Query Processing and Optimization

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Week - 3 ,Topic – 2, Lesson 5 and 6

Query Processing and Optimization

Outline

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- Query optimization techniques (rule-based + practical)
- Cost-based optimization and execution plans
- Use case with examples

Pipelining (Streaming)

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- **Iterator model**: each operator produces the next tuple on demand (next()).
- **Pipelining**: pass tuples directly from one operator to the next (no full intermediate table).
  - Pipelines can be executed in two ways: demand driven and producer driven
- **Materialization**: write intermediate results to disk/temp table (slower, but sometimes required).
- Pipeline breaks: sort, hash build phase, or blocking aggregates often need full input.

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Example pipeline:
Scan → Filter (σ) → Project (π) → Output
```

SELECT Name FROM Student WHERE Marks > 80;

Implementation of demand-driven pipelining

Each operation is implemented as an **iterator** implementing the following operations

- **open()**
  - file scan: initialize file scan
  - state: pointer to beginning of file
  - merge join: sort relations;
  - state: pointers to beginning of sorted relations
- **next()**
  - for file scan: Output next tuple, and advance and store file pointer
  - for merge join: continue with merge from earlier state till next output tuple is found. Save pointers as iterator state.
- **close()**

3: What is Query Optimization?

3. Query optimization techniques

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- Optimization chooses a good plan among many equivalent plans.
- Logical optimization: rewrite query without changing meaning (algebraic rules).
- Physical optimization: pick access paths + join algorithms + join order.
- Two styles: rule-based (heuristics) and cost-based (use a cost model).

Classic Heuristic Rules

Simple rules that often help

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- Push selections down: apply σ as early as possible (reduce rows early).
- Push projections down: keep only needed columns (reduce row width).
- Combine selections: $\sigma_{c1}(\sigma_{c2}(R)) \rightarrow \sigma_{c2 \wedge c2}(R)$
- Reorder joins (when safe): join smaller / filtered relations first.
- Replace Cartesian Products: Use joins with conditions instead of cross products.
- Query Tree: a graphical representation of the operators, relations, attributes and predicates and processing sequence during query processing. It is composed of three main parts:
  - The Leafs: the base relations used for processing the query/ extracting the required information.
  - The Root: the final result/relation as an output based on the operation on the relations used for query processing
  - Nodes: intermediate results or relations before reaching the final result.
  - Sequence of execution of operation in a query tree will start from the leaves and continues to the intermediate nodes and ends at the root.

Example Cont…

Example-

Before optimization

SELECT E.name FROM Employee E, Department D
WHERE E.dept_id = D.dept_id AND D.location = 'Binh Doung';

Problem

- Cartesian product produces huge intermediate results
- Selection is applied too late

π name
|
⋈ E.dept_id = D.dept_id
/ \
Employee σ location=' Binh Doung '
|
Department

After Optimization

SELECT E.name FROM Employee E JOIN Department D ON
E.dept_id = D.dept_id WHERE D.location = ' Binh Doung ';

Query tree –

π name
|
σ E.dept_id = D.dept_id AND D.location=' Binh Doung '
|
Employee × Department

Another Example (Push Selection)

Same result, usually faster

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Original (conceptual):
R ⋈ S  then  σ_{R.x > 10}

Rewrite:
(σ_{R.x > 10}(R)) ⋈ S
```

- Filtering R first shrinks the join input.
- Less data enters the join → fewer comparisons and less I/O.

Physical Aids (Indexes & Views)

Optimization uses what exists in storage

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- Indexes can turn scans into fast lookups (B+ tree, hash index).
- Clustered index: table stored in index order (good for ranges).
- Materialized view: precomputed result stored on disk.
- Partitioning: split table to scan only relevant parts.

Optimizer chooses plans based on available indexes/views + estimated benefit.

Statistics & Selectivity (Basics)

Estimates guide the optimizer

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- DBMS stores stats: #rows, #pages, distinct values, histograms.
- Selectivity estimates how many rows pass a predicate.
- Common assumptions: uniform distribution and independence (not always true).
- Better stats → better plan choices (especially for join order).

Example: if attribute A has V distinct values, sel(A = c) ≈ 1 / V (uniform).

