

Database Systems

Algorithms for Relational Algebra Operators and Query Evaluation

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Relational Query Evaluation

- Relational Algebra Operators
 - Select, Project, Join
 - Union, Intersect, Difference
- Grouping and aggregation
 - Sorting
- How to implement these?
- How do indexes help?
- Any other information is helpful?

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Selection With Equality Conditions

- Single selection condition $X = c_i$
 - Index on X ? Yes: use the index; No: file scan
- Several conjunctive conditions
 - $X_1 = c_1$ and $X_2 = c_2$ and ... and $X_k = c_k$
 - Index on any X_i ?
 - Yes: Get the records and check other conditions
 - No: File scan
- Several disjunctive conditions
 - Index on any *single* X_i - not helpful
 - Difficult compared to conjunctive case

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Predicate Selectivity

- Selectivity s of a condition C -- $0 \leq s \leq 1$
 - (No. of records satisfying C) / (Total no. of records)
 - C_1 : student.dept = "CSE" -- $450 / 8000 = 0.056$
 - C_2 : student.sex = "female" -- $1200 / 8000 = 0.15$
 - C_3 : student.rollNo = "CS10B032" -- $1/8000 = 0.000125$
 - highly selective predicate - very *low* selectivity value
- Conjunction of conditions
 - Choose the one that is *most* selective
 - Get the records and check other conditions
 - Selectivity values (estimates): collect offline

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Selectivity Estimation

- Maintained in the DB *catalog*
 - Used by the query optimizer
- Equality conditions involving a key attribute
 - Selectivity = $1 / (\text{Total no. of records})$
- Equality conditions involving a non-key attribute
 - Selectivity = $1 / (\text{Distinct values of the attribute})$
- Sometimes histograms are also maintained
 - Distinct value or value range -- # of records

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Project Operation

- For every record in the operand
 - Access it, take the required attributes values
 - Construct the result record
- Duplicate Elimination
 - Costly
 - Sort or hash based methods are used
- File scan becomes essential
- Apply project after selection, if possible
 - To reduce the input to project

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External Sorting

- Sorting a file
 - An often required operation
 - Duplicate elimination, Grouping of records, Join etc
- Merge-sort Principle is used
 - $O(n \log n)$ worst-case complexity for n items
 - Two phases
 - **Sort phase** – repeat: read part of data, sort and write
 - Create many sorted files – called *runs*
 - **Merge phase** – repeat: merge *some* sorted files and write
 - Till only one sorted file is left

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Algorithm – Sort Phase

- File: n blocks and Buffer memory: m blocks
- Sort Phase
 - Repeat the following $\lceil n/m \rceil$ times
 - {read the next m blocks; sort in-memory;
write to disk as a single file, called a *run*}
- Number of *runs* $r = \lceil n/m \rceil$
- Complexity: n block reads and n block writes
 - $2n$ block accesses

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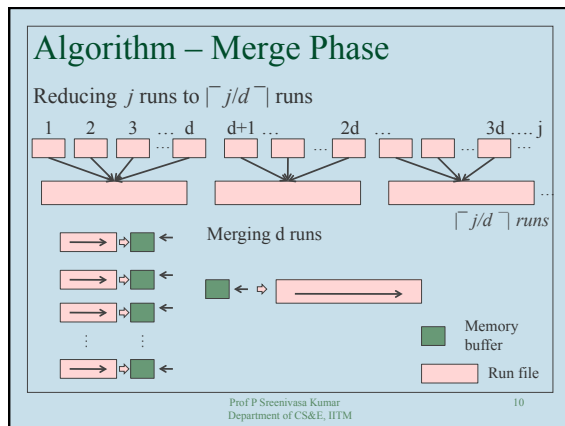
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Algorithm – Merge Phase

- File: n blocks, Memory Buffers: m (≥ 3) blocks, Runs: r
 - Degree of merging d : $2 \leq d \leq (m-1)$
- Merge Phase: repeat the following $\lceil \log_d r \rceil$ times
 - Reduce j runs to $\lceil j/d \rceil$ runs (Initially, $j = r$)
 - By repeatedly merging d runs at a time to get *one* run
 - Use d buffers, one for each of the next d runs; use one for the result
 - Get one block at a time from each run
 - Merge and write the result to disk – one block at a time
- Complexity: $2n \lceil \log_d r \rceil$
 - Each sub-phase : Entire file gets read and written
- Overall: $(2n + 2n \lceil \log_d r \rceil)$ block accesses

