Query Planning and Optimization

Dr. Qichen Wang
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Self-introduction

- Dr. Qichen Wang
  - PhD from Hong Kong University of Science and Technology, 2022
  - Research Assistant Professor, Hong Kong Baptist University 2022-2024
  - Postdoc, EPFL, 2024-now

- Teaching experiences:
  - Lecturer: Cloud Computing, Hong Kong Baptist University
  - TA: Big Data Technology, Combinatorial Optimization, HKUST

- Teaching interests:
  - Databases, Cloud Computing, Big Data Technology, Algorithms, Data Structures
  - Other BS/MS level CS courses

Prerequisite

- Fundamental relational concepts: tables, tuples, columns, primary and foreign keys
- Relational algebra
- Basic concepts of writing SQL queries, SELECT, FROM, WHERE, different types of joins, and subqueries
- Big-O analysis for algorithmic cost

Demo Database

- Student(sid, name, state), Course(cid, title), Enrolled(sid, cid, grade)

sid	name	state
1	Alice	CA
2	Bob	NY
3	Charlie	CA
4	Diana	TX
5	Eve	CA
6	Frank	TX
7	Grace	NY

cid	title
101	Database Systems
102	Operating Systems
103	Algorithms
104	Computer Networks

sid	cid	grade
1	101	A
1	103	B
2	101	B
2	102	A
3	101	A
3	102	B
3	103	A
3	104	A
4	103	C
5	101	B
5	102	A
6	101	A
7	104	A
8	101	A

Download the demo database

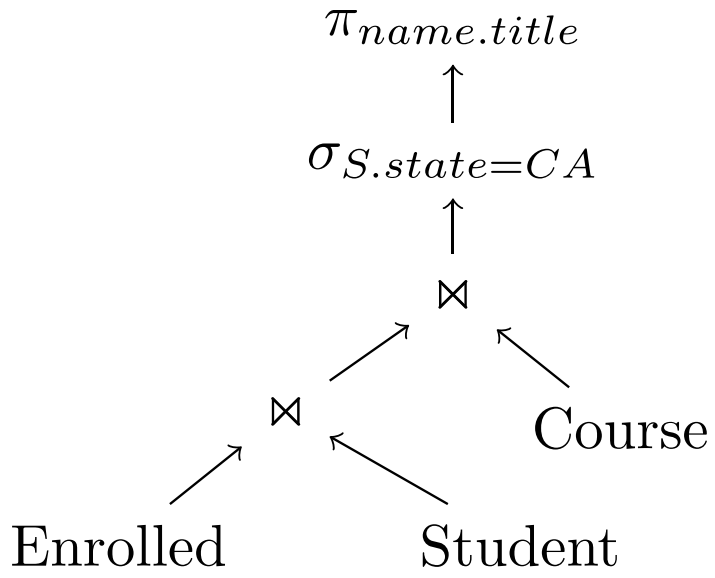
https://qichen-wang.github.io/files/demo.sql

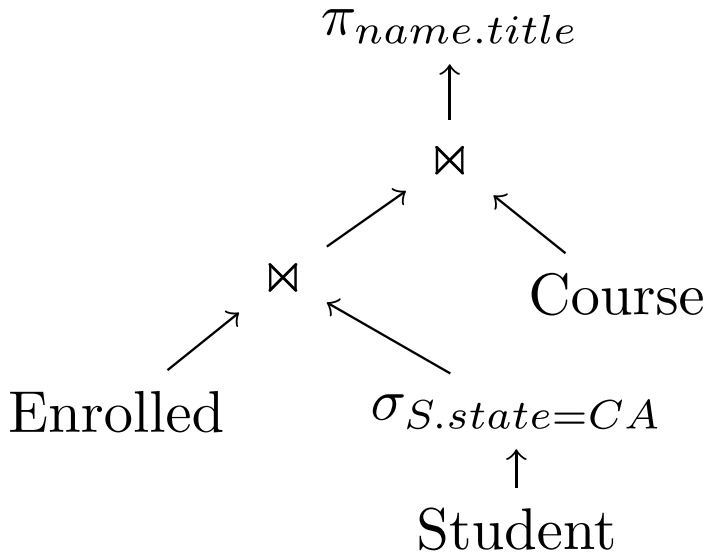
To load it:
For DuckDB:
.read /path/to/demo.sql
For PostgreSQL:
\i /path/to/demo.sql

SQL: A declarative language

- When writing SQL queries, we only express our high-level ideas.
- There can be different ways of evaluating the query.
  - *"Listing all students from CA and the courses they have enrolled in."*

```
SELECT name, title
FROM Student s, Course c, Enrolled e
WHERE s.sid = e.sid
AND c.cid = e.cid
AND s.state = 'CA';
```

