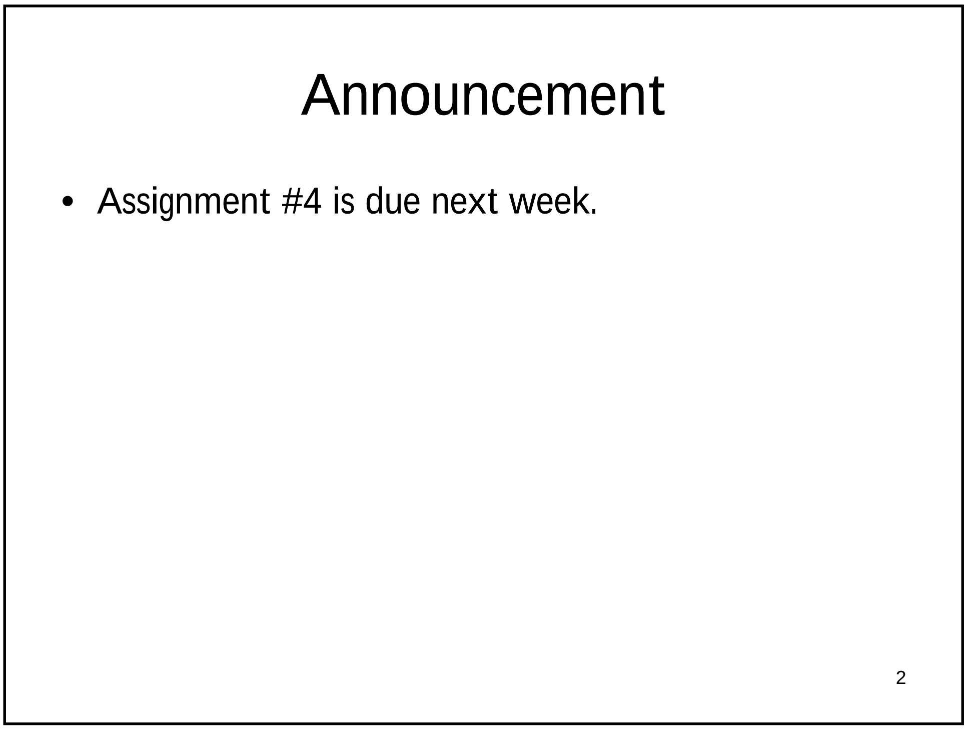
Database Systems (資料庫系統)

December 13/14, 2006

Lecture #10



Announcement

- Assignment #4 is due next week.

Overview of Query Evaluation

Chapter 12

3

Outline

- Query evaluation (Overview)
- Relational Operator Evaluation Algorithms (Overview)
- Statistics and Catalogs
- Query Optimization (Overview)
- Example

4

Tables

Sailors(sid, sname, rating, age)

Reserves(sid, bid, day, rname)

Overview of Query Evaluation (1)

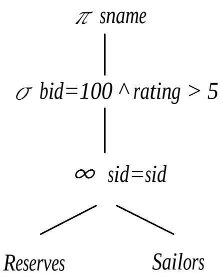
- What is Query Evaluation?
- What is a good Query Evaluation?
  - Find an efficient plan (minimal disk I/Os)
- How do you find a good plan?

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

Overview of Query Evaluation (II)

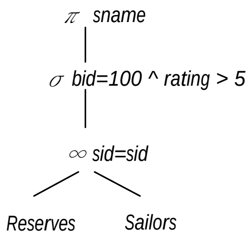
- Step 1: a query is translated into a relational algebra tree
  - σ (selection), π (projection), and ∞ (join)

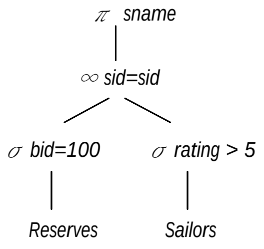
```
SELECT  S.sname
FROM  Reserves R, Sailors S
WHERE  R.sid=S.sid ^ R.bid=100 ^ S.rating>5
```



Overview of Query Evaluation (III)

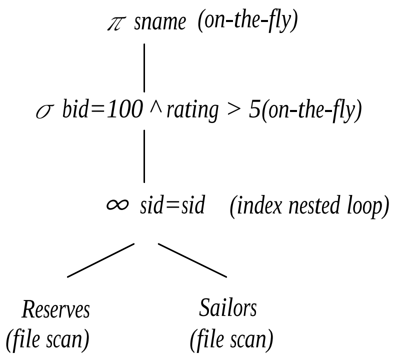
- Step 2: Find a good evaluation plan (Query Optimization)
  - Estimate costs for several alternative equivalent evaluation plans.
  - How to estimate disk I/O cost?
    - access method & evaluation algorithm
    - statistics on table sizes, etc.
  - Different order of evaluations gives different cost.
  - How does it affect cost?
    - Push selection (bid=100) before join)





Overview of Query Evaluation (IV)

- (continue step 2)
  - An evaluation plan is consisted of choosing access method & evaluation algorithm.
  - Selecting an access method to retrieve records for each table on the tree (e.g., file scan, index search, etc.)
  - Selecting an evaluation algorithm for each relational operator on the tree (e.g., index nested loop join, sort-merge join, etc.)