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Join Processing

- Join – A very important operation
- 2-way join
 - Two files of records, join condition – given
- Multi-way join
- Choice of algorithm depends on ...
 - Sizes of files
 - Primary organization of the files
 - Availability of indices
 - Selectivity of the join condition etc

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Nested Loop Join (or block nested loop join)

- Brute force join
- Two data files

for each record x in R do
 for each record y in S do
 check if x, y join ...
- Buffer Usage: One block for the result of join
 - One for inner file (say, S); $(m - 2)$ for outer file (R)
- For each set of $(m - 2)$ blocks of R read-in, do
 - For each block of S do
 - Read it in, compute join, write to result block
 - Write the result block to disk whenever it fills up

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Nested Loop Join - Performance

- Two data files
 - $R : b_1$ blocks, $S : b_2$ blocks, Buffer : m blocks
- Outer file : b_1 blocks accesses
- # times inner file blocks accessed: $\lceil b_1/(m-2) \rceil$
- Overall: $b_1 + \lceil b_1/(m-2) \rceil b_2$
- Or, symmetrically: $b_2 + \lceil b_2/(m-2) \rceil b_1$
 - when we have S in the outer loop and R inside
- Which file in the outer loop?

Time for writing the result needs to be added

 - The one with fewer blocks!

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Nested Loop Join - Example

- Two data files
 - $R : b_1 = 5600$ blocks, $S : b_2 = 120$ blocks, Buffer : 52 blocks
- If R is used in the outer loop
 - $b_1 + \lceil b_1/(m-2) \rceil b_2$
 - $5600 + \lceil 5600 / 50 \rceil * 120 = 19040$ disk ops
- If S is used in the outer loop
 - $120 + \lceil 120 / 50 \rceil * 5600 = 16920$ disk ops
- Assuming 10 msec per disk op

Time for writing the result needs to be added

 - It is 190 secs versus 169 secs

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Single Loop Join (or index loop join)

- Two data files

Time for writing the result needs to be added

 - $R : b_1$ blocks, $S : b_2$ blocks
 - Need to compute **equi-join** with $R.A = S.B$
 - We have index on one of them, say S on B
- For each record x of R read in, do
 - Use the index on B for S
 - Get all the matching records (having $B = x.A$)
- Time taken: $b_1 + |\text{distinct}(R.A)| * h_B(S)$
 - $h_B(S)$ – # of block accesses of the index on B for S

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Join Selection Factor

- Fraction of records in a file that join with records of the other for the given condition
- Consider: professor $\bowtie_{\text{empId} = \text{hod}}$ department
 - Only 5% of professor rows join with department rows
 - 100% of department rows join with professor rows
- Impacts performance of single loop join
 - If indexes are available on both files
 - Loop over records of the file with high join selection factor

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Join Selection Factor - Example

- Impacts single loop join performance
 - If indexes are available on both files
- Consider: professor $\bowtie_{\text{empId} = \text{hod}}$ department
 - Loop over *professor* records and probe *department* using index on *hod* (option 1) OR
 - Loop over *department* records and probe *professor* using index on *empId* (option 2)
 - Option 1: 95% probes don't give a match
 - Option 2: All probes give a match
- Option 2 is the right choice

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Hash Join

- Consider a 2-way equi-join $R \bowtie_{R.A=S.B} S$
 - Assume that *S fits into memory*
- Use a hash function *h*
 - Hash the records of *S* into *M* buckets using *B*-values
 - Called the **partitioning** of *S*
- To compute join result
 - Hash records of *R*, one by one, using *A* values
 - Use the *same* *M* buckets and the *same* hash function *h*
 - Matching pair of records will hash to same bucket

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Partition Hash Join

- Consider a 2-way equi-join $R \bowtie_{R.A=S.B} S$
 - **Neither R nor S fits into the memory**
- Partition Phase: use a hash function h
 - Hash the records of R into m buckets using A-values
 - We get R_1, R_2, \dots, R_m - write them to files
 - Hash the records of S into m buckets using B-values
 - We get S_1, S_2, \dots, S_m - write them to files
 - Goals: ensure that distribution is uniform and
 - At least one of R_i or S_i fit into the memory
- To compute join result: join R_i with S_i only!

