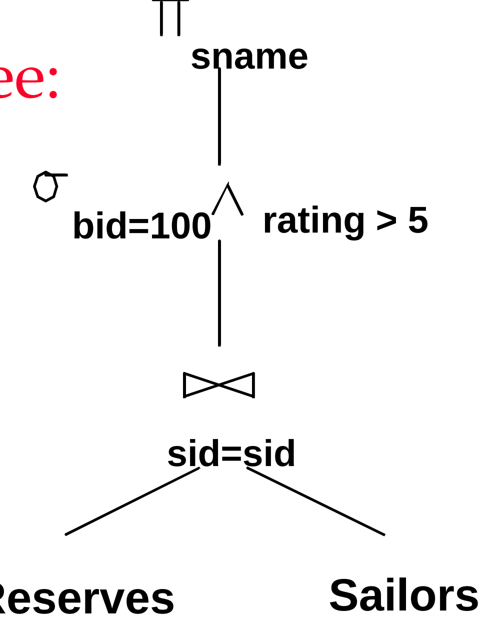
Relational Algebra Tree:



# Naïve Plan 1

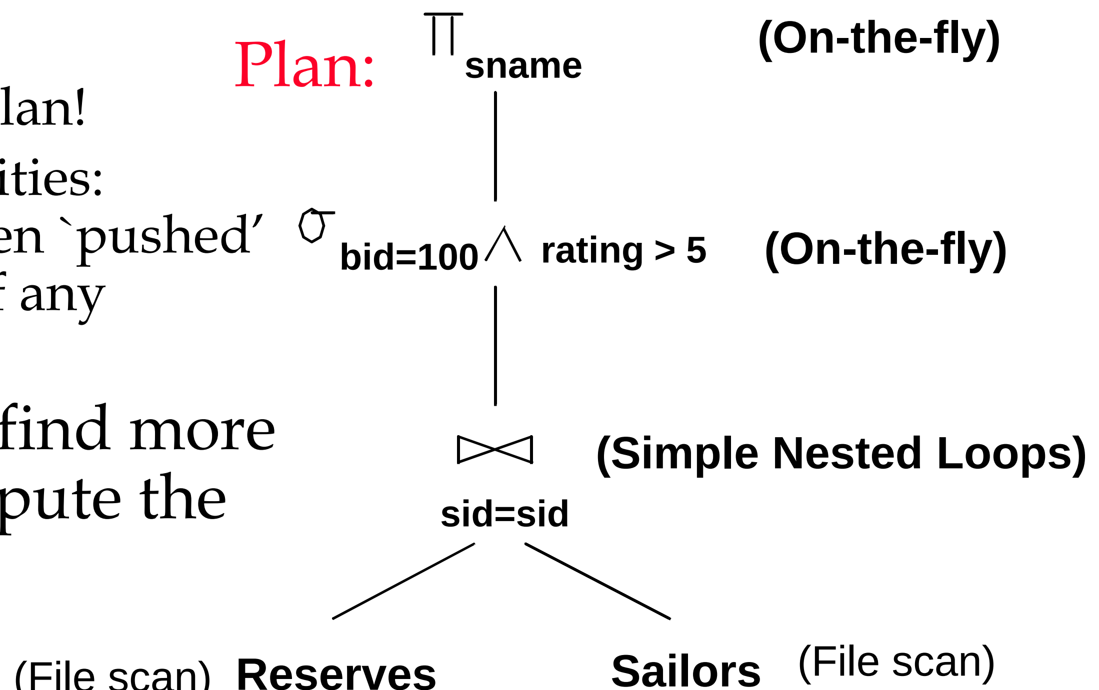
```
SELECT  S.sname
FROM  Reserves R, Sailors S
WHERE  R.sid=S.sid AND
   R.bid=100 AND S.rating>5
```

RA Tree:

