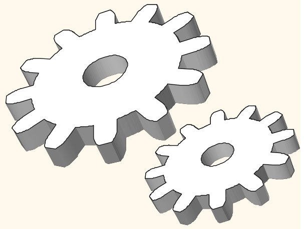
Overview of Implementing Relational Operators and Query Evaluation

Chapter 12

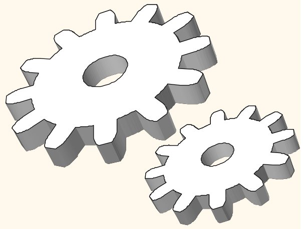
Motivation: Evaluating Queries

- The same query can be evaluated in different ways.
- The evaluation strategy (plan) can make orders of magnitude of difference.
- Query efficiency is one of the main areas where DBMS systems compete with each other.
- Person-decades of development, secret details.



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.
  - Much like cursor/iterator.
- 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 (IBM).



Some Common Techniques

- Algorithms for evaluating relational operators use some simple ideas extensively:
  - Indexing: Can use WHERE conditions and indexes 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 on a sort key, 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!*

Examples

Example Relations

Sailors

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

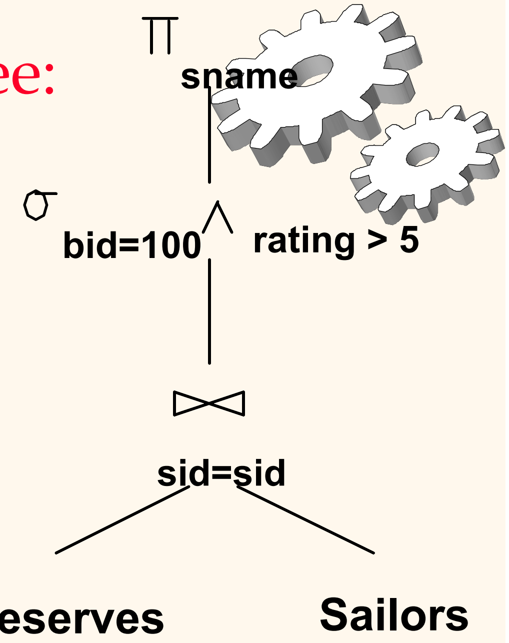
Reservations

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

Query Plan Example

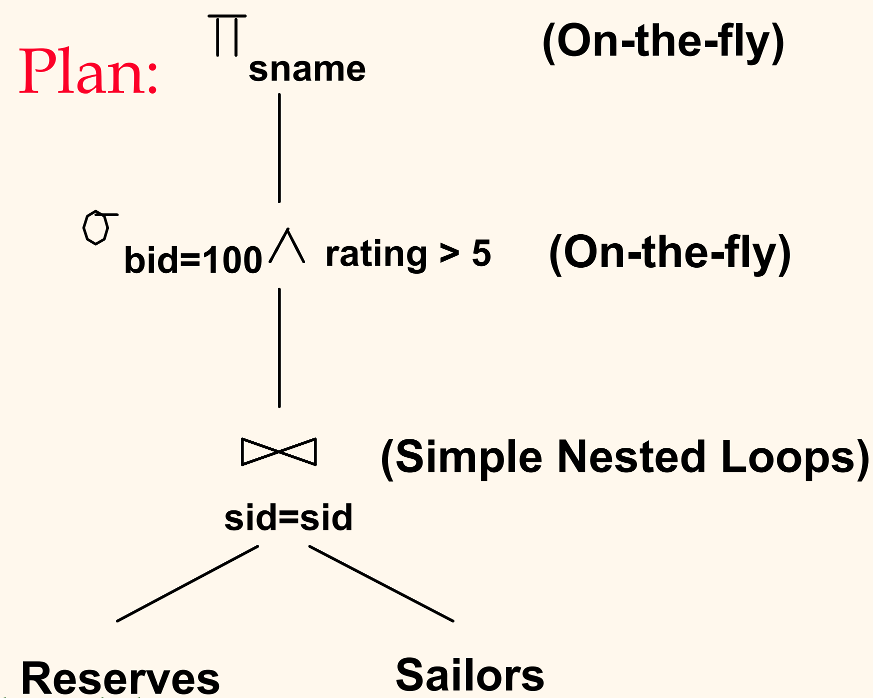
```
SELECT  S.sname
FROM  Reserves R, Sailors S
WHERE  R.sid=S.sid AND
   R.bid=100 AND S.rating>5
```

