Intro to Database Systems (15-445/645)

14 Query Planning & Optimization

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ADMINISTRIVIA

**Mid-Term Exam** is available for review with solutions during in my office.
→ Bring your CMU ID card.
→ Use my calendar link if you need other times.

**Project #2 - Checkpoint #2** is due **Wednesday Oct 26th @ 11:59pm**
QUERY OPTIMIZATION

For a given query, find a **correct** execution plan that has the lowest "cost".

This is the part of a DBMS that is the hardest to implement well (proven to be NP-Complete).
→ If you are good at this, you will get paid $$$.

No optimizer truly produces the "optimal" plan
→ Use estimation techniques to guess real plan cost.
→ Use heuristics to limit the search space.
LOGICAL VS. PHYSICAL PLANS

The optimizer generates a mapping of a **logical** algebra expression to the optimal equivalent physical algebra expression.

**Physical** operators define a specific execution strategy using an access path.
- They can depend on the physical format of the data that they process (i.e., sorting, compression).
- Not always a 1:1 mapping from logical to physical.
ARCHITECTURE OVERVIEW

1. SQL Query
2. SQL Query
3. Abstract Syntax Tree
4. Logical Plan
5. Logical Plan
6. Physical Plan

Application ➔ SQL Query ➔ SQL Rewriter (Optional / Rare) ➔ Binder ➔ Parser ➔ System Catalog ➔ Schema Info ➔ Optimizer ➔ Cost Model ➔ Estimates

Parser
Catalog
Tree Rewriter (Optional / Common)
Optimizer
Cost Model
Estimates

Application Name→Internal ID
Schema Info
Name→Internal ID
Logical Plan
Physical Plan

SQL Query
Binder
Logical Plan

QUERY OPTIMIZATION

Heuristics / Rules
→ Rewrite the query to remove stupid / inefficient things.
→ These techniques may need to examine catalog, but they do not need to examine data.

Cost-based Search
→ Use a model to estimate the cost of executing a plan.
→ Enumerate multiple equivalent plans for a query and pick the one with the lowest cost.
TODAY'S AGENDA

Heuristic/Ruled-based Optimization
Query Cost Models
Cost-based Optimization
LOGICAL PLAN OPTIMIZATION

Transform a logical plan into an equivalent logical plan using pattern matching rules.

The goal is to increase the likelihood of enumerating the optimal plan in the search.

Cannot compare plans because there is no cost model but can "direct" a transformation to a preferred side.
LOGICAL QUERY OPTIMIZATION

Split Conjunctive Predicates
Predicate Pushdown
Replace Cartesian Products with Joins
Projection Pushdown

Source: Thomas Neumann
SELECT ARTIST.NAME
FROM ARTIST, APPEARS, ALBUM
WHERE ARTIST.ID=APPEARS.ARTIST_ID
   AND APPEARS.ALBUM_ID=ALBUM.ID
   AND ALBUM.NAME="Andy's OG Remix"

Decompose predicates into their simplest forms to make it easier for the optimizer to move them around.
SELECT ARTIST.NAME 
FROM ARTIST, APPEARS, ALBUM 
WHERE ARTIST.ID=APPEARS.ARTIST_ID 
AND APPEARS.ALBUM_ID=ALBUM.ID 
AND ALBUM.NAME="Andy's OG Remix"

Move the predicate to the lowest applicable point in the plan.
SELECT ARTIST.NAME
FROM ARTIST, APPEARS, ALBUM
WHERE ARTIST.ID=APPEARS.ARTIST_ID
AND APPEARS.ALBUM_ID=ALBUM.ID
AND ALBUM.NAME="Andy's OG Remix"

Replace all Cartesian Products with inner joins using the join predicates.
SELECT ARTIST.NAME
FROM ARTIST, APPEARS, ALBUM
WHERE ARTIST.ID=APPEARS.ARTIST_ID
AND APPEARS.ALBUM_ID=ALBUM.ID
AND ALBUM.NAME="Andy's OG Remix"

Eliminate redundant attributes before pipeline breakers to reduce materialization cost.
SELECT ARTIST.NAME 
FROM ARTIST, APPEARS, ALBUM 
WHERE ARTIST.ID=APPEARS.ARTIST_ID 
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Eliminate redundant attributes before pipeline breakers to reduce materialization cost.
NESTED SUB-QUERIES

The DBMS treats nested sub-queries in the where clause as functions that take parameters and return a single value or set of values.