π sname (on-the-fly)

σ bid=100 ^ rating > 5(on-the-fly)

∞ sid=sid (index nested loop)

Reserves (file scan)

Sailors (file scan)

Overview of Query Evaluation (V)

- Two main issues in query optimization:
  - For a given query, what plans are considered?
    - Consider a few plans (considering all is too many & expensive), and find the one with the cheapest (estimated) cost.
  - How is the cost of a plan estimated?
    - Examine **catalog table** that has data schemas and statistics.
    - There are system-wide factors that can also affect cost, such as size of buffer pool, buffer replacement algorithm.

Statistics and Catalogs

- Need information about the relations and indexes involved. Catalogs typically contain at least:
  - # tuples (NTuples) and # pages (NPages) for each table.
  - # distinct key values (NKeys) and NPages for each index.
  - Index height, low/high key values (Low/High) for each tree index.
- How are they used to estimate the cost?
- Consider:
  - Reserves $\bowtie_{\text{reserves.sid = sailors.sid}}$ Sailors (assume simple nested loop join)

```
Foreach tuple r in reserves
    Foreach tuple s in sailors
        If (r.sid = s.sid) then add <r,s> to the results
```

  - Sailors $\bowtie$ ($\sigma_{\text{bid} = 10}$ Reserves)
  - Sailors $\bowtie$ ($\sigma_{\text{bid} > 5}$ Reserves)

Statistics and Catalogs

- Catalogs are updated periodically.
  - Updating whenever lots of data changes; lots of approximation anyway, so slight inconsistency is ok.
- More detailed information (e.g., histograms of the values in some fields) are sometimes stored.
  - They can be used to estimate # tuples matching certain conditions (bid > 5)

Relational Operator Evaluation

- There are several alternative algorithms for implementing each relational operator (selection, projection, join, etc.).
- No algorithm is always better (disk I/O costs) than the others. It depends on the following factors:
  - Sizes of tables involved
  - Existing indexes and sort orders
  - Size of buffer pool (Buffer replacement policy)
- Describe (1) common techniques for relational operator algorithms, (2) access path, and (3) details of these algorithms.

Some Common Techniques

- Algorithms for evaluating relational operators use some simple ideas repeatedly:
  - Indexing: If a selection or join condition is specified (e.g., $\sigma_{bid = 10}$ Reserves), use an index (<bid>) to retrieve the tuples that satisfy the condition.
  - Iteration: Sometimes, faster to scan all tuples even if there is an index ($\sigma_{bid \neq 10}$ Reserves, bid = 1 .. 1000). Sometimes, scan the data entries in an index instead of the table itself. (π_{bid} Reserves).
  - Partitioning: By using sorting or hashing, partition the input tuples and replace an expensive operation by similar operations on smaller inputs (e.g., $\pi_{sid, rname}$ Reserves)

Access Paths

- An access path is a method of retrieving tuples.
  - Note that every relational operator takes one or two tables as its input.
  - There are two possible methods: (1) file scan, or (2) index that matches a selection condition.
- Can we use an index for a selection condition? How does an index match a selection condition?
  - Selection condition can be rewritten into Conjunctive Normal Form (CNF), or a set of terms (conjuncts) connected by ^ (and).
    - Example: (rname='Joe') ^ (bid = 5) ^ (sid = 3)
  - Intuitively, an index matching conjuncts means that it can be used to retrieve (just) tuples that satisfy the conjunct.

