Lecture #17 – Query Planning (Optimizer Implementation)

Andy Pavlo // Carnegie Mellon University // Spring 2016

TODAY'S AGENDA

Background
Optimization Basics
Search Strategies
Adaptive Query Processing

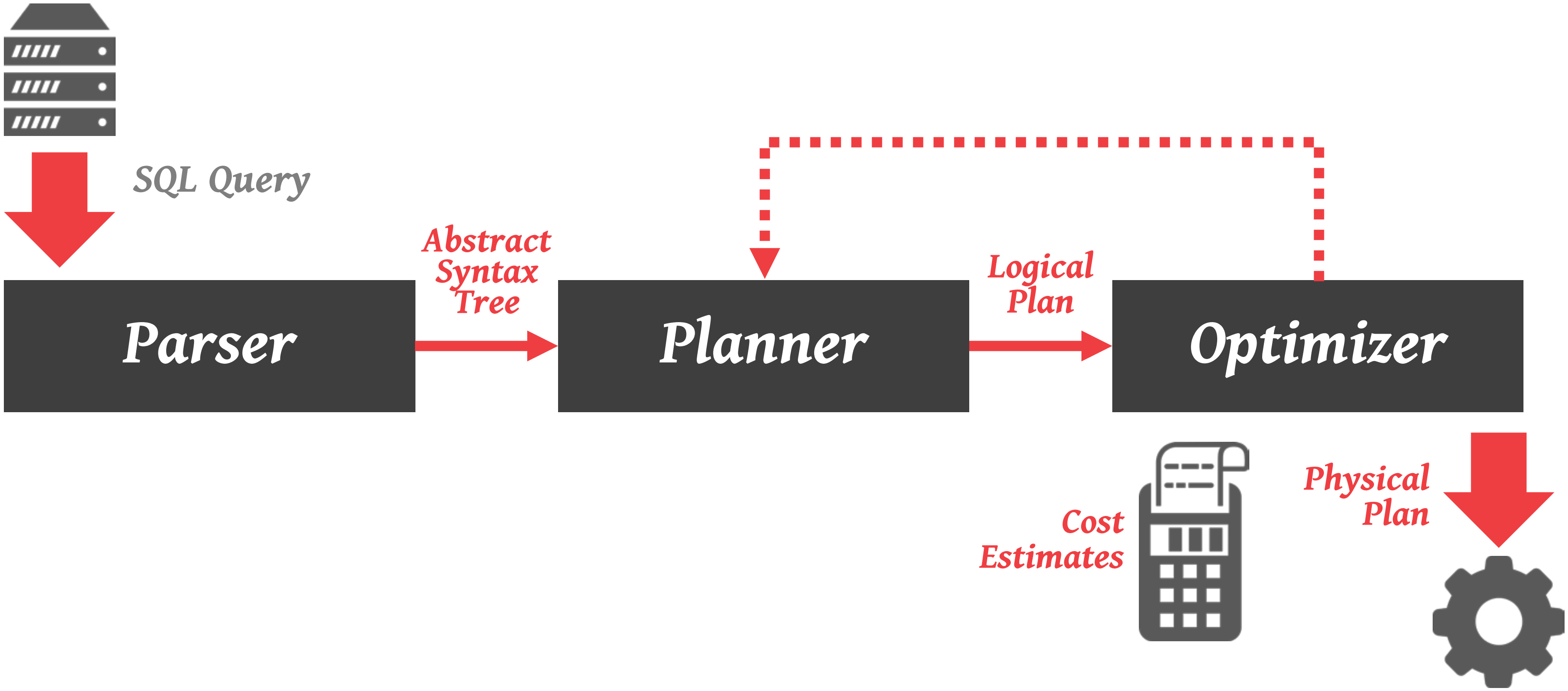
QUERY OPTIMIZATION

For a given query, find an execution plan for it that has the lowest "cost".