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Partition Hash Join – Probe Phase

- Probe Phase: Join R_i with S_i for all i
- If one of R_i or S_i fit into the memory
 - Use the idea of hash join again!
 - Hash the smaller of the two into main memory using a *different* hash function, say h_2
 - Read the other file, probe and produce result records
 - Overall cost: $(3(|R|+|S|) + |\text{result}|)$ block accesses
- Else use nested loops join
 - Overall cost: $2(|R|+|S|) + \text{cost of nested loop joins}$

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Sort-merge join

- Consider a 2-way equi-join $R \bowtie_{R.A=S.B} S$
- If R is sorted on A, S is sorted on B
 - Merge R and S to get join results
 - Called merge join - - very efficient - - linear
- If one of them is sorted on join attribute
 - Sorting the other and merging may be cost-effective
- Of course, we can
 - Sort R on A, sort S on B and use merge
 - Cost might be high

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Set Operations

- Hash based join method
 - Can be adapted to compute Union, Intersect and Difference
- Sort-Merge method
 - Can be adapted to compute Union, Intersect and Difference
- Please study the details!

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Query Optimization

- An SQL query - converted to a RA expression tree
- Initial RA expression is re-written
 - Using heuristic and algebraic transformation rules that preserve the meaning of the expression
 - Called algebraic optimization
 - Final RA expression tree is generated
- Cost-based query optimization
 - Cost estimates of *methods* for RA ops are computed
 - Execution plan with least estimated cost is chosen

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Heuristic Optimization

- An SQL query - converted to a RA expression tree
- This RA expression tree is to be re-written
- Main heuristic rule
 - Apply *select* and *project* before other operations
 - Reduces the size of intermediate results
 - Reduces the number of fields in the intermediate results
- Make use of relational algebraic laws
 - *Select, project, join, union, intersect* - commutative
 - *Join, union, intersect* - associative
 - There are many more....(Read about them)

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Cost-based Optimization

- After initial RA expression tree is re-written using heuristics and algebraic laws....
- Each RA operator
 - Can be evaluated using *many* methods
 - For a method, its *cost function* gives *estimated cost*
 - By taking file sizes, access path costs etc into account
 - Choice made at a node may effect choices at others
- Evaluate different plans based on estimated costs
 - Choose the plan with least estimated cost

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Query Optimization – Example

- Obtain the name and phone details of professors who taught the courses taken by student with roll number “CS08B027” in the even semester of 2010
- *select* p.empId, p.name, p.phone
from professor p, teaching t, enrollment e
where e.rollNo = “CS08B027”
and e.courseId = t.courseId
and e.sem = “even” and e.year = 2010
and t.sem = “even” and t.year = 2010
and p.empId = t.empId

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Query Optimization – Example

- Obtain the name and phone details of professors who taught the courses taken by student with roll number “CS08B027” in the even semester of 2010
- Initial RA Expr: $\Pi_{p.empId, p.name, p.phone} (\sigma_{\theta} (p \times t \times e))$
where
p: professor, t: teaching, e: enrollment
 $\theta = (e.rollNo = \text{“CS08B027” and } e.courseId = t.courseId$
and e.sem = “even” and e.year = 2010
and t.sem = “even” and t.year = 2010
and p.empId = t.empId)

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Query Optimization – Example

$$\begin{aligned} & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_0 (p \times t \times e)) \\ \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_2} (t) \times \sigma_{\theta_1}(e))) \end{aligned}$$

p: professor, t: teaching, e: enrollment

$\theta_1 = (e.\text{rollNo} = \text{"CS08B027"} \text{ and } e.\text{sem} = \text{"even"} \text{ and } e.\text{year} = 2010)$

$\theta_2 = (t.\text{sem} = \text{"even"} \text{ and } t.\text{year} = 2010)$

$\theta_3 = (p.\text{empId} = t.\text{empId} \text{ and } e.\text{courseId} = t.\text{courseId})$