Access Paths for Tree Index

- A tree index matches conjuncts that involve only attributes in a prefix of its index search key.
  - E.g., Tree index on <a, b, c> matches the selection condition (a=5 ^ b=3), (a=5 ^ b>6), but not (b=0).
    - Tree index on <a, b, c>: <a0, b0, c0>, <a0, b0, c1>, <a0, b0, c2>, …, <a0, b1, c0>, <a0, b1, c1>, …<a1, b0, c0>, …
  - Can match range condition (a=5 ^ b>3).
- How about (a=5 ^ b=3 ^ c=2 ^ d=1)?
  - (a=5 ^ b=3 ^ c=2) is called primary conjuncts. Use index to get tuples satisfying primary conjuncts, then check the remaining condition (d=1) for each retrieved tuple.
- How about two indexes <a,b> & <c,d>?
  - Many access paths: (1) use <a,b> index, (2) use <c,d> index, …
  - Pick the access path with the best selectivity (fewest page I/Os)

Access Paths for Hash Index

- A hash index matches a conjunct 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 ^ b=3 ^ c=5), but it does not match (b=3), (a=5 ^ b=3), or (a>5 ^ b=3 ^ c=5).
- Compare to Tree Index:
  - Cannot match range condition.
  - Partial matching on primary conjuncts is ok.

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.

Selectivity of Access Paths

- Selectivity of an access path is the number of page I/Os needed to retrieve the tuples satisfying the desired condition.
- Why do we want to use the most selective access path (with the fewest page I/Os)?
- What are the possible access paths for selections?
  - Use an index that matches the selection condition.
  - Scan the file records.
  - Scan the index (e.g., π_{bid} Reserves, index on bid)
- Access path using index may not be the most selective!
  - Why not?
  - Example: ($\sigma_{bid \neq 10}$ Reserves, unclustered index on bid).

Selection

SELECT (*)
FROM Reserves R
WHERE day<8/9/94 ^ bid=5 ^ sid=3

1.
2.
3.

- Consider $\sigma_{day<8/9/94 \wedge bid=5 \wedge sid=3}$.
  - A B+ tree index on day can be used; then, (bid=5 ^ sid=3) must be checked for each retrieved tuple.
  - A hash index on <bid, sid> could be used; day<8/9/94 must then be checked.

Example

- Use the following example to estimate page I/O cost of different algorithms.
- Sailors(sid:integer, sname:string, rating:integer, age:real)
  - Each Sailor tuple is 50 bytes long
  - A page is 4KB. It can hold 80 sailor tuples.
  - We have 500 pages of Sailors (total 40,000 sailor tuples).
- Reserves(sid:integer, bid:integer, day:dates, rname:string)
  - Each reserve tuple is 40B long
  - A page is 4KB. It can hold 100 reserve tuples.
  - We have 1000 pages of Reserves (total 100,000 reserve tuples).

Reduction Factor & Catalog Stats

- Reduction factor is the fraction of tuples in the table that satisfy a given conjunct.
- Example #1:
  - Index H on Sailors with search key <bid>
  - Selection condition (bid=5)
  - Stats from Catalog: NKeys(H) = # of distinct key values = 10
  - Reduction factor =
- Examples #2:
  - Index on Reserves <bid, sid> (not a key, no stats on them)
  - Selection condition (bid=5 ^ sid=3)
  - Typically, can use default fraction of 1/10 for each conjunct.
  - Reduction factor =

More on Reduction Factor

- Examples 3:
  - Range condition as (day > 9/1/2002)
  - Index Key T on day
  - Stats from Catalog: High(T) = highest day value, Low(T) = lowest day value.
  - Reduction factor =
  - Say: High(T) = 12/31/2002, Low(T) =1/1/2002
  - Reduction factor = 1/3

Using an Index for Selections

- Cost depends on #matched tuples and clustering.
  - Cost of finding qualifying data entries (typically small) plus cost of retrieving records (could be large w/o clustering)
    - Why large? Each matched entry could be on a different page.
  - Assume uniform distribution, 10% of tuples matched (100 pages, 10,000 tuples).
    - With a clustered index on <rid>, cost is little more than 100 I/Os;
    - If unclustered, worse case is 10,000 I/Os.
    - Faster to do file scan => 1,000 I/Os

```
SELECT  *
FROM    Reserves R
WHERE   R.rid mod 10 = 1
```

Projection

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

- Projection drops columns not in the select attribute list.
- The expensive part is removing duplicates.
- If no duplicate removal,
  -
  - Given index <sid, bid>, scan the index entries.
- If duplicate removal

More on Projection

- Hash-based projection:
  - Hash on <sid, bid> (#buckets = #buffer pages).
  - Load buckets into memory one at a time and eliminate duplicates.

Join: Index Nested Loops

Reserves (R) ⋈ Sailors (S)

```
foreach tuple r in R do
    foreach tuple s in S where $r_{.sid} = s_{.sid}$ do
        add <r, s> to result
```

- There exists an index <sid> for Sailors.
- Index Nested Loops: Scan R, for each tuple in R, then use index to find matching tuple in S.
- Say we have unclustered static hash index <sid> in Sailors. What is the cost of join operation?
  - Scan R = 1000 I/Os
  - R has 100,000 tuples. For each R tuple, retrieve index page (1.2 I/Os on average for hashing) and data page (1 I/O).
  - Total cost = 1,000 + 100,000 *(1.2 + 1) = 221,000 I/Os.

