# *Overview of Query Evaluation*

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- *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!*

# *Statistics and Catalogs*

- Need information about the relations and indexes involved. ***Catalogs*** typically contain at least:
  - # tuples (NTuples) and # pages (NPages) for each relation.
  - # distinct key values (NKeys) and NPages for each index.
  - Index height, low/high key values (Low/High) for each tree 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.

# *System Catalogs (aka System Tables)*

- For each index:
  - structure (e.g., B+ tree) and search key fields
- For each relation:
  - name, file structure (e.g., Heap file)
  - attribute name and type, for each attribute
  - index name, for each index
  - integrity constraints
- For each view:
  - view name and definition
- Plus statistics, authorization, buffer pool size, etc.

*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 |

# *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.

# *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.

# *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, 10,000 tuples). With a clustered index, cost is little more than 100 I/Os; if unclustered, upto 10,000 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: Block (Index) Nested Loops* ($R \bowtie_{i=j} S$)

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)
  - M=#pages of R, $p_R$=# R tuples per page
- For each R tuple, cost of probing S index is about 1 for hash index, 3 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.

# *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!)

# *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))*

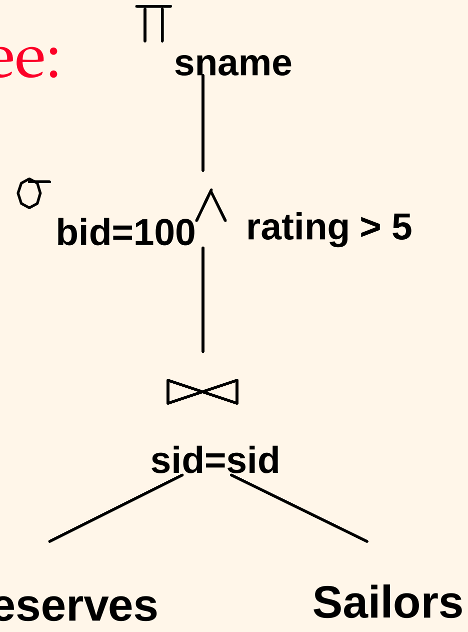
# *Schema for Examples*

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.

# Motivating Example

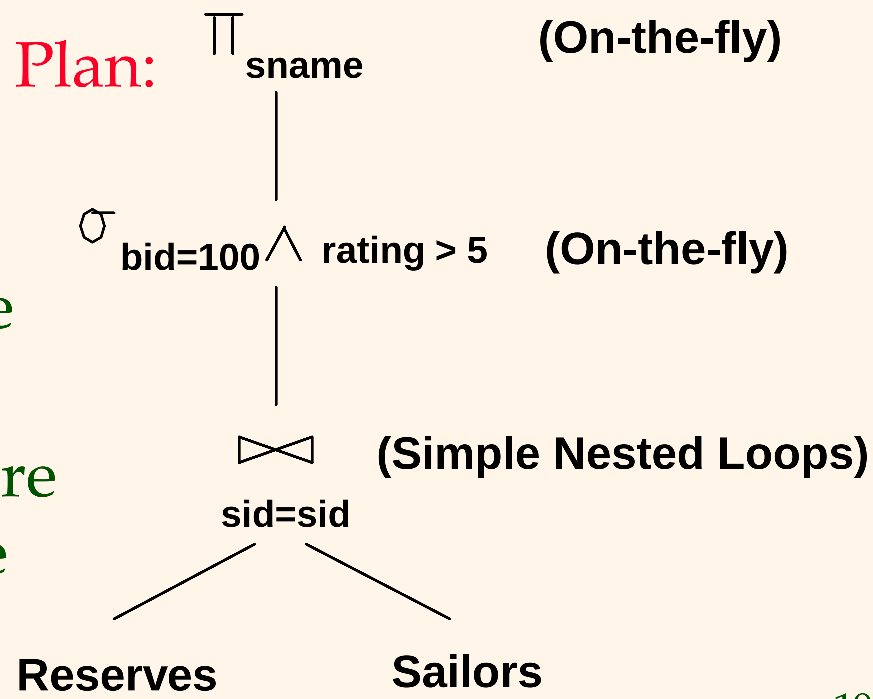
RA Tree:



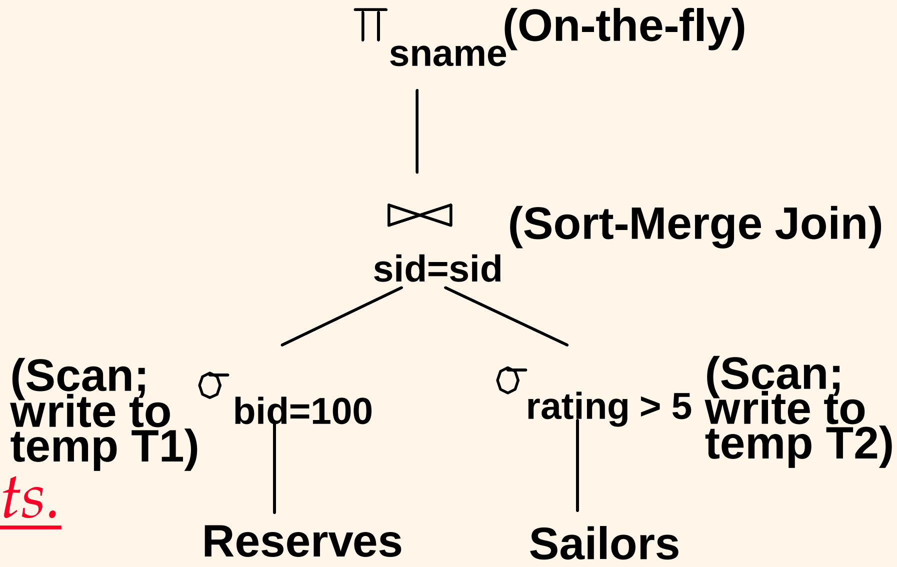

```
SELECT  S.sname
FROM  Reserves R, Sailors S
WHERE  R.sid=S.sid AND
   R.bid=100 AND S.rating>5
```

- Cost of plan = cost of join
- 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:

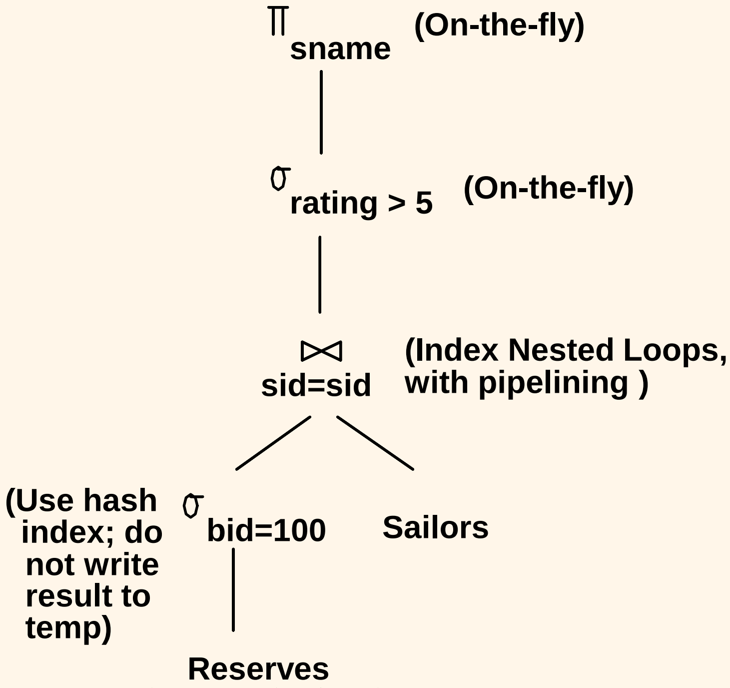


# *Alternative Plans 1 (No Indexes)*




- ***Main difference:*** *push down selects.*
- Cost of plan =
  - Cost of selection (bid=100) + write results to temp file T1 +
  - Cost of selection (rating>5) + write results to temp file T2 +
  - Cost of sort-merge join of T1 and T2
- Significant cost improvement due to the fact that we join smaller tables.
- If we push projections, T1 has only *sid*, T2 only *sid* and *sname*:
  - Even smaller tables to perform the join.

# Alternative Plans 2 With Indexes




- With clustered index on *bid* of Reserves
- 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; for each, must get matching Sailors tuple.

# 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.