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Query Optimization – Example

$$\begin{aligned} & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_0 (p \times t \times e)) \\ \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_2} (t) \times \sigma_{\theta_1}(e))) \\ \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_4} (\sigma_{\theta_2} (t) \times \sigma_{\theta_1}(e)))) \end{aligned}$$

p: professor, t: teaching, e: enrollment

$\theta_1 = (e.\text{rollNo} = \text{"CS08B027"} \text{ and } e.\text{sem} = \text{"even"} \text{ and } e.\text{year} = 2010)$

$\theta_2 = (t.\text{sem} = \text{"even"} \text{ and } t.\text{year} = 2010)$

$\theta_3 = (p.\text{empId} = t.\text{empId})$

$\theta_4 = (e.\text{courseId} = t.\text{courseId})$

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Query Optimization – Example

$$\begin{aligned} & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_0 (p \times t \times e)) \\ \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_2} (t) \times \sigma_{\theta_1}(e))) \\ \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_4} (\sigma_{\theta_2} (t) \times \sigma_{\theta_1}(e)))) \\ \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (p \stackrel{\theta_3}{\bowtie} (\sigma_{\theta_2}(t) \stackrel{\theta_4}{\bowtie} \sigma_{\theta_1}(e))) \end{aligned}$$

$\theta_1 = (e.\text{rollNo} = \text{"CS08B027"} \text{ and } e.\text{sem} = \text{"even"} \text{ and } e.\text{year} = 2010)$

$\theta_2 = (t.\text{sem} = \text{"even"} \text{ and } t.\text{year} = 2010)$

$\theta_3 = (p.\text{empId} = t.\text{empId})$

$\theta_4 = (e.\text{courseId} = t.\text{courseId})$

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Query Optimization – Example

$$\begin{aligned}
 & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta} (p \times t \times e)) \\
 \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_2}(t) \times \sigma_{\theta_1}(e))) \\
 \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_4} (\sigma_{\theta_2}(t) \times \sigma_{\theta_1}(e)))) \\
 \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (p \bowtie_{\theta_3} (\sigma_{\theta_2}(t) \bowtie_{\theta_4} \sigma_{\theta_1}(e))) \\
 \equiv & (\Pi_{\text{empId}, \text{name}, \text{phone}}(p) \bowtie_{\theta_3} \Pi_{\text{empId}} (\Pi_{\text{courseId}, \text{empId}} \sigma_{\theta_2}(t) \bowtie_{\theta_4} \Pi_{\text{courseId}} \sigma_{\theta_1}(e)))
 \end{aligned}$$

$\theta_1 = (e.\text{rollNo} = \text{"CS08B027"} \text{ and } e.\text{sem} = \text{"even"} \text{ and } e.\text{year} = 2010)$

$\theta_2 = (t.\text{sem} = \text{"even"} \text{ and } t.\text{year} = 2010)$

$\theta_3 = (p.\text{empId} = \text{empId}) \quad \theta_4 = (t.\text{courseId} = e.\text{courseId})$

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Cost-based Optimization

$$\begin{aligned}
 & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta} (p \times t \times e)) \\
 \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_2}(t) \times \sigma_{\theta_1}(e))) \\
 \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (\sigma_{\theta_3} (p \times \sigma_{\theta_4} (\sigma_{\theta_2}(t) \times \sigma_{\theta_1}(e)))) \\
 \equiv & \Pi_{p.\text{empId}, p.\text{name}, p.\text{phone}} (p \bowtie_{\theta_3} (\sigma_{\theta_2}(t) \bowtie_{\theta_4} \sigma_{\theta_1}(e))) \\
 \equiv & (\Pi_{\text{empId}, \text{name}, \text{phone}}(p) \bowtie_{\theta_3} \Pi_{\text{empId}} (\Pi_{\text{courseId}, \text{empId}} \sigma_{\theta_2}(t) \bowtie_{\theta_4} \Pi_{\text{courseId}} \sigma_{\theta_1}(e)))
 \end{aligned}$$

Evaluate costs of using different methods for
the two selections, two joins
and choose the plan with least estimated cost

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Query Plan Execution

Intermediate Tables:

Store as files on disk (materialization), if necessary

Use pipelining, as much as possible

Query Types and Optimization

Compiled Queries

Optimization can be done offline

cost of optimization – does not matter

Ad-hoc Queries – Optimization should finish fast

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