4: Cost-Based Optimization (CBO)

4. Cost-based optimization and execution plans

- CBO picks the plan with the lowest estimated cost.
- Cost is usually dominated by disk I/O, then CPU, Network cost (in distributed databases), then memory.
- DBMS uses table/index statistics to estimate: cardinalities and costs.
- The chosen plan is an execution plan (physical operator tree).
- Highly efficient and Adapts to data size and distribution

Techniques Used

- Evaluates multiple query plans
- Uses statistics about tables and indexes

Chooses optimal:

- ❑ Join order
- ❑ Join method (Nested Loop, Hash Join, Merge Join)
- ❑ Access path (Index scan vs. Table scan)

A Simple Cost Model

Not exact—just useful for comparisons

- I/O Cost : Represents the cost of reading and writing data pages from disk. Since disk access is slow, I/O cost is usually the largest contributor to total cost.
  - ➢ I/O cost = Number of page reads / writes × Cost per I/O operation
- CPU Cost: Represents the processing cost of evaluating tuples (rows). Includes comparisons, joins, filtering, and aggregation.
  - ➢ CPU cost = Number of tuples processed × Cost per tuple operation
- Memory Cost (Impact): Memory is not always counted directly.

If sufficient memory is available:

- ✓ Operations like sorting and hashing stay in memory → **lower I/O cost**

If memory is insufficient:

- ✓ Intermediate results are written to disk → **higher I/O cost**

The total cost of an execution plan is often estimated using:

$$Cost(plan) = (N_{IO} \times t_{IO}) + (N_{CPU} \times t_{CPU})$$

Where

N_{IO} = Number of page I/O operations

t_{IO} = Time per I/O operation

N_{CPU} = Number of tuple (row) operations

t_{CPU} = Time per CPU operation

Cost Based Optimization Example

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Assume
Employee has 1,000 rows
Department has 10 rows
Index exists on Employee.dept_id

Query -
SELECT name, dept_name FROM Employee E, Department D WHERE E.dept_id = D.dept_id;

Possible Execution Plans
Plan 1: Nested Loop Join (Employee → Department)
- Outer table: Employee (1,000 rows)
- Inner table: Department (10 rows)
- Cost ≈ 1,000 × 10 = 10,000 comparisons

Plan 2: Index Join (Department → Employee)
- Outer table: Department (10 rows)
- Use index on Employee.dept_id
- Cost ≈ 10 index lookups = very low

Optimizer chooses Plan 2 because it has lower estimated cost based on:
- Table size
- Index availability
- Number of comparisons

⋈ (Index Join)
/ \
Department Employee (using index)

Name	Dept_name
Kim	IT
Nygen	IT
Tien	HR

More Example….

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Assume the database system uses the following costs:
Time per I/O operation
t_{IO} = 5 ms
Time per CPU operation
t_{CPU} = 0.01

Plan A: Full Table Scan
Number of page I/Os
N_{IO} =200
Number of tuple operations
N_{CPU} = 10000

Sol: Cost(A) = (200×5) + (10,000×0.01)
= 1,000 + 100
= 1,100 ms

Plan B: Index Scan
Number of page I/Os
N_{IO} = 50
Number of tuple operations
N_{CPU} = 2,000

Sol:
Cost(B) = (50×5) + (2,000×0.01)
= 250+20
=270 ms

emp_id	name
101	Kim
105	Nyugen

Searching Join Orders (Idea Only)

Enumerating plans without exploding

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- Join order matters a lot (A ⋈ B) ⋈ C may be much faster than A ⋈ (B ⋈ C).
- Optimizers often search “left-deep” trees (one join at a time).
- Dynamic programming idea: reuse best plan for each subset of tables.
- Heuristics/pruning stop the search from becoming too large.

Key point: the optimizer explores alternatives and keeps the cheapest (estimated) ones.