The part of a DBMS that is the hardest to implement well (proven to be NP-Complete).

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

CLASSIC ARCHITECTURE



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 a particular 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.

RELATIONAL ALGEBRA EQUIVALENCES

Two relational algebra expressions are said to be **equivalent** if on every legal database instance the two expressions generate the same set of tuples.

Example: $(A \bowtie (B \bowtie C)) = (B \bowtie (A \bowtie C))$

OBSERVATION

Query planning for OLTP queries is easy because they are **sargable**.

→ 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.

We will focus on OLAP queries in this lecture.

OBSERVATION

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.

We will focus on OLAP queries in this lecture.

COST ESTIMATION

Generate an estimate of the cost of executing a plan for the current state of the database.

- → Interactions with other work in DBMS
- → Size of intermediate results
- → Choices of algorithms, access methods
- → Resource utilization (CPU, I/O, network)
- → Data properties (skew, order, placement)

We will discuss this more on Wednesday...

DESIGN CHOICES

Optimization Granularity

Optimization Timing

Plan Stability

OPTIMIZATION GRANULARITY

Choice #1: Single Query

→ Much smaller search space.
→ DBMS cannot reuse results across queries.
→ In order to account for resource contention, the cost model must account for what is currently running.

Choice #2: Multiple Queries

→ More efficient if there are many similar queries.
→ Search space is much larger.
→ Useful for scan sharing.

OPTIMIZATION TIMING

Choice #1: Static Optimization

→ Select the best plan prior to execution.
→ Plan quality is dependent on cost model accuracy.
→ Can amortize over executions with prepared stmts.

Choice #2: Dynamic Optimization

→ Select operator plans on-the-fly as queries execute.
→ Will have reoptimize for multiple executions.
→ Difficult to implement/debug (non-deterministic)

Choice #3: Hybrid Optimization

→ Compile using a static algorithm.
→ If the error in estimate > threshold, reoptimize

PLAN STABILITY

Choice #1: Hints

→ Allow the DBA to provide hints to the optimizer.

Choice #2: Fixed Optimizer Versions

→ Set the optimizer version number and migrate queries one-by-one to the new optimizer.

Choice #3: Backwards-Compatible Plans

→ Save query plan from old version and provide it to the new DBMS.

OPTIMIZATION SEARCH STRATEGIES

Heuristics

Heuristics + Cost-based Join Order Search

Randomized Algorithms

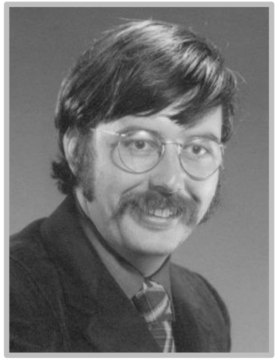
Stratified Search

Unified Search

HEURISTIC-BASED OPTIMIZATION

Define static rules that transform logical operators to a physical plan.

→ Perform most restrictive selection early
→ Perform all selections before joins
→ Predicate/Limit/Projection pushdowns
→ Join ordering based on cardinality



Stonebraker

Example: Original versions of INGRES and Oracle (until mid 1990s)

QUERY PROCESSING IN A RELATIONAL DATABASE MANAGEMENT SYSTEM
VLDB 1979

EXAMPLE DATABASE

```
CREATE TABLE ARTIST (
  ID INT PRIMARY KEY,
  NAME VARCHAR(32)
);
```

```
CREATE TABLE ALBUM (
  ID INT PRIMARY KEY,
  NAME VARCHAR(32) UNIQUE
);
```

```
CREATE TABLE APPEARS (
  ARTIST_ID INT
   ↪REFERENCES ARTIST(ID),
  ALBUM_ID INT
   ↪REFERENCES ALBUM(ID),
  PRIMARY KEY
   ↪(ARTIST_ID, ALBUM_ID)
);
```