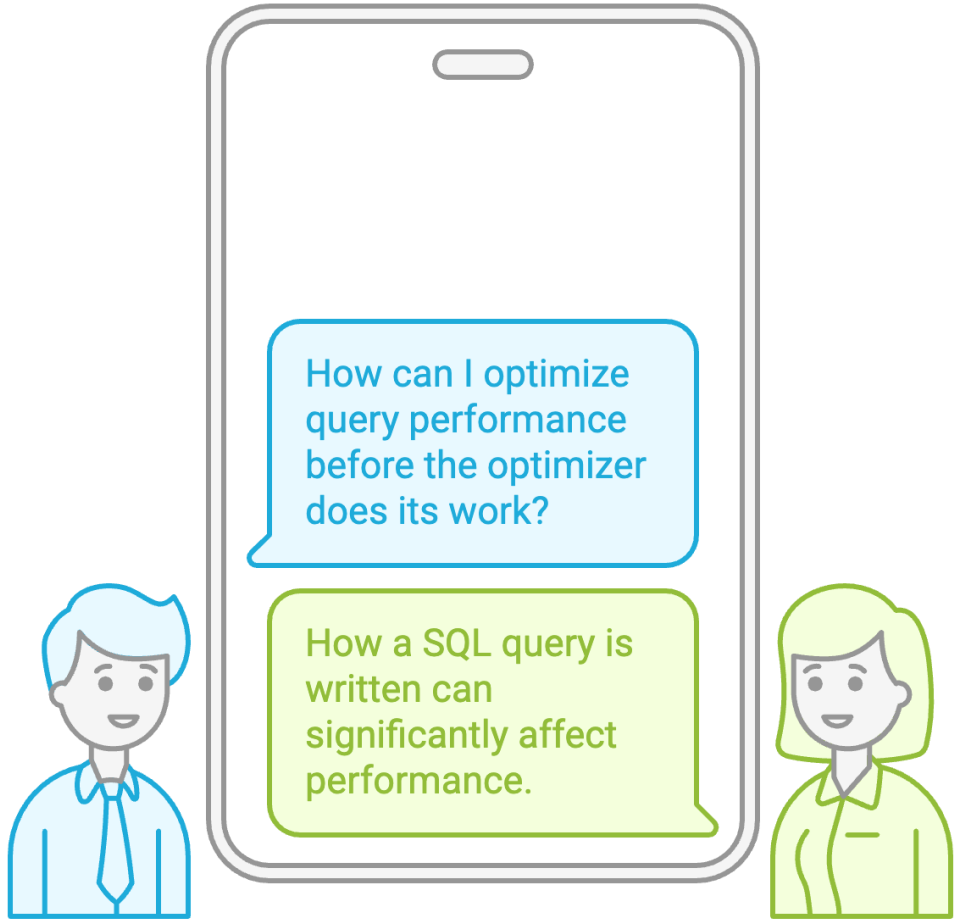




Before Optimization

The first step of optimization

- Ideally, the optimizer should do everything for you.
  - But that is not the case for current database systems.



An example:

Student(sid, name, state), Course(cid, title), Enrolled(sid, cid, grade)

- Suppose you want to find the students who have enrolled in all courses
- What will you do?
- 'For all' is hard to represent in SQL
- A direct translation: **Find the students for whom there are no course they have not enrolled in.**

```
SELECT sid
FROM Student s
WHERE NOT EXISTS (
        SELECT * FROM Course c
        WHERE NOT EXISTS (
                SELECT * FROM Enrolled e
                WHERE s.sid = e.sid AND c.cid = e.cid
));
```

It takes $O(n^2)$ time
Loop over all students and courses and check the Enrolled table for every possible combination.

How to do better?

Student(sid, name, state), Course(cid, title), Enrolled(sid, cid, grade)

- Suppose you want to find the students who have enrolled in all courses

- Another possible way: **Find the students whose enrolled course count matches the total number of courses in the Course table.**

```
SELECT sid
FROM Enrolled e
GROUP BY sid
HAVING count(*) = (SELECT count(*) FROM Course c);
```

Can be done in linear time $O(n)$

- The first SQL query is 2x slower than the second SQL query on the toy database. The gap can be more significant with more records in the database.
- **Writing a good SQL can reduce the complexity at the beginning.**

Query Optimization by Quantifier Elimination, Christoph Koch and Peter Lindner, *PODS 2024*

Some good practices you should know

- **Rule 1: Select Only Necessary Columns**
  - To avoid select * queries.
  - It is hard to find a query requiring every table column.
  - For some databases, data is stored in columnar format.
  - Selecting only required columns can significantly reduce the I/O cost.

Some good practices you should know

- **Rule 2: Remove redundant filter conditions and avoid functions in filter conditions**
  - For example, having both ”data >= 2025-01-01 and data <= 2025-12-31” and “YEAR(date) = 2025”
  - YEAR(date) = 2025 is redundant
  - Also, YEAR(date) = 2025 is not index-friendly; databases usually have indices on the range queries, but not for functions.

Some good practices you should know

- **Rule 3: Replace IN with EXISTS**
  - For some databases, the EXISTS clause often offers better performance.

```
SELECT name
FROM Student
WHERE state = 'CA'
 AND sid IN ( SELECT E.sid
      FROM Enrolled e, Course c
      WHERE e.cid = c.cid
      AND c.title = 'Database Systems'
      AND e.grade = 'A');
```

```
SELECT name
FROM Student s
WHERE EXISTS (SELECT 1
      FROM Enrolled e, Course c
      WHERE e.cid = c.cid
      AND s.sid = e.sid
      AND c.title = 'Database Systems'
      AND e.grade = 'A')
AND state = 'CA';
```

  - Some databases can optimize that for you (e.g., DuckDB) while some cannot (e.g., PostgreSQL)
  - Always use EXISTS if the right-hand side is a subquery.

Some good practices you should know

- **Rule 4: Replace unnecessary joins with semi-joins (EXISTS)**
  - Some join queries can be replaced with a semi-join if the output attributes are only located in one of the two relations.

```
SELECT DISTINCT S.name
FROM Student s, Enrolled e, Course c
WHERE S.state = 'CA'
AND C.title = 'Database Systems'
AND E.grade = 'A'
AND s.sid = e.sid AND c.cid = e.cid;
```