Reading an Execution Plan

What you see in EXPLAIN output

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- Operators: Seq Scan, Index Scan, Hash Join, Sort, Aggregate, etc.
- Estimated rows/cardinality at each node.
- Estimated cost (often “startup..total”).
- Actual runtime (if you run EXPLAIN ANALYZE) may differ from estimates.

```
Mini example (conceptual):
Hash Join
  -> Seq Scan on R
  -> Hash
       -> Index Scan on S
```

Employee Use Case Example -

CREATE TABLE Employee (emp_id INT, name VARCHAR(20), dept_id INT, salary INT);

CREATE TABLE Department (dept_id INT, dept_name VARCHAR(20), location VARCHAR(20));

INSERT INTO Employee VALUES (1, ‘Kim', 10, 60000), (2, ‘Nyugen', 20, 45000), (3, ‘Nahi', 10, 70000), (4, ‘Tien', 30, 40000);

INSERT INTO Department VALUES (10, 'IT', ‘Binh Dung’), (20, 'HR', ‘Ho Chi Minh City’), (30, 'Sales', ‘Hanoi');

Classical JOIN Query:
SELECT E.name, D.dept_name FROM Employee E, Department D WHERE E.dept_id = D.dept_id AND D.location = ' Binh Dung ‘ AND E.salary > 50000;

Heuristic (Rule-Based) Optimization - Optimized SQL (Logical)

Rule Applied - Combine selections, Push selection down, Replace Cartesian product with JOIN and Project required columns early

SELECT E.name, D.dept_name FROM Employee E JOIN Department D ON E.dept_id = D.dept_id WHERE D.location = ' Binh Dung ’ AND E.salary > 50000;

Employee Use Case Example -

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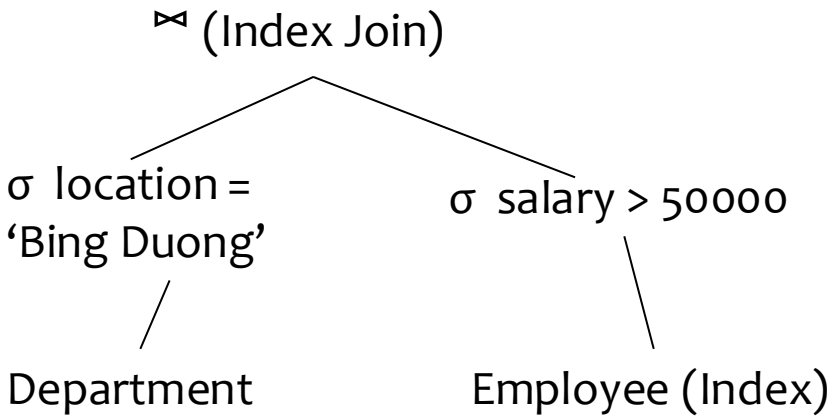
Cost-Based Optimization:
Assume information-

- Employee table = 1000 rows (200 pages)
- Department table = 50 rows (5 pages)
- Index on Employee.dept_id
- Disk I/O cost t_{IO} = 5 ms
- CPU cost t_{CPU} = 0.01 ms

Plan B: Index Join (Chosen Plan)
N_{IO} = 55 pages
N_{CPU} = 2,000 tuple operations
Cost(B) = (55×5)+(2,000×0.01)
=275+20
=295 ms
Cost-based optimizer selects Plan B

Final Query Execution plan



Plan A: Full Table Scan + Nested Loop Join
Solutions-
N_{IO} = 205 pages
N_{CPU} = 10,000 tuple operations

Cost(A) = (205×5) + (10,000×0.01)
= 1025+100
= 1125 ms

Revision

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- Query processing: parse → rewrite → optimize → execute.
- Joins have multiple algorithms; pick based on size, indexes, and predicates.
- Optimization uses rules + statistics to reduce work early.
- Cost-based optimizers compare many plans and choose the cheapest estimate.

Tip for practice: write a query, guess the plan, then check with EXPLAIN in a DBMS.

Further Reading and Practice

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* Silberschatz, A., Korth, H. F., & Sudarshan, S. (2020). Database System Concepts (7th ed.). McGraw-Hill. (Part six, Chapter 16. Query optimization page no-743 to 794)
* Rupley Jr, Michael L. "Introduction to query processing and optimization." Indiana University at South Bend (2008).

* Practice Relational database with SQL compiler Such as MySQL, PostgreSQL, SQL Workbench
  * Online compiler - https://sqlfiddle.com/

    https://sqlzoo.net/wiki/SQL_Tutorial