INGRES OPTIMIZER

Retrieve the names of people that appear on Joy's mixtape

```
SELECT ARTIST.NAME
  FROM ARTIST, APPEARS, ALBUM
 WHERE ARTIST.ID=APPEARS.ARTIST_ID
   AND APPEARS.ALBUM_ID=ALBUM.ID
   AND ALBUM.NAME="Joy's Slag Remix"
```

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Step #1: Decompose into single-variable queries

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```

Q1

```
SELECT ALBUM.ID AS ALBUM_ID INTO TEMP1
  FROM ALBUM
 WHERE ALBUM.NAME="Joy's Slag Remix"
```

Q2

```
SELECT ARTIST.NAME
  FROM ARTIST, APPEARS, TEMP1
 WHERE ARTIST.ID=APPEARS.ARTIST_ID
   AND APPEARS.ALBUM_ID=TEMP1.ALBUM_ID
```

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Q1

```
SELECT ALBUM.ID AS ALBUM_ID INTO TEMP1
  FROM ALBUM
 WHERE ALBUM.NAME="Joy's Slag Remix"
```

Q2

```
SELECT ARTIST.NAME
  FROM ARTIST, APPEARS, TEMP1
 WHERE ARTIST.ID=APPEARS.ARTIST_ID
   AND APPEARS.ALBUM_ID=TEMP1.ALBUM_ID
```

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```

Q1

```
SELECT ALBUM.ID AS ALBUM_ID INTO TEMP1
  FROM ALBUM
 WHERE ALBUM.NAME="Joy's Slag Remix"
```

Q3

```
SELECT APPEARS.ARTIST_ID INTO TEMP2
  FROM APPEARS, TEMP1
 WHERE APPEARS.ALBUM_ID=TEMP1.ALBUM_ID
```

Q4

```
SELECT ARTIST.NAME
  FROM ARTIST, TEMP2
 WHERE ARTIST.ARTIST_ID=TEMP2.ARTIST_ID
```

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```

Q1

```
SELECT ALBUM.ID AS ALBUM_ID INTO TEMP1
  FROM ALBUM
 WHERE ALBUM.NAME="Joy's Slag Remix"
```

Q3

```
SELECT APPEARS.ARTIST_ID INTO TEMP2
  FROM APPEARS, TEMP1
 WHERE APPEARS.ALBUM_ID=TEMP1.ALBUM_ID
```

Q4

```
SELECT ARTIST.NAME
  FROM ARTIST, TEMP2
 WHERE ARTIST.ARTIST_ID=TEMP2.ARTIST_ID
```

Step #1: Decompose into single-variable queries

Step #2: Substitute the values from Q1→Q3→Q4

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SELECT ARTIST.NAME
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 WHERE ARTIST.ID=APPEARS.ARTIST_ID
   AND APPEARS.ALBUM_ID=ALBUM.ID
   AND ALBUM.NAME="Joy's Slag Remix"
```

ALBUM_ID
9999

Q3

```
SELECT APPEARS.ARTIST_ID INTO TEMP2
  FROM APPEARS, TEMP1
 WHERE APPEARS.ALBUM_ID=TEMP1.ALBUM_ID
```

Q4

```
SELECT ARTIST.NAME
  FROM ARTIST, TEMP2
 WHERE ARTIST.ARTIST_ID=TEMP2.ARTIST_ID
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   AND ALBUM.NAME="Joy's Slag Remix"
```

ALBUM_ID
9999

```
SELECT APPEARS.ARTIST_ID
  FROM APPEARS
 WHERE APPEARS.ALBUM_ID=9999
```

Q4

```
SELECT ARTIST.NAME
  FROM ARTIST, TEMP2
 WHERE ARTIST.ARTIST_ID=TEMP2.ARTIST_ID
```

Step #1: Decompose into single-variable queries

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```

ALBUM_ID
9999

ARTIST_ID
123
456

Step #1: Decompose into single-variable queries

Step #2: Substitute the values from Q1→Q3→Q4

Q4