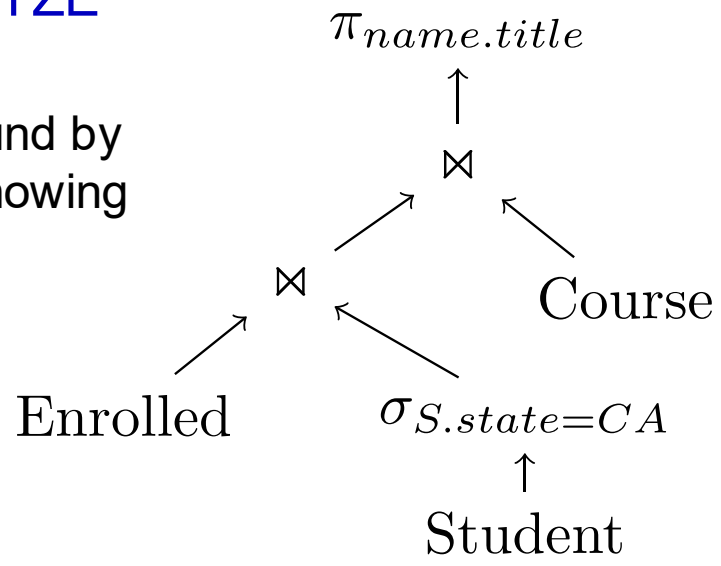
```
SELECT name
FROM Student s
WHERE EXISTS (SELECT 1
      FROM Enrolled e
      WHERE s.sid = e.sid
      AND e.grade = 'A'
      AND EXISTS (SELECT 1
            FROM Course c
            WHERE c.cid = e.cid
            AND c.title = 'Database Systems'))
AND S.state = 'CA';
```

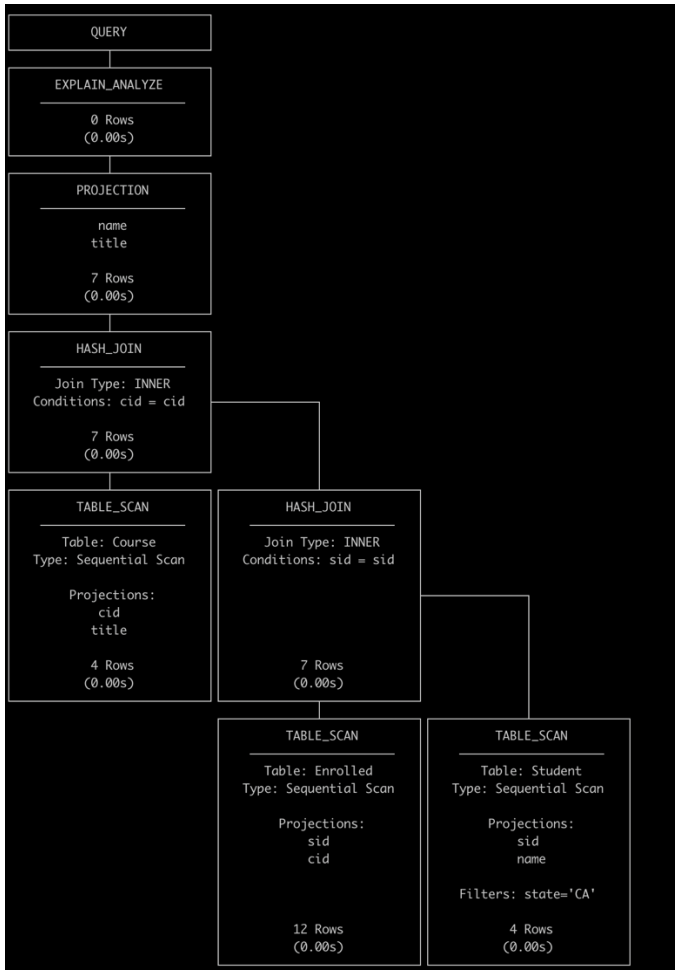
  - Avoid costly full join computation.

Viewing Query Evaluation Plans

```
EXPLAIN ANALYZE SELECT name, title
FROM Student s, Course c, Enrolled e
WHERE s.sid = e.sid
AND c.cid = e.cid
AND s.state = 'CA';
```

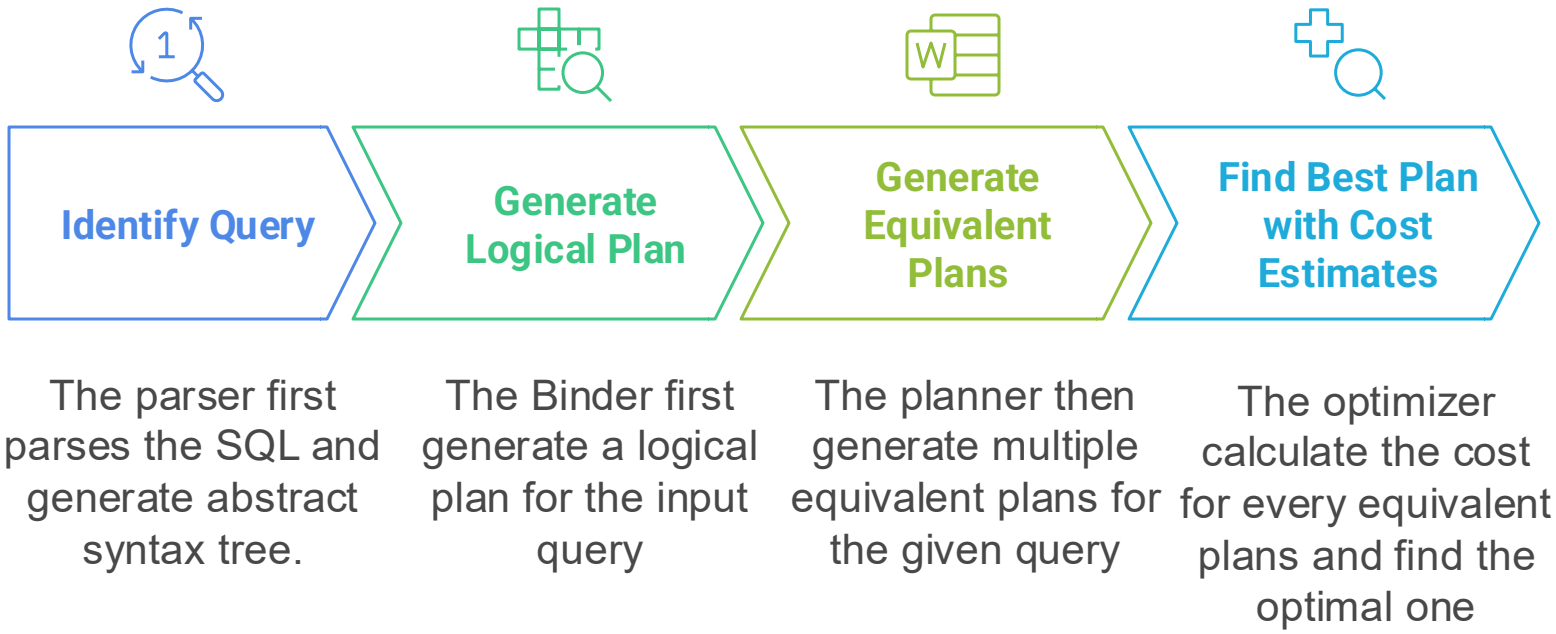
- Most databases support 'EXPLAIN <query>' to display the query execution plan.
  - Display plan chosen by query optimizer, along with cost estimation
- Some databases (e.g., PostgreSQL, DuckDB) support 'EXPLAIN ANALYZE <query>'
  - Shows actual runtime statistics found by running the query, in addition to showing the plan