Two Approaches:
→ Rewrite to de-correlate and/or flatten them
→ Decompose nested query and store result to temporary table
NESTED SUB-QUERIES: REWRITE

```
SELECT name FROM sailors AS S
WHERE EXISTS ( 
    SELECT * FROM reserves AS R
    WHERE S.sid = R.sid
    AND R.day = '2022-10-25'
)
```

```
SELECT name
FROM sailors AS S, reserves AS R
WHERE S.sid = R.sid
AND R.day = '2022-10-25'
```
DECOMPOSING QUERIES

For harder queries, the optimizer breaks up queries into blocks and then concentrates on one block at a time.

Sub-queries are written to a temporary table that are discarded after the query finishes.
DECOMPOSING QUERIES

```
SELECT S.sid, MIN(R.day)
FROM sailors S, reserves R, boats B
WHERE S.sid = R.sid
  AND R.bid = B.bid
  AND B.color = 'red'
  AND S.rating = (SELECT MAX(S2.rating)
                   FROM sailors S2)
GROUP BY S.sid
HAVING COUNT(*) > 1
```
DECOMPOSING QUERIES

```
SELECT MAX(rating) FROM sailors

SELECT S.sid, MIN(R.day)
    FROM sailors S, reserves R, boats B
WHERE S.sid = R.sid
    AND R.bid = B.bid
    AND B.color = 'red'
    AND S.rating = ###
GROUP BY S.sid
HAVING COUNT(*) > 1
```
DECOMPOSING QUERIES

**Outer Block**

```
SELECT MAX(rating) FROM sailors
```

```
SELECT S.sid, MIN(R.day) 
FROM sailors S, reserves R, boats B 
WHERE S.sid = R.sid 
    AND R.bid = B.bid 
    AND B.color = 'red' 
    AND S.rating = ###
GROUP BY S.sid 
HAVING COUNT(*) > 1
```
An optimizer transforms a query's expressions (e.g., `WHERE/ON` clause predicates) into the minimal set of expressions.

Implemented using if/then/else clauses or a pattern-matching rule engine.
→ Search for expressions that match a pattern.
→ When a match is found, rewrite the expression.
→ Halt if there are no more rules that match.
Impossible / Unnecessary Predicates

```
SELECT * FROM A WHERE 1 = 0
```
EXPRESSION REWRITING

Impossible / Unnecessary Predicates

```
SELECT * FROM A WHERE false;
SELECT * FROM A WHERE NOW() IS NULL;
```
Impossible / Unnecessary Predicates

- `SELECT * FROM A WHERE false;`
- `SELECT * FROM A WHERE false;`
- `SELECT * FROM A WHERE RANDOM() IS NULL;`
EXPRESSION REWRITING

Impossible / Unnecessary Predicates

```
SELECT * FROM A WHERE false;
SELECT * FROM A WHERE false;
SELECT * FROM A WHERE RANDOM() IS NULL;
```

Merging Predicates

```
SELECT * FROM A
WHERE val BETWEEN 1 AND 100
  OR val BETWEEN 50 AND 150;
```
EXPRESSSION REWRITING

Impossible / Unnecessary Predicates

```sql
SELECT * FROM A WHERE false;
SELECT * FROM A WHERE false;
SELECT * FROM A WHERE RANDOM() IS NULL;
```

Merging Predicates

```sql
SELECT * FROM A
WHERE val BETWEEN 1 AND 150;
```
**QUERY OPTIMIZATION**

**Heuristics / Rules**

→ Rewrite the query to remove stupid / inefficient things.
→ These techniques may need to examine catalog, but they do not need to examine data.