```
SELECT ARTIST.NAME
  FROM ARTIST, TEMP2
 WHERE ARTIST.ARTIST_ID=TEMP2.ARTIST_ID
```

INGRES OPTIMIZER

Retrieve the names of people that appear on Joy's mixtape

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SELECT ARTIST.NAME
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 WHERE ARTIST.ID=APPEARS.ARTIST_ID
   AND APPEARS.ALBUM_ID=ALBUM.ID
   AND ALBUM.NAME=“Joy's Slag Remix”
```

ALBUM_ID
9999

ARTIST_ID
123
456

```
SELECT ARTIST.NAME
  FROM ARTIST
 WHERE ARTIST.ARTIST_ID=123
```

```
SELECT ARTIST.NAME
  FROM ARTIST
 WHERE ARTIST.ARTIST_ID=456
```

Step #1: Decompose into single-variable queries

Step #2: Substitute the values from Q1→Q3→Q4

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```

ALBUM_ID
9999

ARTIST_ID
123
456

NAME
O.D.B.

NAME
DJ Premier

Step #1: Decompose into single-variable queries

Step #2: Substitute the values from Q1→Q3→Q4

HEURISTIC-BASED OPTIMIZATION

Advantages:

→ Easy to implement and debug.
→ Works reasonably well and is fast for simple queries.

Disadvantages:

→ Relies on magic constants that predict the efficacy of a planning decision.
→ Nearly impossible to generate good plans when operators have complex inter-dependencies.

HEURISTICS + COST-BASED JOIN SEARCH

Use static rules to perform initial optimization. Then use dynamic programming to determine the best join order for tables.

→ First cost-based query optimizer

→ **Bottom-up planning** (forward chaining) using a divide-and-conquer search method

Selinger

Example: System R, early IBM DB2, most open-source DBMSs

ACCESS PATH SELECTION IN A RELATIONAL DATABASE MANAGEMENT SYSTEM
SIGMOD 1979

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” tree that minimizes the estimated amount of work to execute the plan.

SYSTEM R OPTIMIZER

Retrieve the names of people that appear on Joy's mixtape ordered by their artist id.

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

SYSTEM R OPTIMIZER

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 ORDER BY ARTIST.ID
```

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

SYSTEM R OPTIMIZER

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 ORDER BY ARTIST.ID
```

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

ARTIST: Sequential Scan

APPEARS: Sequential Scan

ALBUM: Index Look-up on NAME

SYSTEM R OPTIMIZER

Retrieve the names of people that appear on Joy's mixtape ordered by their artist id.