RA Tree:



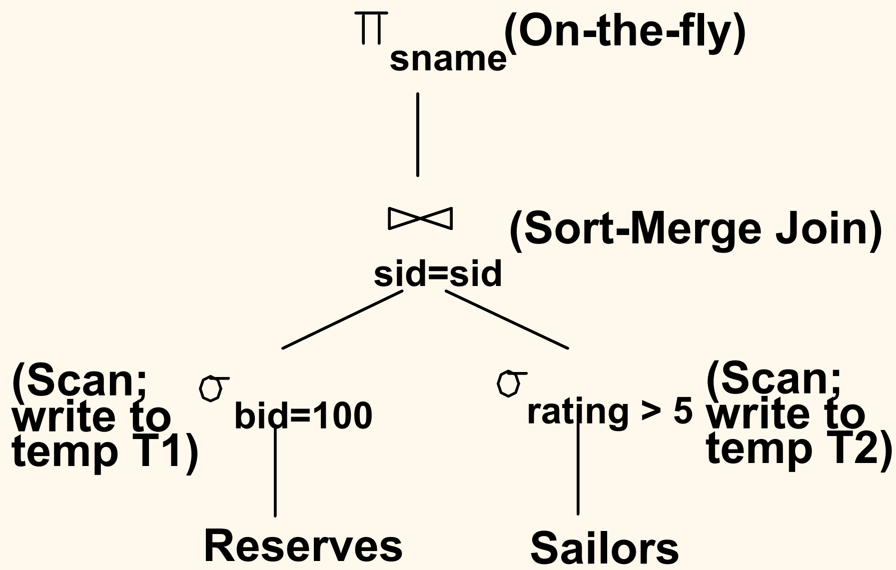
- RA Tree: expression tree.
- Each leaf is a schema table.
- Internal nodes: relational algebra operator applied to children.
- Full plan labels each internal node with implementation strategy.

Plan:



Alternative Plan

- *Goal of optimization:* To find efficient plans that compute the same answer.



Computing Relational Operators

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*.

Exercise 12.4

Consider the following schema with the Sailors relation:

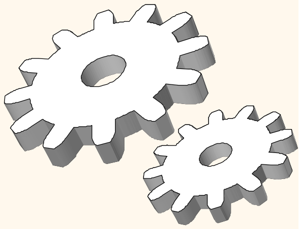
Sailors(<u>sid: integer</u>, sname: string, rating: integer, age: real)

- For each of the following indexes, list whether the index matches the given selection conditions.
  1. A hash index on the search key <Sailors.sid>
     a. $\sigma_{sid<50,000}$ (Sailors)
     b. $\sigma_{sid=50,000}$ (Sailors)
  2. A B+-tree on the search key <Sailors.sid>
     a. $\sigma_{sid<50,000}$ (Sailors)
     b. $\sigma_{sid=50,000}$ (Sailors)

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.

Selection and Projection



One Approach to Selections

- Estimate 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 requires 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.

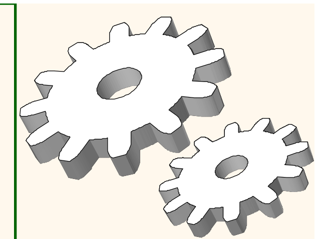
Using an Index for Selections

- 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, assume that about 10% of tuples qualify (100 pages, 10000 tuples). With a clustered index, cost is little more than 100 I/Os; if unclustered, up to 10000 I/Os!