**Cost-based Search**

→ Use a model to estimate the cost of executing a plan.
→ Enumerate multiple equivalent plans for a query and pick the one with the lowest cost.
COST ESTIMATION

The DBMS uses a cost model to predict the behavior of a query plan given a database state. → This is an internal cost that allows the DBMS to compare one plan with another.

It is too expensive to run every possible plan to determine this information, so the DBMS need a way to derive this information.
COST MODEL COMPONENTS

Choice #1: Physical Costs
→ Predict CPU cycles, I/O, cache misses, RAM consumption, network messages…
→ Depends heavily on hardware.

Choice #2: Logical Costs
→ Estimate output size per operator.
→ Independent of the operator algorithm.
→ Need estimations for operator result sizes.

Choice #3: Algorithmic Costs
→ Complexity of the operator algorithm implementation.
POSTGRES COST MODEL

Uses a combination of CPU and I/O costs that are weighted by “magic” constant factors.

Default settings are obviously for a disk-resident database without a lot of memory:
→ Processing a tuple in memory is 400x faster than reading a tuple from disk.
→ Sequential I/O is 4x faster than random I/O.
19.7.2. Planner Cost Constants

The cost variables described in this section are measured on an arbitrary scale. Only their relative values matter, hence scaling them all up or down by the same factor will result in no change in the planner’s choices. By default, these cost variables are based on the cost of sequential page fetches; that is, \texttt{seq\_page\_cost} is conventionally set to 1.0 and the other cost variables are set with reference to that. But you can use a different scale if you prefer, such as actual execution times in milliseconds on a particular machine.

\textbf{Note:} Unfortunately, there is no well-defined method for determining ideal values for the cost variables. They are best treated as averages over the entire mix of queries that a particular installation will receive. This means that changing them on the basis of just a few experiments is very risky.

\texttt{seq\_page\_cost (floating point)}

Sets the planner’s estimate of the cost of a disk page fetch that is part of a series of sequential fetches. The default is 1.0. This value can be overridden for tables and indexes in a particular tablespace by setting the tablespace parameter of the same name (see \texttt{ALTER TABLESPACE}).

\texttt{random\_page\_cost (floating point)
STATISTICS

The DBMS stores internal statistics about tables, attributes, and indexes in its internal catalog. Different systems update them at different times.

Manual invocations:
→ Postgres/SQLite: **ANALYZE**
→ Oracle/MySQL: **ANALYZE TABLE**
→ SQL Server: **UPDATE STATISTICS**
→ DB2: **RUNSTATS**
SELECTION CARDINALITY

Formula depends on type of predicate:
→ Equality
→ Range
→ Negation
→ Conjunction
→ Disjunction
The selectivity (sel) of a predicate $P$ is the fraction of tuples that qualify.

**Equality Predicate:** $A=\text{constant}$

$\rightarrow \text{sel}(A=\text{constant}) = \frac{\#\text{occurrences}}{|R|}$

$\rightarrow$ Example: $\text{sel}(\text{age}=9) = \frac{4}{45}$
Assumption #1: Uniform Data
→ The distribution of values (except for the heavy hitters) is the same.

Assumption #2: Independent Predicates
→ The predicates on attributes are independent

Assumption #3: Inclusion Principle
→ The domain of join keys overlap such that each key in the inner relation will also exist in the outer table.
CORRELATED ATTRIBUTES

Consider a database of automobiles:
→ # of Makes = 10, # of Models = 100

And the following query:
→ (make="Honda" AND model="Accord")

With the independence and uniformity assumptions, the selectivity is:
→ 1/10 × 1/100 = 0.001

But since only Honda makes Accords the real selectivity is 1/100 = 0.01

Source: Guy Lohman
Choice #1: Histograms
→ Maintain an occurrence count per value (or range of values) in a column.

Choice #2: Sketches
→ Probabilistic data structure that gives an approximate count for a given value.

Choice #3: Sampling
→ DBMS maintains a small subset of each table that it then uses to evaluate expressions to compute selectivity.
Our formulas are nice, but we assume that data values are uniformly distributed.