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 ORDER BY ARTIST.ID
```

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

Step #2: Enumerate all possible join orderings for tables

ARTIST: Sequential Scan

APPEARS: Sequential Scan

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

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ARTIST: Sequential Scan
APPEARS: Sequential Scan
ALBUM: Index Look-up on NAME

ARTIST ⋈ APPEARS ⋈ ALBUM
APPEARS ⋈ ALBUM ⋈ ARTIST
ALBUM ⋈ APPEARS ⋈ ARTIST
APPEARS ⋈ ARTIST ⋈ ALBUM
ARTIST ALBUM ⋈ APPEARS
ALBUM ARTIST ⋈ APPEARS
⋮ ⋮ ⋮

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ARTIST: Sequential Scan
APPEARS: Sequential Scan
ALBUM: Index Look-up on NAME

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

ARTIST	⋈	APPEARS	⋈	ALBUM
APPEARS	⋈	ALBUM	⋈	ARTIST
ALBUM	⋈	APPEARS	⋈	ARTIST
APPEARS	⋈	ARTIST	⋈	ALBUM
ARTIST		ALBUM	⋈	APPEARS
ALBUM		ARTIST	⋈	APPEARS
⋮		⋮		⋮

SYSTEM R OPTIMIZER

ARTIST⋈APPEARS
ALBUM

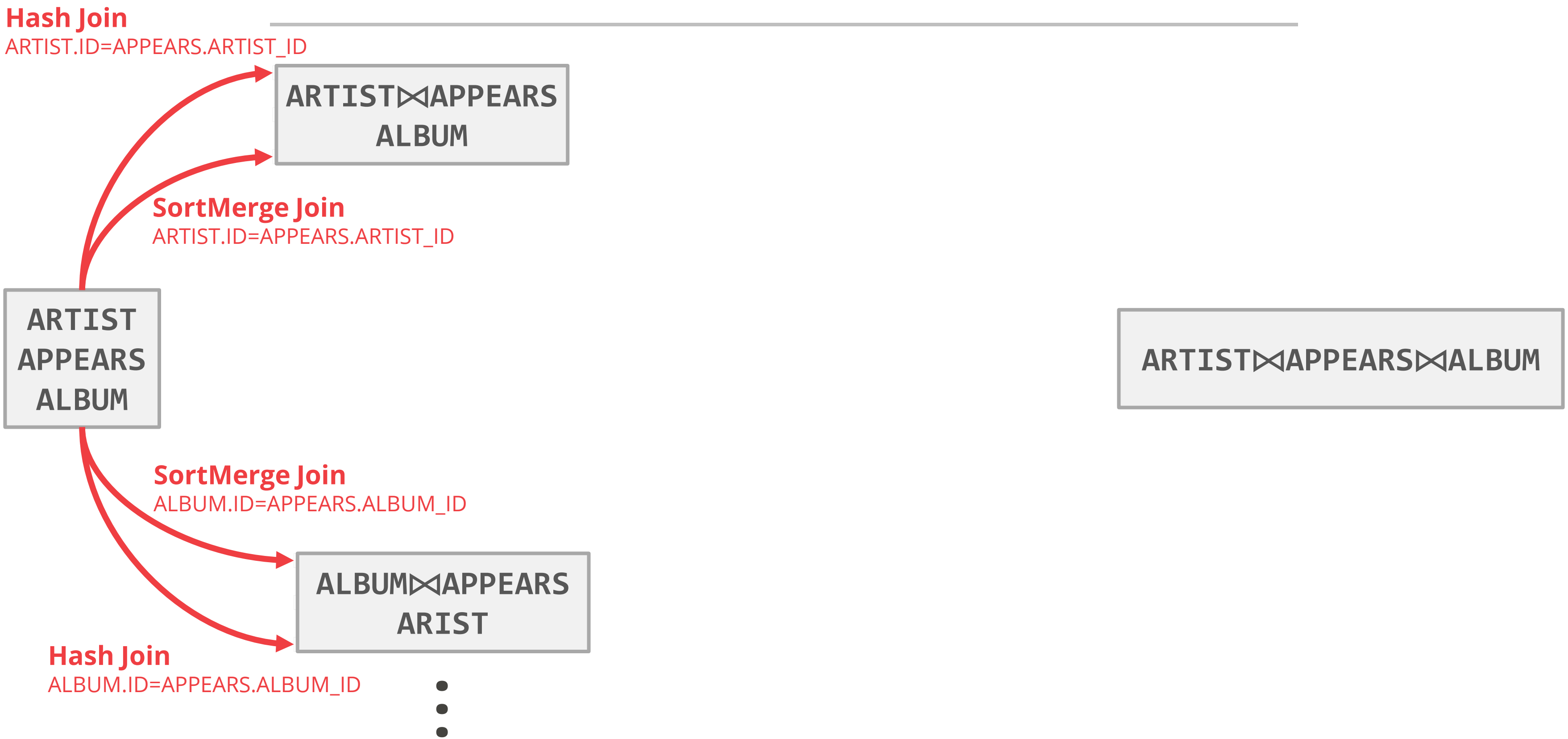
ARTIST
APPEARS
ALBUM