Join: Sort-Merge

- It does not use any index.
- Sort R and S on the join column
- Scan sorted lists to find matches, like a merge on join column
- Output resulting tuples.
- More details about Sort-Merge in Chapter 14.

Example of Sort-Merge Join

sid	*sname*	*rating*	*age*
22	*dustin*	*7*	*45.0*
28	*yuppy*	*9*	*35.0*
28	*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*

- The cost of a merge sort is 2*M $\log_{(B-1)}$ M, whereas M = #pages, B = size of buffer.
  - B-1 is quite large, so $\log_{(B-1)}$ M is generally just 2.
- Total cost = cost of sorting R & S + Cost of merging = 2*2*(1000+500) + (1000+500) = 7500 I/Os. (a lot less than index nested loops join!)

Index Nested Loop Join vs. Sort-Merge Join

Reserves (R) ⋈ Sailors (S)

- Sort-merge join does not require a pre-existing index, and …
  - Performs better than index-nested loop join.
  - Resulting tuples sorted on sid.
- Index-nested loop join has a nice property: incremental.
  - The cost proportional to the number of Reserves tuples.
    - Cost = #tuples(R) * Cost(accessing index+record)
  - Say we have very selective condition on Reserves tuples.
    - Additional selection: R.bid=101
    - Cost small for index nested loop, but large for sort-merge join (sort Sailors & merging)
  - Example of considering the cost of a query (including the selection) as a whole, rather than just the join operation → query optimization.

Other Relational Operators

- Discussed simple evaluation algorithms for
  - Projection, Selection, and Join
- How about other relational operators?
  - Set-union, set-intersection, set-difference, etc.
  - The expensive part is duplicate elimination (same as in projection).
  - How to do R1 U R2 ?
- SQL aggregation (group-by, max, min, etc.)
  - Group-by is typically implemented through sorting (without search index on group-by attribute).
  - Aggregation operators are implemented using counters as tuples are retrieved.

Query Optimization

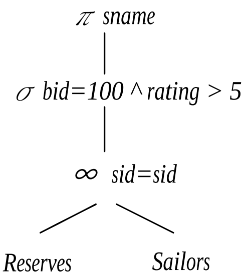
- Find a good plan for an entire query consisting of many relational operators.
  - So far, we have seen evaluation algorithms for each relational operator.
- Query optimization has two basic steps:
  - Enumerate alternative plans for evaluating the query
  - Estimating the cost of each enumerated plan & choose the one with lowest estimated cost.
    - Consult the catalog for estimation.
    - Estimate size of result for each operation in tree (reduction factor).
- More details on query optimization in Chapter 15.

Motivating Example

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

- Cost: 1000+1000*500 I/Os
- 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.

RA Tree:



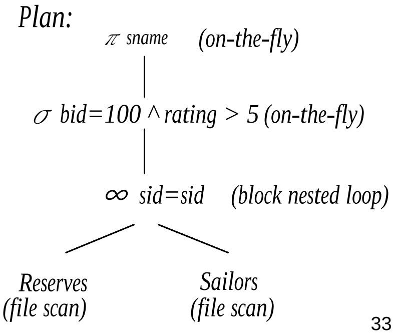
π sname

σ bid=100 ^ rating > 5

∞ sid=sid

Reserves *Sailors*

Plan:



π sname (on-the-fly)

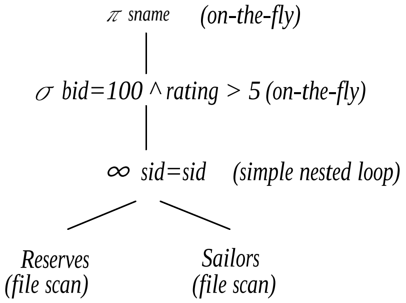
σ bid=100 ^ rating > 5 (on-the-fly)

∞ sid=sid (block nested loop)

Reserves (file scan) *Sailors (file scan)*

Pipeline Evaluation

- How to avoid the cost of physically writing out intermediate results between operators?
  - Example: between join and selection
  - Use pipelining, each join tuple (produced by join) is (1) checked with selection condition, and (2) projected out on the fly, before being physically written out (materialized).