**Histogram**

- **15 Keys × 32-bits = 60 bytes**
- **Distinct values of attribute**
EQUI-WIDTH HISTOGRAM

Maintain counts for a group of values instead of each unique key. All buckets have the same width (i.e., same # of value).

Non-Uniform Approximation

15 Values $\times$ 32-bits = 60 bytes
EQUI-WIDTH HISTOGRAM

Maintain counts for a group of values instead of each unique key. All buckets have the same width (i.e., same # of value).

Non-Uniform Approximation
Maintain counts for a group of values instead of each unique key. All buckets have the same width (i.e., same # of value).
Vary the width of buckets so that the total number of occurrences for each bucket is roughly the same.
EQUI-DEPTH HISTOGRAMS

Vary the width of buckets so that the total number of occurrences for each bucket is roughly the same.
SKETCHES

Probabilistic data structures that generate approximate statistics about a data set. Cost-model can replace histograms with sketches to improve its selectivity estimate accuracy.

Most common examples:
→ **HyperLogLog** (2007): Approximate the number of distinct elements in a set.
Modern DBMSs also collect samples from tables to estimate selectivities.

Update samples when the underlying tables changes significantly.

Table Sample

<table>
<thead>
<tr>
<th>id</th>
<th>name</th>
<th>age</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>Obama</td>
<td>61</td>
<td>Rested</td>
</tr>
<tr>
<td>1003</td>
<td>Tupac</td>
<td>25</td>
<td>Dead</td>
</tr>
<tr>
<td>1005</td>
<td>Andy</td>
<td>41</td>
<td>Illin</td>
</tr>
</tbody>
</table>

\[ \text{sel}(\text{age}>50) = \frac{1}{3} \]

1 billion tuples

\[
\text{SELECT \ AVG(age) FROM people WHERE age > 50}
\]

<table>
<thead>
<tr>
<th>id</th>
<th>name</th>
<th>age</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>Obama</td>
<td>61</td>
<td>Rested</td>
</tr>
<tr>
<td>1002</td>
<td>Kanye</td>
<td>45</td>
<td>Weird</td>
</tr>
<tr>
<td>1003</td>
<td>Tupac</td>
<td>25</td>
<td>Dead</td>
</tr>
<tr>
<td>1004</td>
<td>Bieber</td>
<td>28</td>
<td>Crunk</td>
</tr>
<tr>
<td>1005</td>
<td>Andy</td>
<td>41</td>
<td>Illin</td>
</tr>
<tr>
<td>1006</td>
<td>TigerKing</td>
<td>59</td>
<td>Jailed</td>
</tr>
</tbody>
</table>
OBSERVATION

Now that we can (roughly) estimate the selectivity of predicates, and subsequently the cost of query plans, what can we do with them?
After performing rule-based rewriting, the DBMS will enumerate different plans for the query and estimate their costs.

→ Single relation.
→ Multiple relations.
→ Nested sub-queries.

It chooses the best plan it has seen for the query after exhausting all plans or some timeout.
SINGLE-RELATION QUERY PLANNING

Pick the best access method.
→ Sequential Scan
→ Binary Search (clustered indexes)
→ Index Scan

Predicate evaluation ordering.

Simple heuristics are often good enough for this. OLTP queries are especially easy…
Query planning for OLTP queries is easy because they are **sargable** (Search Argument Able).

→ It is usually just picking the best index.

→ Joins are almost always on foreign key relationships with a small cardinality.

→ Can be implemented with simple heuristics.

```
CREATE TABLE people (id INT PRIMARY KEY, val INT NOT NULL,);
```

```
SELECT * FROM people WHERE id = 123;
```
MULTI-RELATION QUERY PLANNING

Choice #1: Bottom-up Optimization
→ Start with nothing and then build up the plan to get to the outcome that you want.

Choice #2: Top-down Optimization
→ Start with the outcome that you want, and then work down the tree to find the optimal plan that gets you to that goal.
Use static rules to perform initial optimization. Then use dynamic programming to determine the best join order for tables using a divide-and-conquer search method.

**Examples:** IBM System R, DB2, MySQL, Postgres, most open-source DBMSs.
SYSTEM R OPTIMIZER

Break query up into blocks and generate the logical operators for each block.