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

Projection

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



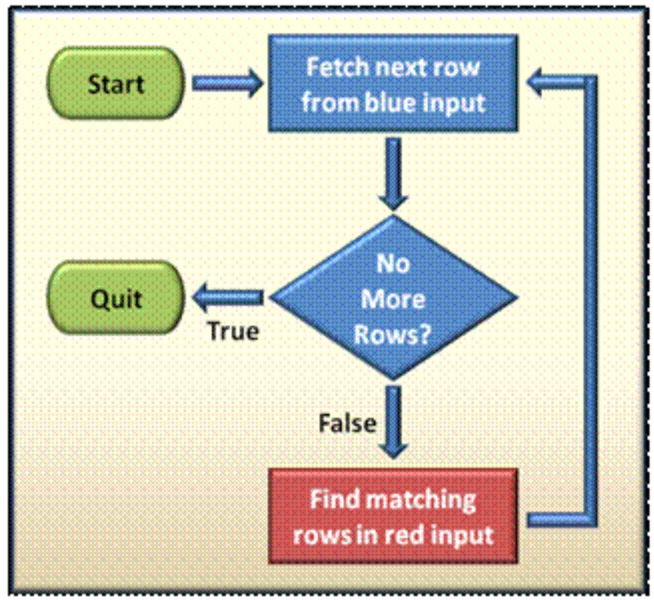
- *The expensive part is removing duplicates.*
  - SQL systems don't remove duplicates unless the keyword DISTINCT is specified in a query.
- Sorting Approach: Sort on <sid, bid> and remove duplicates. (Can optimize this by dropping unwanted information while sorting.)
- Hashing Approach: Hash on <sid, 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!

The Biggie: Join

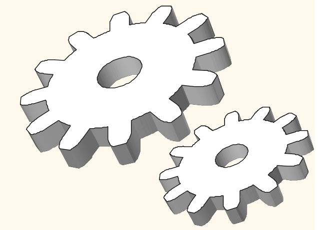
Nested Loops

Sort-Merge

Nested Loops: Flowchart



- From http://www.dbsophic.com/physical-join-operators-in-sql-server-nested-loops/.



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: Pages_in_r * (1 + tup_per_page* 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 on S: 1 I/O (typical) for each R tuple, unclustered: up to 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 for finding matches.
- 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 R/ 40,000 S). Cost of retrieving them is 1 or 2.5 I/Os depending on whether the index is clustered.

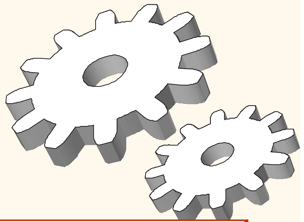
Exercise 14.4.1

- Consider the join R.A with S.b given the following information. The cost measure is the number of page I/Os, ignoring the cost of writing out the result.
  - Relation R contains 10,000 tuples and has 10 tuples per page.
  - Relation S contains 2000 tuples, also 10 tuples per page.
  - Attribute b is the primary key for S.
  - Both relations are stored as heap files. No indexes are available.
- What is the cost of joining R and S using nested loop join? R is the outer relation.
- How many tuples does the join of R and S produce, at most, and how many pages are required to store the result of the join back on disk?

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.

Example of Sort-Merge Join



sid	sname	rating	age
22	dustin	7	45.0
28	yuppy	9	35.0
31	lubber	8	55.5
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58	rusty	10	35.0

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- Cost: sort + scan =
- (M log M + N log N) + (M+N) [sid is key]
  - The cost of scanning, M+N, could be M*N (very unlikely!)
- With enough buffer pages, both Reserves and Sailors can be sorted in 2 passes; total join cost: 7500.

Exercise 14.4.3

- Consider the join R.A with S.b given the following information. The cost measure is the number of page i/Os, ignoring the cost of writing out the result.
  - Relation R contains 10,000 tuples and has 10 tuples per page.
  - Relation S contains 2000 tuples, also 10 tuples per page.
  - Attribute b is the primary key for S.
  - Both relations are stored as heap files. No indexes are available.
- What is the cost of joining R and S using a sort-merge join? Assume that the number of I/Os for sorting a table T is 4 *pages_in_T .

Query Planning

Highlights of System R Optimizer

- Impact:
  - Most widely used currently; works well for < 10 joins.
- Cost estimation: NP-hard, 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. (see text)
  - Cartesian products avoided.

Cost Estimation

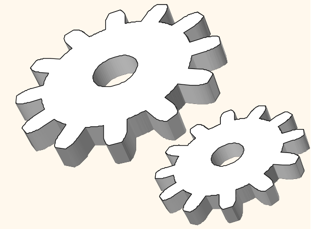
- For each plan considered, must estimate cost:
  - Must estimate *cost* of each operation in plan tree.
    - Depends on input cardinalities.
    - We've already discussed how to estimate the cost of operations (sequential scan, index scan, joins, etc.)
  - Must also estimate *size of result* for each operation in tree!
    - Use information about the input relations.
    - For selections and joins, assume independence of predicates.