Logical Plans and Rule-based Optimization

Logical Query Optimization



- The logical plan corresponds to a relational algebra expression.
- We need to find the equivalent relational algebra expressions to find equivalent plans.

Transformation of Relational Expressions

- Two relational algebra expressions are said to be equivalent if the two expressions generate the same set of tuples on every legal database instance.
  - Note: order of tuples is irrelevant
- An **equivalence rule** says that expressions of two forms are equivalent.
  - Can replace the expression of the first form by the second, or vice versa
- It is actually hard to find all possible equivalent expressions
  - NP-hard problem
- **Practically**: Choose from a subset of all possible plans

Equivalence Rules

1. Conjunctive selection operations can be deconstructed into a sequence of individual selections.

$$\sigma_{\theta_1 \wedge \theta_2}(E) \equiv \sigma_{\theta_1}\left(\sigma_{\theta_2}(E)\right)$$

$$\sigma_{s.sid<10 \wedge s.state='CA'}(Student) \equiv \sigma_{s.sid<10}\left(\sigma_{s.state='CA'}(Student)\right)$$

2. Selection operation is commutative.

$$\sigma_{\theta_1}\left(\sigma_{\theta_2}(E)\right) \equiv \sigma_{\theta_2}\left(\sigma_{\theta_1}(E)\right)$$

$$\sigma_{s.sid<10}\left(\sigma_{s.state='CA'}(Student)\right) \equiv \sigma_{s.state='CA'}\left(\sigma_{s.sid<10}(Student)\right)$$

Equivalence Rules

3. Join is commutative

$$E_1 \bowtie E_2 \equiv E_2 \bowtie E_1$$

$$Student \bowtie Enrolled \equiv Enrolled \bowtie Student$$

4. Natural join are associative

$$(E_1 \bowtie E_2) \bowtie E_3 \equiv E_1 \bowtie (E_2 \bowtie E_3)$$

$$(Student \bowtie Enrolled) \bowtie Course \equiv Student \bowtie (Enrolled \bowtie Course)$$

- The associative of natural join can create a lot of equivalence plans.
  - Will discuss later.

Equivalence Rules

5. Only the last in a sequence of projection operations is needed, the others can be omitted.

$$\pi_{L_1}\left(\pi_{L_2}\left(\cdots\left(\pi_{L_n}(E)\right)\right)\right) \equiv \pi_{L_1}(E)$$

where $L_1 \subseteq L_2 \subseteq \cdots \subseteq L_n$.

$$\pi_A\left(\pi_{A,B,C}(R)\right) \equiv \pi_A(R)$$

Predicate Pushdown

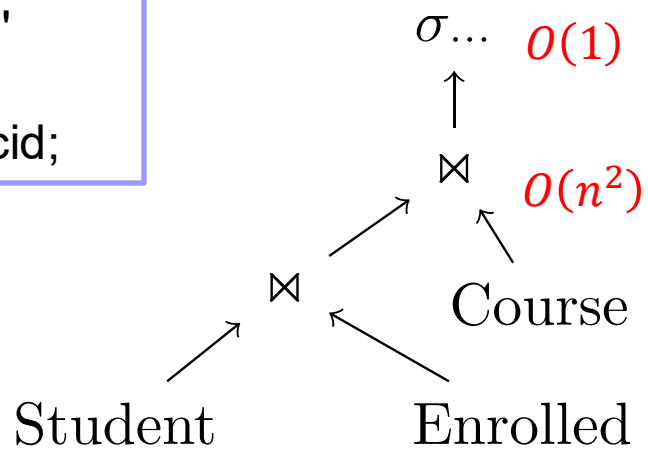
6. The selection operation can be distributed over the join operations if all the attributes in θ involve only those from one of the expressions (E_1) being joined.

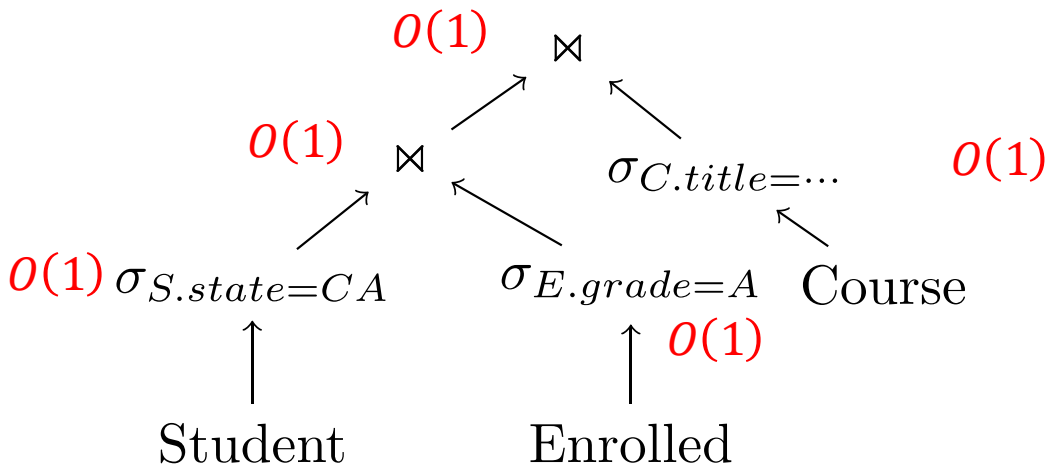
$$\sigma_\theta(E_1 \bowtie E_2) \equiv \left(\sigma_\theta(E_1)\right) \bowtie E_2$$

```
SELECT DISTINCT S.name
FROM Student s, Enrolled e, Course c
WHERE S.state = 'CA'
AND C.title = 'Database Systems'
AND E.grade = 'A'
AND s.sid = e.sid AND c.cid = e.cid;
```