For each logical operator, generate a set of physical operators that implement it.
→ All combinations of join algorithms and access paths

Then iteratively construct a "left-deep" join tree that minimizes the estimated amount of work to execute the plan.
**SYSTEM R OPTIMIZER**

**Step #1:** Choose the best access paths to each table

**Step #2:** Enumerate all possible join orderings for tables

**Step #3:** Determine the join ordering with the lowest cost

```sql
SELECT ARTIST.NAME
FROM ARTIST, APPEARS, ALBUM
WHERE ARTIST.ID=APPEARS.ARTIST_ID
   AND APPEARS.ALBUM_ID=ALBUM.ID
   AND ALBUM.NAME="Andy's OG Remix"
ORDER BY ARTIST.ID
```

**ARTIST:** Sequential Scan

**APPEARS:** Sequential Scan

**ALBUM:** Index Look-up on NAME

<table>
<thead>
<tr>
<th>ARTIST</th>
<th>×</th>
<th>APPEARS</th>
<th>×</th>
<th>ALBUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPEARS</td>
<td>×</td>
<td>ALBUM</td>
<td>×</td>
<td>ARTIST</td>
</tr>
<tr>
<td>ALBUM</td>
<td>×</td>
<td>APPEARS</td>
<td>×</td>
<td>ARTIST</td>
</tr>
<tr>
<td>APPEARS</td>
<td>×</td>
<td>ARTIST</td>
<td>×</td>
<td>ALBUM</td>
</tr>
<tr>
<td>ARTIST</td>
<td>×</td>
<td>ALBUM</td>
<td>×</td>
<td>APPEARS</td>
</tr>
<tr>
<td>ALBUM</td>
<td>×</td>
<td>ARTIST</td>
<td>×</td>
<td>APPEARS</td>
</tr>
</tbody>
</table>
SYSTEM R OPTIMIZER

ARTIST $\bowtie$ APPEARS $\bowtie$ ALBUM

• • •

HASH_JOIN(A1, A3)  SM_JOIN(A1, A3)  HASH_JOIN(A2, A3)  SM_JOIN(A2, A3)  HASH_JOIN(A3, A2)  SM_JOIN(A3, A2)  • • •
HASH_JOIN(A1, A3), A2)

ARTIST \join APPEARS \join ALBUM

HASH_JOIN(A2, A3, A1)

APPEARS.ALBUM_ID = ALBUM.ID

APPEARS.ARTIST_ID = ARTIST.ID

HASH_JOIN(A3, A2, A1)

APPEARS.ARTIST_ID = ARTIST.ID

SM_JOIN(A3, A2)

ARTIST.ID = APPEARS.ARTIST_ID

APPEARS.ALBUM_ID = ALBUM.ID

ALBUM.ID = APPEARS.ALBUM_ID

ARTIST ALBUM APPEARS
The query has **ORDER BY** on **ARTIST.ID** but the logical plans do not contain sorting properties.
Start with a logical plan of what we want the query to be. Perform a branch-and-bound search to traverse the plan tree by converting logical operators into physical operators.

→ Keep track of global best plan during search.
→ Treat physical properties of data as first-class entities during planning.

**Example:** MSSQL, Greenplum, CockroachDB
TOP-DOWN OPTIMIZATION

Invoke rules to create new nodes and traverse tree.

→ Logical → Logical:
  JOIN(A, B) to JOIN(B, A)

→ Logical → Physical:
  JOIN(A, B) to HASH_JOIN(A, B)
Invoke rules to create new nodes and traverse tree.

→ Logical→Logical:
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Can create "enforcer" rules that require input to have certain properties.
Invoke rules to create new nodes and traverse tree.

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Invoke rules to create new nodes and traverse tree.

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Can create "enforcer" rules that require input to have certain properties.
CONCLUSION

We use static rules and heuristics to optimize a query plan without needing to understand the contents of the database.

We use cost model to help perform more advanced query optimizations.
Transactions!
→ aka the second hardest part about database systems