Size Estimation and Reduction Factors

- Consider a query block:

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

- 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

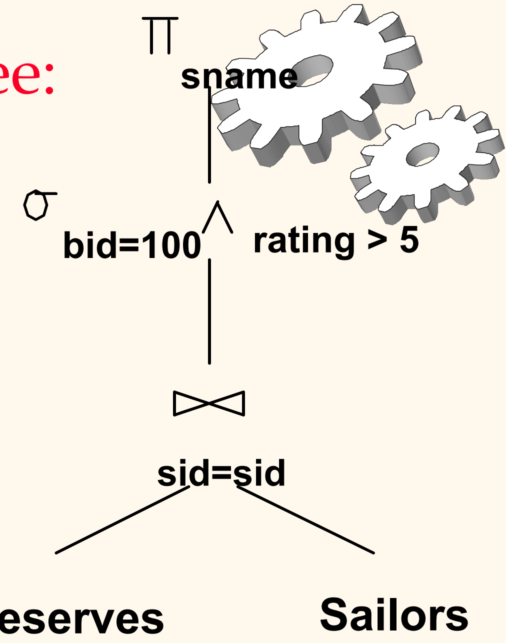
Sailors (*sid*: integer, *sname*: string, *rating*: integer, *age*: real)
Reserves (*sid*: integer, *bid*: integer, *day*: dates, *rname*: string)

- 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

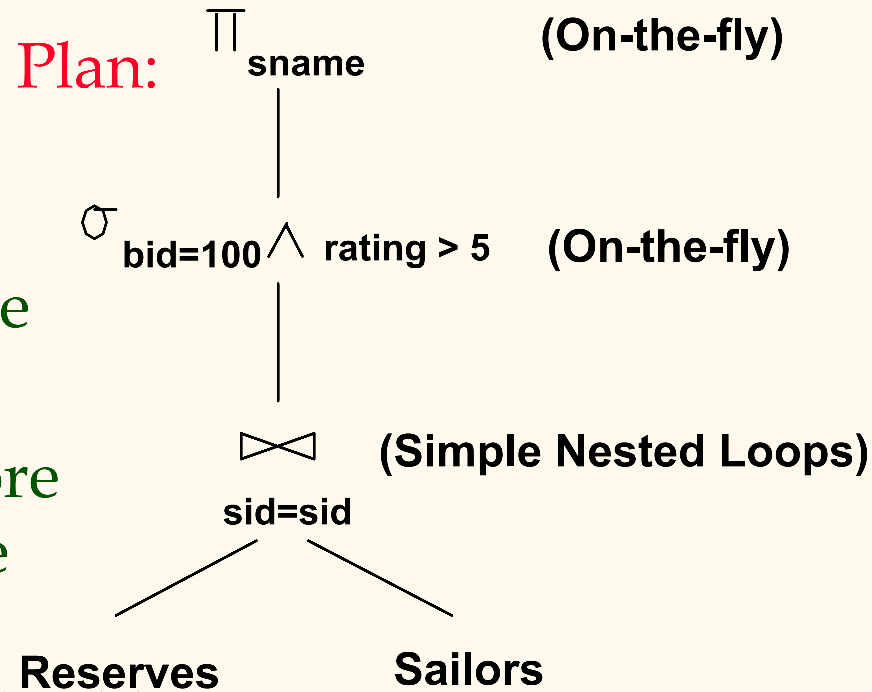
```
SELECT  S.sname
FROM  Reserves R, Sailors S
WHERE  R.sid=S.sid AND
   R.bid=100 AND S.rating>5
```

RA Tree:

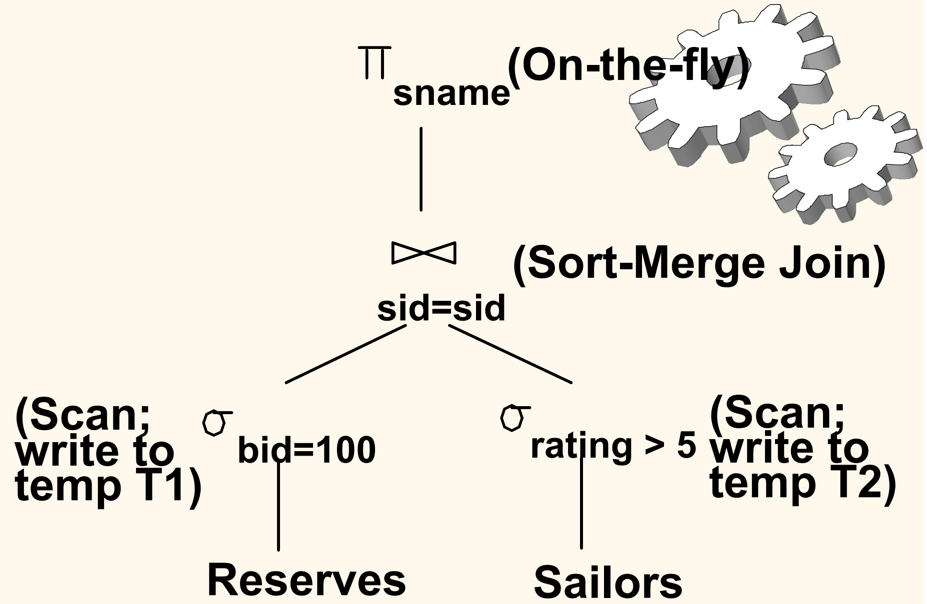


- Cost: 1000+1000*500 I/Os
- By no means the worst plan!
- Misses several opportunities: selections could have been \`pushed' earlier, no use is made of any available indexes, etc.
- *Goal of optimization:* To find more efficient plans that compute the same answer.

Plan:

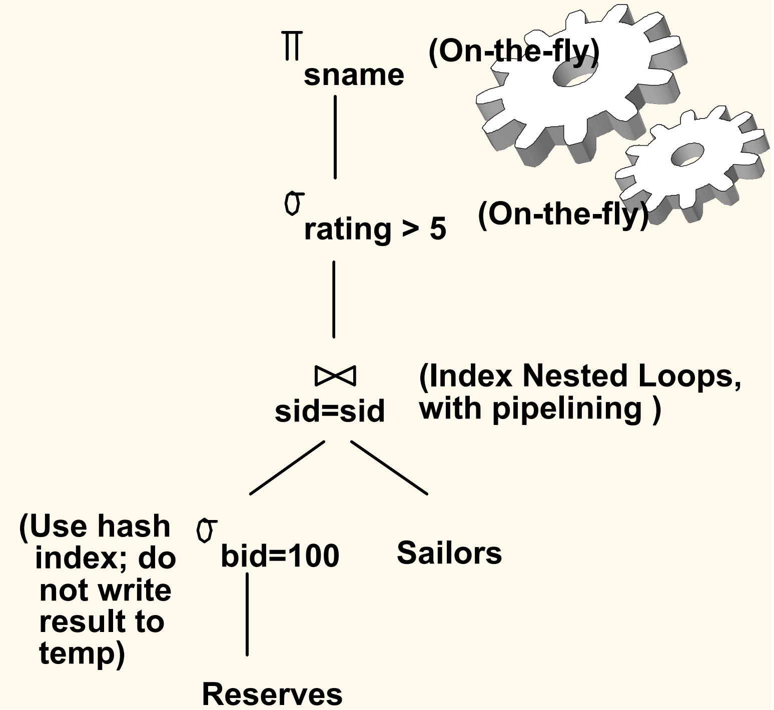


Alternative Plans 1 (No Indexes)



- ***Main difference:*** *push selects.*
- 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.

Alternative Plan 2 With Indexes



- With clustered index on *bid* of Reserves, we get 100,000/100 = 1000 tuples on 1000/100 = 10 pages for selection.
- INL with ***pipelining*** (outer is not materialized).
  - ⇒ Projecting out unnecessary fields 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:
  - there is an index on sid of Sailors, don't want to compute selection
- Cost: Selection of Reserves tuples (10 I/Os).
  - For each, must get matching Sailors tuple (1000*(1.2+1)).
  - Total 2210 page I/Os.

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.