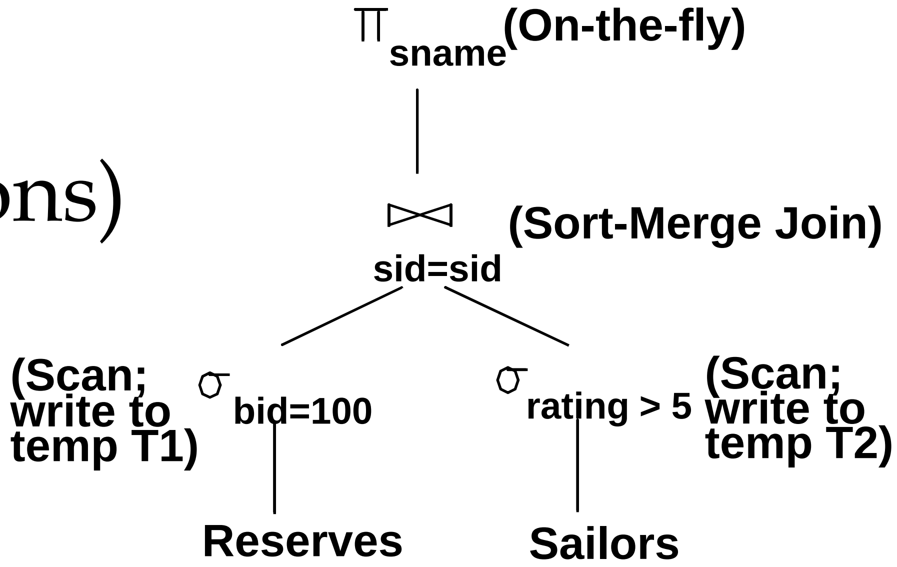



- Cost:  500+500*1000 I/Os= 501,000 page I/O s
  - By no means the worst plan!
  - Misses several opportunities: selections could have been `pushed' earlier, no use is made of any available indexes, etc.
- *Goal of optimization:* To find more efficient plans that compute the same answer.

Plan:

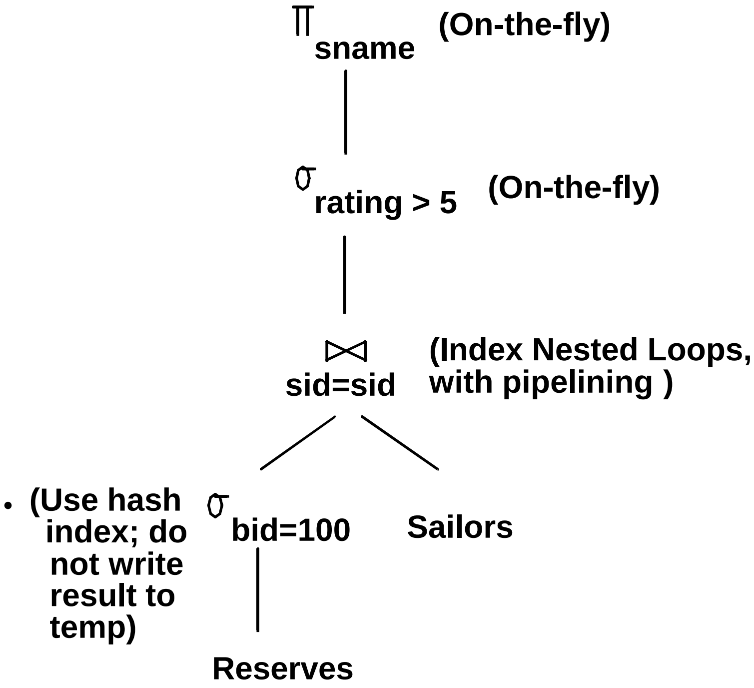


# Alternative Plans
## (No Indexes; Push selections)




- *Push selects (no index).*
  - With 5 buffers, cost of plan:
  - Scan Reserves (1000) + write temp T1 (10 pages, if we have 100 boats, uniform distribution).
  - Scan Sailors (500) + write temp T2 (250 pages, if we have 10 ratings).
  - Sort T1 (2*2*10), sort T2 (2*3*250), merge (10+250)
  - Total: 3560 page I/Os.
  - If we used BNL (Block Nested Loops) join, join cost = 10+4*250, total cost = 2770.
- Push Projections
  - If we `push' projections, T1 has only *sid*, T2 only *sid* and *sname*:
  - T1 fits in 3 pages, cost of BNL drops to under 250 pages, total < 2000.

# Alternative Plans 2 With Indexes




- With clustered index on *bid* of Reserves, we get 100,000/100 = 1000 tuples on 1000/100 = 10 pages.
- INL with ***pipelining*** (outer is 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); for each, must get matching Sailors tuple (1000*1.2); total 1210 I/Os.

# What a typical optimizer does ?

- Uses relational algebra equivalences to identify many equivalent expressions for a given query.
- For each such equivalent, all available implementation techniques are considered for the relational operators involved, generating alterative query evaluation plans.
- The optimizer estimates the cost of each such plan and chooses the one with the lowest estimated cost.

# Alternative Plans considered

- Selections and cross-products can be conbined into joins.
- Joins can be extensively ordered.
- Selections and projections, which reduce the size of the input , can be pushed ahead of joins.
- Left-deep plans
  - Right child of each join node is a base table.
  - Alternative is bushy tree
- Optimizers use left-deep plans
  - Allows to generate fully pipelined plans.

# Alternative Plans considered…

- Estimating the cost of a plan
  - Cost of the plan is sum of costs for the operators it contains.
  - Cost of individual relational operator in the plan is estimated using information from system catalog.
  - Metric is number of I/Os.
    - Reading input tables
    - Writing intermediate results
    - Sorting the final result. (common to all plans)
- The cost of fully pipelined plan is dominated by the step `reading the input values'.
  - Depends on access paths used to read input tables
- If the plans are not fully pipelined, the cost of materializing temporary tables can be significant.

# Summary

- There are several alternative evaluation algorithms for each relational operator.
- A query is evaluated by converting it to a tree of operators and evaluating the operators in the tree.
- Must understand query optimization in order to fully 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.