$$\sigma_{S.state=CA \wedge C.title=Database\ Systems \wedge E.grade=A}(s \bowtie e \bowtie c)$$

$$\left(\sigma_{s.state=CA}(s)\right) \bowtie \left(\sigma_{e.grade=A}(e)\right) \bowtie \left(\sigma_{c.title=Database\ System}(c)\right)$$





Projection Pushdown

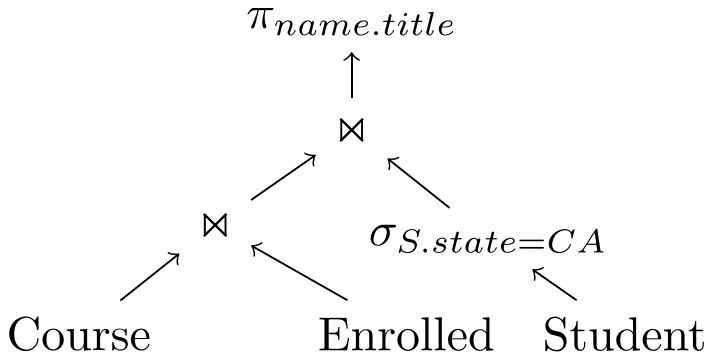
7. The projection operation distributes over the join operation as follows:

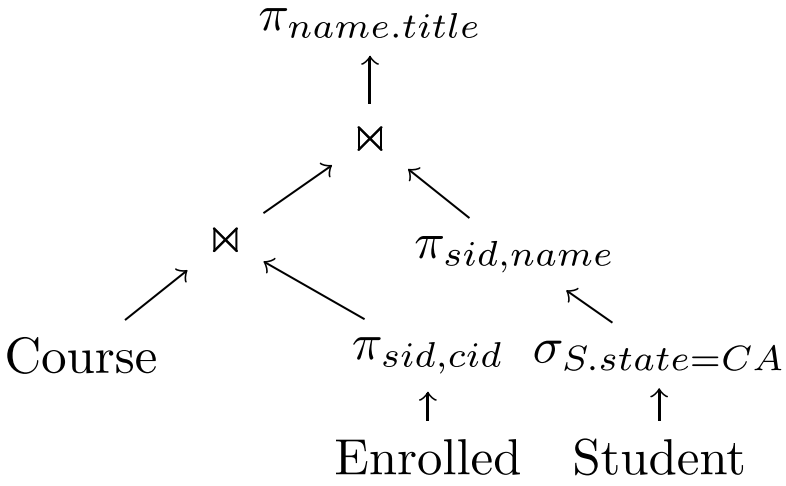
   Assume L_1/L_2 only involves attributes from E_1/E_2, L_3 are the set of join attributes:

$$\pi_{L_1 \cup L_2}(E_1 \bowtie E_2) \equiv \pi_{L_1 \cup L_2}\left(\pi_{L_1 \cup L_3}(E_1) \bowtie \pi_{L_2 \cup L_3}(E_2)\right)$$

i.e., we first project all attributes in E_1/E_2 that are either not in the final output attributes, or the join attributes. After calculating the join, we remove all the non-output join attributes ($\pi_{L_1 \cup L_2}$)

```
SELECT name, title
FROM Student s, Course c, Enrolled e
WHERE s.sid = e.sid
AND c.cid = e.cid
AND s.state = 'CA';
```





Heuristic Optimizations

- There are more rules (even rules that have not been discovered yet).
- These techniques **do not need** to examine data.
  - Predicate pushdown
  - Projection pushdown
- Idea: drop unused data as much as possible and as early as possible without affecting the efficiency
- Provide a much better starting point for the next stage of optimization.

Cost-based Optimization

Cost-based Query Optimization

- The efficiency of a query plan depends on multiple factors:
  - CPU time
  - I/O operations
  - Memory usage
  - Cache misses
- Cost Model: a weighted formula that combines all these factors:

$$c_1(CPU\ Ops) + c_2(I/O\ Ops) + \cdots$$

  - The constants $c_1, c_2, \cdots$ depend heavily on hardware
  - They are determined by the database system.
  - The formula can be simpler or more complicated.
- Also, heavily depends on the output size of each operator, which determine the number of CPU and I/O operations

Cost Estimation

- Need statistics of input relations.
  - E.g., number of tuples, sizes of tuples
- Need to estimate the statistics of expression results
  - Can work as the input of another expression
  - To do so, we require additional statistics
    - E.g., the number of distinct values for an attribute
    - Selectivity of a predicate conditions

How to Get Estimated Statistics

- Choice #1: Histograms
  - Maintain an occurrence count per value (or range of values) in a column
- Choice #2: Sketches
  - A probabilistic data structure that gives an approximate count for a given value
- Choice #3: Sampling
  - DMBS maintains a small subset of each table that it then uses to evaluate expressions to compute selectivity.
- Not covered in this lecture.
  - Let's assume we have a perfect estimator that can always return the actual number.