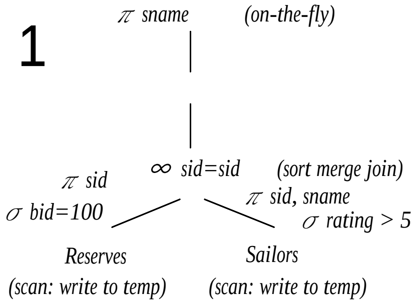
π sname (on-the-fly)

σ bid=100 ^ rating > 5 (on-the-fly)

∞ sid=sid (simple nested loop)

Reserves (file scan) *Sailors (file scan)*

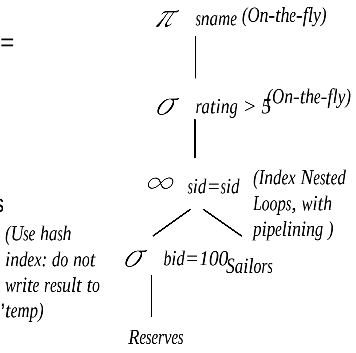
Alternative Plan 1 (No Indexes)

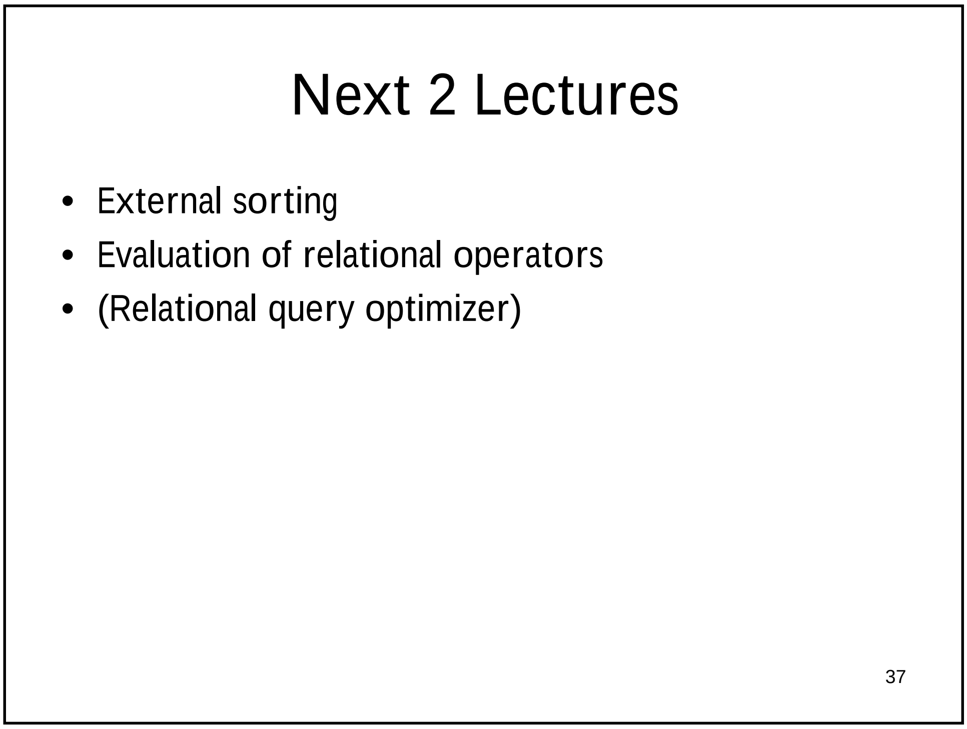


- Main difference: push selects.
- With 5 buffers, cost of plan:
  - Scan Reserves (1000 pages) for selection + write temp T1 (10 pages, if we have 100 boats, uniform distribution).
  - Scan Sailors (500 pages) for selection + write temp T2 (250 pages, if we have 10 ratings, uniform distribution).
  - Sort T1 (2*2*10), sort T2 (2*4*250), merge (10+250)
  - Total: (1000 + 500 + 10 + 250) + (40 + 2000 + 260) = 4060 page I/Os.
- If we used BNL join, join cost = 10+4*250, total cost = 2770.
- If we `push' projection, 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 Plan 2 With Indexes

- With clustered index on bid of Reserves, we get 100,000/100 = 1000 tuples on 1000/100 = 10 pages.
- Use pipelining (the join tuples are not materialized).
- Join column *sid* is a key for Sailors.
- Projecting out unnecessary fields from Sailors may not help.
  - Why not? Need Sailors.sid for join.
- Not to push *rating>5* before the join because,
  - Want to use *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.


π sname (On-the-fly)
σ rating > 5 (On-the-fly)
∞ sid=sid (Index Nested Loops, with pipelining)
(Use hash index: do not write result to temp)
σ bid=100
Sailors
Reserves



Next 2 Lectures

- External sorting
- Evaluation of relational operators
- (Relational query optimizer)