Single-Relation Query Planning

- Pick the best access method.
  - Sequential Scan

  e.g. , Select * From R, which requires accessing all records
  - Binary Search (clustered indexes)

  e.g. , Range filter conditions like Select … From R Where R.x <= 10;
  - Index Scan

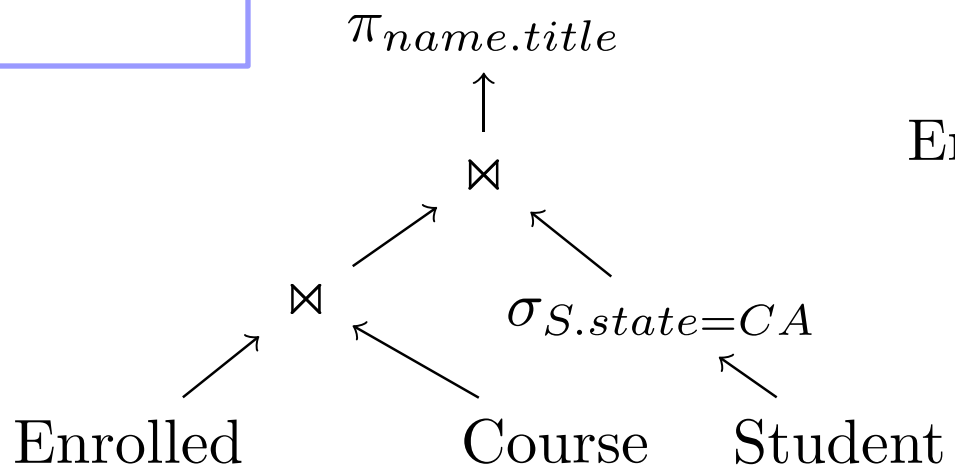
  e.g., Point filter conditions like Select … From R Where R.x = 'A';
- Predicate evaluation ordering
  - Apply the predicates with indexes first to avoid a sequential scan
  - Apply the most restricted predicate first

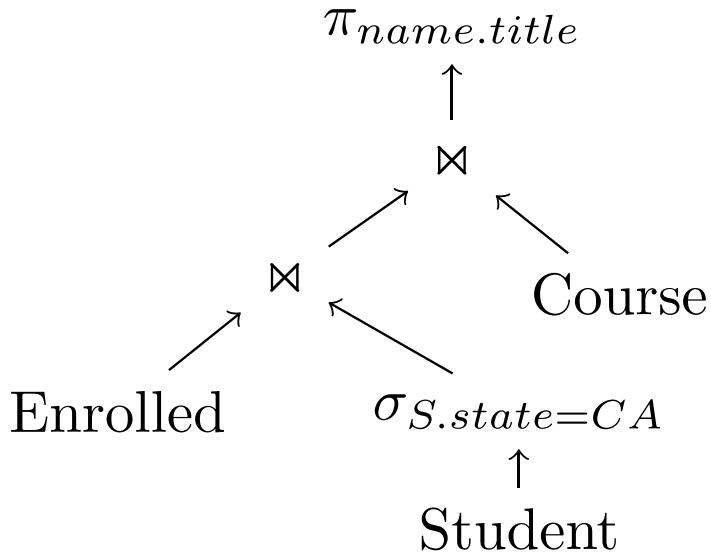
- Simple heuristics are often good enough for this

How to choose a better plan: Join Reordering

- Unlike predicate pushdown and projection pushdown, we cannot determine which relational expression is better after applying associative rules for multiple joins.

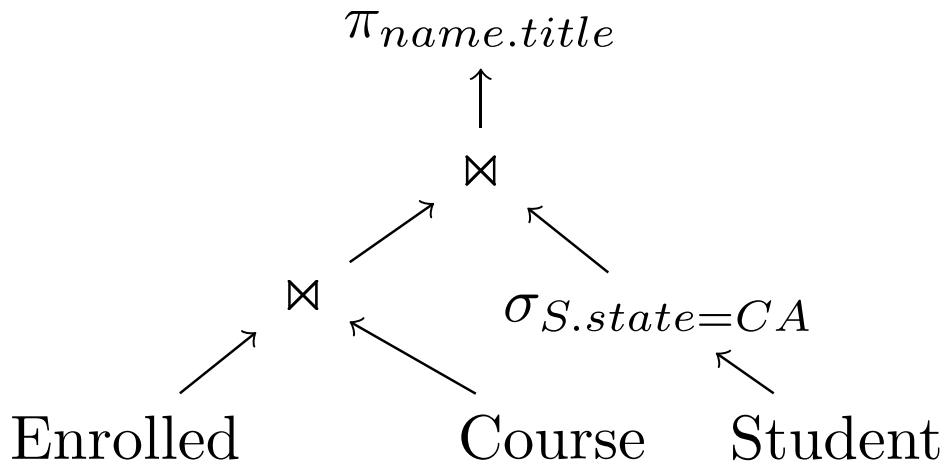
```
SELECT name, title
FROM Student s, Course c, Enrolled e
WHERE s.sid = e.sid
AND c.cid = e.cid
AND s.state = 'CA';
```





Join Reordering

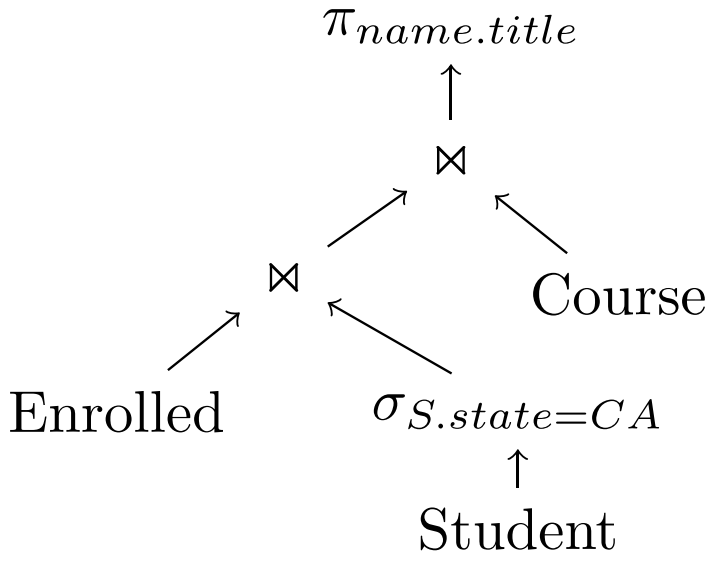
- Let's assume there are
  - 10000 records in the Enrolled relation
  - 50 records in the Course relation
  - 2000 records in the Student relation
  - Only 100 students are from CA
  - Every student enrolls in at most 10 courses



- Cost of the plan (The output size of each operation)
  - $Course \bowtie Enrolled$: returns 10000 records.
  - The filter predicate returns 100 records.
  - The final join returns at most 1000 records.

Join Reordering

- Let's assume there are
  - 10000 records in the Enrolled relation
  - 50 records in the Course relation
  - 2000 records in the Student relation
  - Only 100 students are from CA
  - Every student enrolls in at most 10 courses



- Cost of the plan (The output size of each operation)
  - The selective predicate returns 100 records.
  - The first join returns at most 1000 records.
  - The final join returns at most 1000 records.
- Assuming that generating one record requires a unit of time:
  - The first plan takes 11100 units
  - The second plan takes 2100 units

Join Reordering

- Consider a chain join query:

$$R_1(x_1, x_2) \bowtie R_2(x_2, x_3) \bowtie \cdots \bowtie R_n(x_n, x_{n+1})$$

- There can be $O(4^n)$ different join orders (Catalan number)
  - With 10 relations, total 4862 plans
  - With 20 relations, more than 1.7 billion plans

Join Reordering (cont.)

- But there are a lot of duplicates for plans:

$$\Big(\big(R_1(x_1, x_2) \bowtie R_2(x_2, x_3)\big) \bowtie R_3(x_3, x_4)\Big) \bowtie \Big(\big(R_4(x_4, x_5) \bowtie R_5(x_5, x_6)\big) \bowtie R_6(x_6, x_7)\Big)$$

and

$$\Big(\big(R_1(x_1, x_2) \bowtie R_2(x_2, x_3)\big) \bowtie R_3(x_3, x_4)\Big) \bowtie \Big(R_4(x_4, x_5) \bowtie \big(R_5(x_5, x_6) \bowtie R_6(x_6, x_7)\big)\Big)$$

shares the same plan for evaluating the joins between R_1, R_2, R_3

- The problem has **overlapping sub-problems** and show **optimal sub-structure**.

Dynamic Programming!

Dynamic Programming for Join Ordering

- Let $cost[i, j]$ store the minimal cost for calculating chain query $R_i \bowtie \cdots \bowtie R_j$, with $plan[i, j]$ store the corresponding query plan. Assume the cost of calculating a join query is the size of the result.
  - When $i > j$, the problem is invalid
  - When $i = j$, return the relation R_i directly with the cost of $|R_i|$

- When calculating the optimal plan for chain query $R_i \bowtie \cdots \bowtie R_j$, we determine the position k for performing the last join
  - i.e., we calculate $R_i \bowtie \cdots \bowtie R_k$ and $R_{k+1} \bowtie \cdots \bowtie R_j$ first, and then calculate the join query
$$(R_i \bowtie \cdots \bowtie R_k) \bowtie (R_{k+1} \bowtie \cdots \bowtie R_j)$$
  - There are totally $j - i$ different choices
- The cost of choosing k will be
$$cost[i, k] + cost[k + 1, j] + |R_i \bowtie \cdots \bowtie R_j|$$

Bottom-up Procedure

- To calculate the optimal cost for $[i, j]$, we first calculate all $cost[l, m]$ with $i \leq l \leq m \leq j$ and $m - l < j - i$
- Then we try all possible k and keep only the optimal one.

Input: $R_1, \ldots, R_n$ in chain order;
for $i \leftarrow 1$ **to** n **do**
  $cost[i, i] \leftarrow |R_i|$ `// single relation cost`
end
`// Outer loop, set segment length`
for $L \leftarrow 2$ **to** n **do**
  `// Middle loop, set the start index` i
  for $i \leftarrow 1$ **to** $n - L + 1$ **do**
    $j \leftarrow i + L - 1$
    $cost[i, j] \leftarrow \infty$
    `// Inner loop, set the split point`
    for $k \leftarrow i$ **to** $j - 1$ **do**
      $c \leftarrow cost[i, k] + cost[k + 1, j] + |R_i \bowtie \cdots \bowtie R_j|$
      if $c < cost[i, j]$ **then**
        $cost[i, j] \leftarrow c$;
        $plan[i, j] \leftarrow k$
      end
    end
  end
end
Output: $cost[1, n]$ and query plan via $plan$

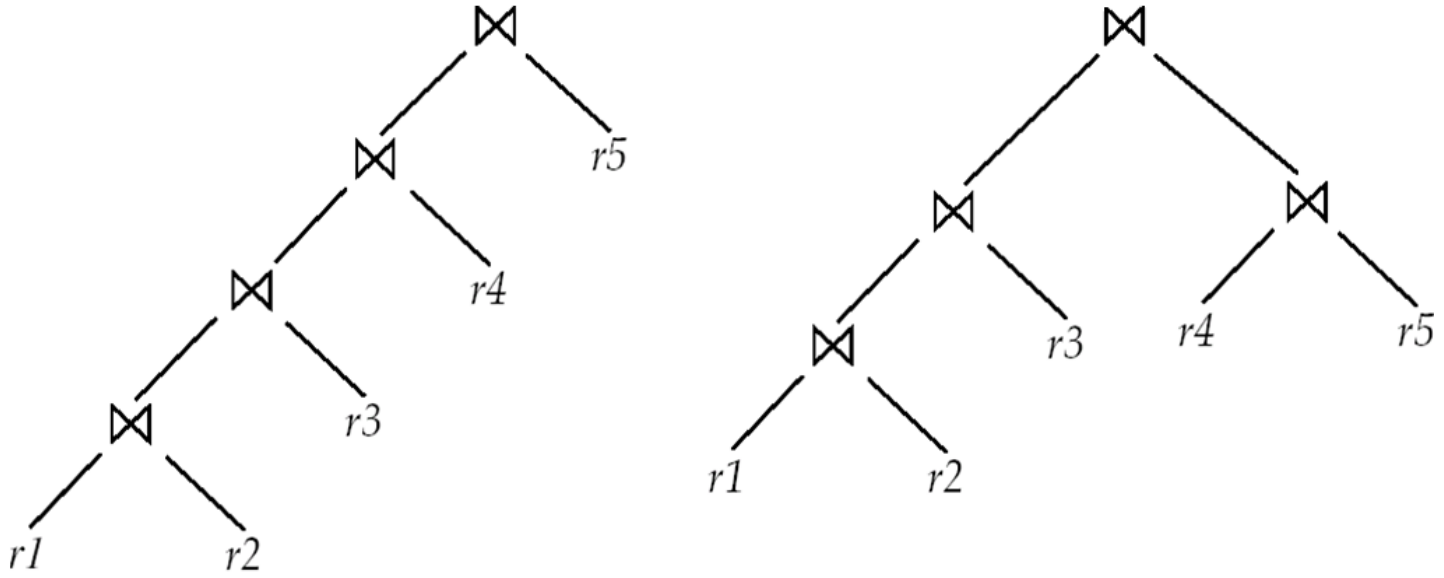
Complexity Analysis

- $O(n^2)$ memory cost
- $O(n^3)$ time complexity
  - When n = 20, the cost is 8000 instead of 1.7 billion.

- It is still costly if n is large.

Left-Deep Query Plans

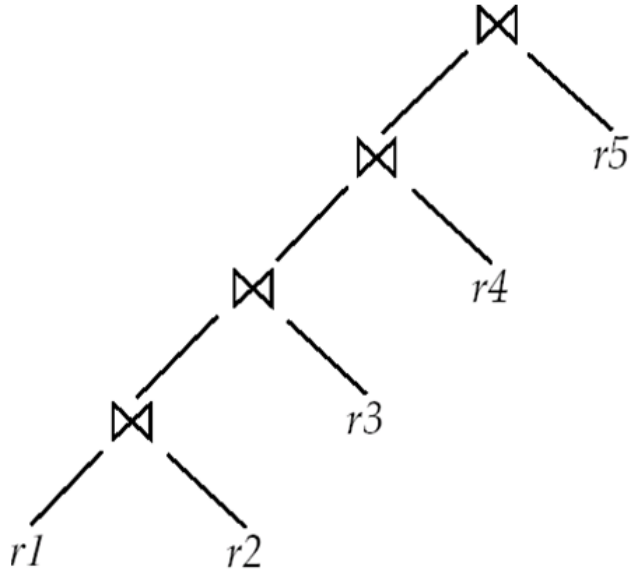
- In left-deep query plans, the right-hand side for each join is a relation, not the result of an intermediate join.
- Left-deep plan allows pipelining and avoids materialization of intermediate results.
  - If the join is not a sort-merge join.



(a) Left-deep join tree (b) Non-left-deep join tree

Left-Deep Query Plans (cont.)

- If only the left deep query plans are considered, the number of query plans is significantly reduced.
  - Partition n relations into $n - 1$ and 1 relation
  - For the chain query, only R_1 and R_n can be the right-most relation



Left-Deep Query Plans (cont.)

- For calculating $cost[i,j]$, we only need to consider the right-most relation to be R_i or R_j
  - No need to choose split point k anymore.
  - Reduce a factor of n for time complexity.

Input: $R_1, \ldots, R_n$ in chain order;
for $i \leftarrow 1$ **to** n **do**
  $cost[i,i] \leftarrow |R_i|$ `// single relation cost`
end
`// Outer loop, set segment length`
for $L \leftarrow 2$ **to** n **do**
  `// Middle loop, set the start index` i
  for $i \leftarrow 1$ **to** $n - L + 1$ **do**
    $j \leftarrow i + L - 1$
    `// Choose` R_i `or` R_j `to be the right-most relation`
    $c_1 \leftarrow cost[i, j-1] + cost[j,j] + |R_i \bowtie \cdots \bowtie R_j|$
    $c_2 \leftarrow cost[i,i] + cost[i+1, j] + |R_i \bowtie \cdots \bowtie R_j|$
    if $c_1 < c_2$ **then**
      $cost[i,j] \leftarrow c_1$
      $plan[i,j] \leftarrow j$
    else
      $cost[i,j] \leftarrow c_2$
      $plan[i,j] \leftarrow i$
  end
end
Output: $cost[1,n]$ and query plan via $plan$

Conclusion

- Query optimization is critical for a database system.
  - SQL -> Logical Plan -> Physical Plan
- The optimization step:
  - Write good SQL if possible.
  - Rule-based optimization for filtering logical plans.
    - Finding equivalent relational expressions
  - Cost-based optimization is used to select the best logical and physical plan.
    - A dynamic programming-based algorithm to avoid plan recomputation
- What is missing:
  - Some equivalent rules (read Database System Concepts, Section 13.2.1, and finish the practice exercises)
  - The cost estimation methods (Section 13.3)

- If you like this and want to make cash money in the database industry, consider earning a PhD in the database team at NTU.

Reference

- Lecture Note 14: Query Planning and Optimization, 15-445/645 Database Systems (Fall 2023), Andy Pavlo, Jignesh Patel
- “The Alice book”, S. Abiteboul, R. Hull and V. Vianu, “Foundations of Databases.”
- “Database System Concepts”, Avi Silberschatz, Henry F. Korth, S. Sudarshan, 6th edition

- Some figures in this slide are from the textbook “Database System Concepts”.