ARTIST⋈APPEARS⋈ALBUM

ALBUM⋈APPEARS
ARIST

⋮

SYSTEM R OPTIMIZER



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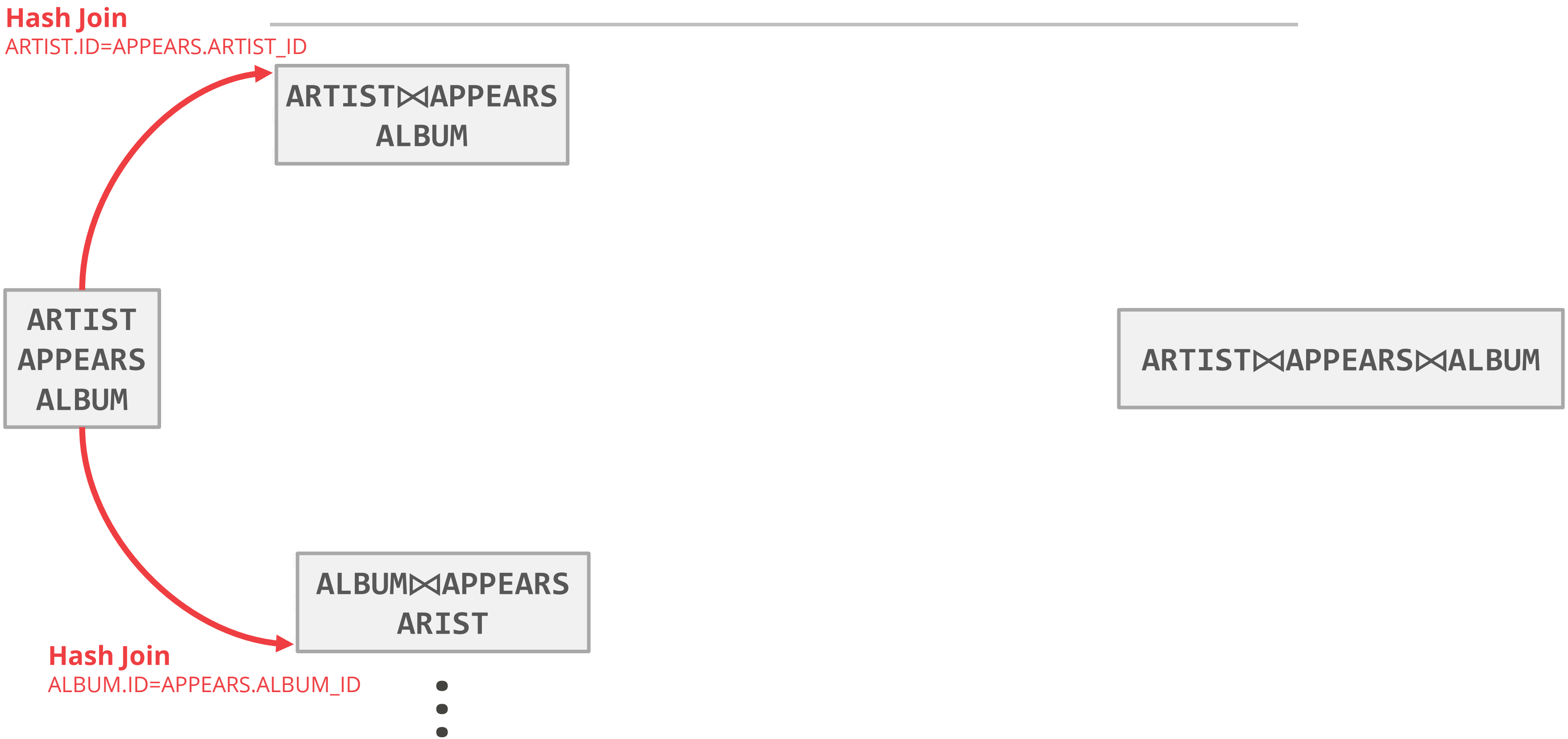

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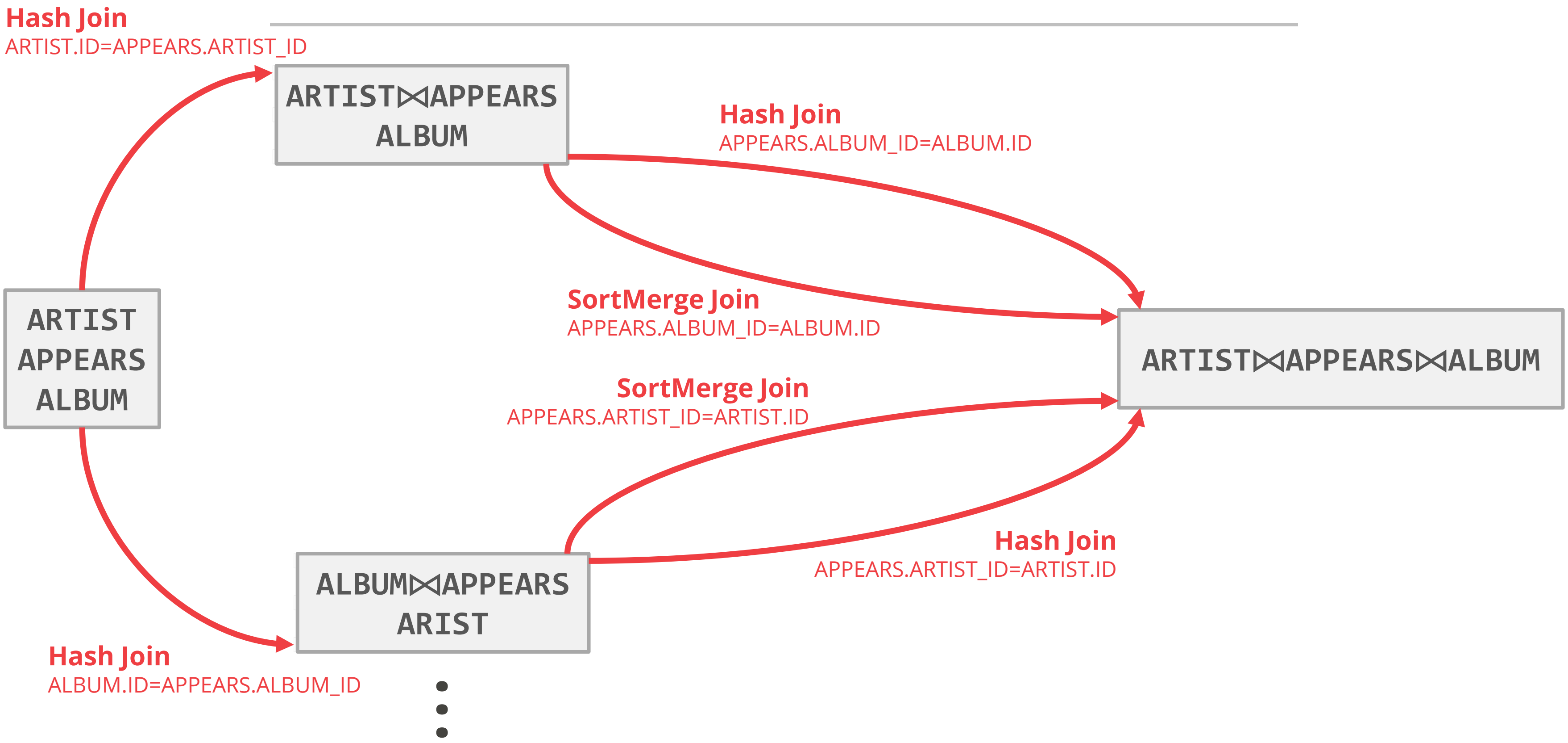

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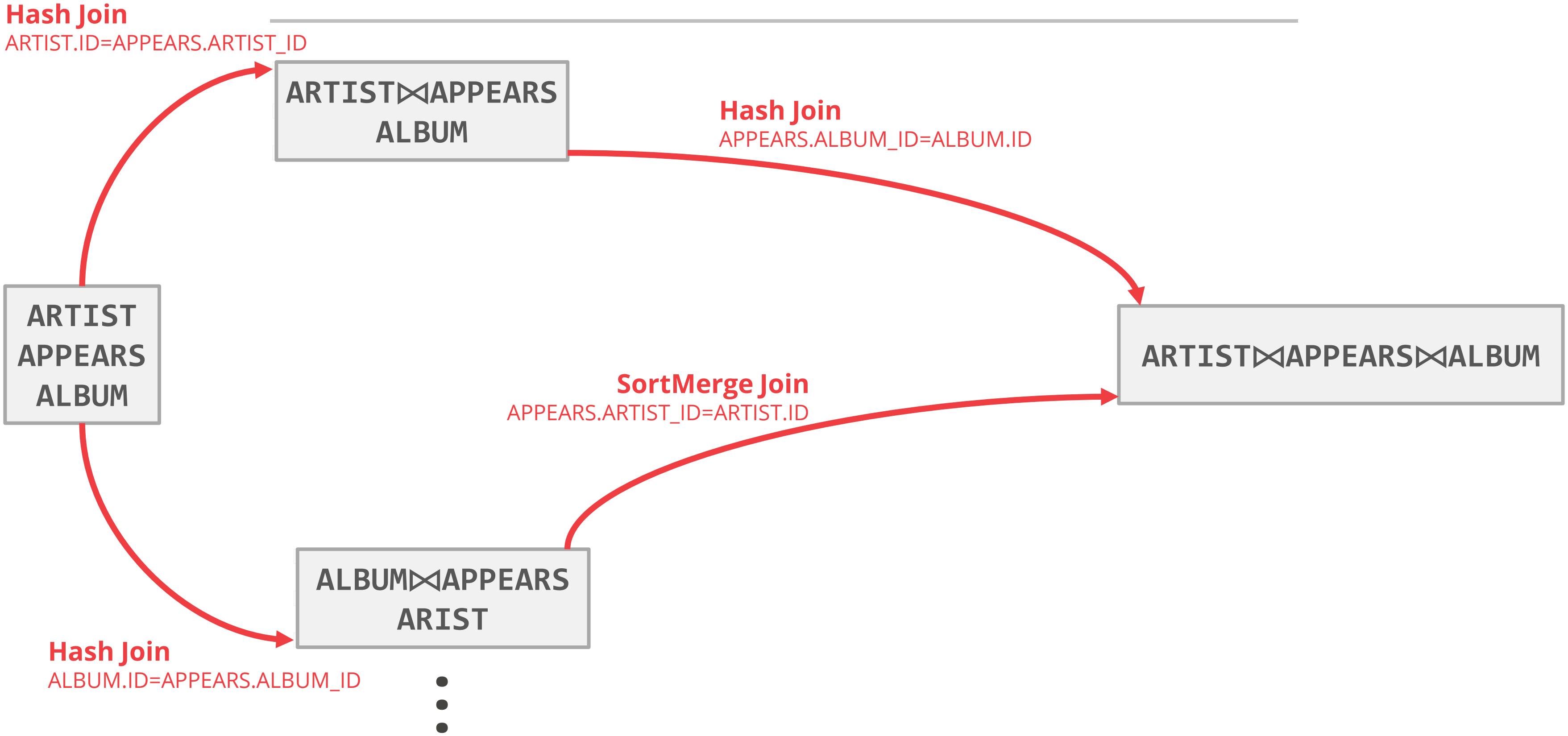
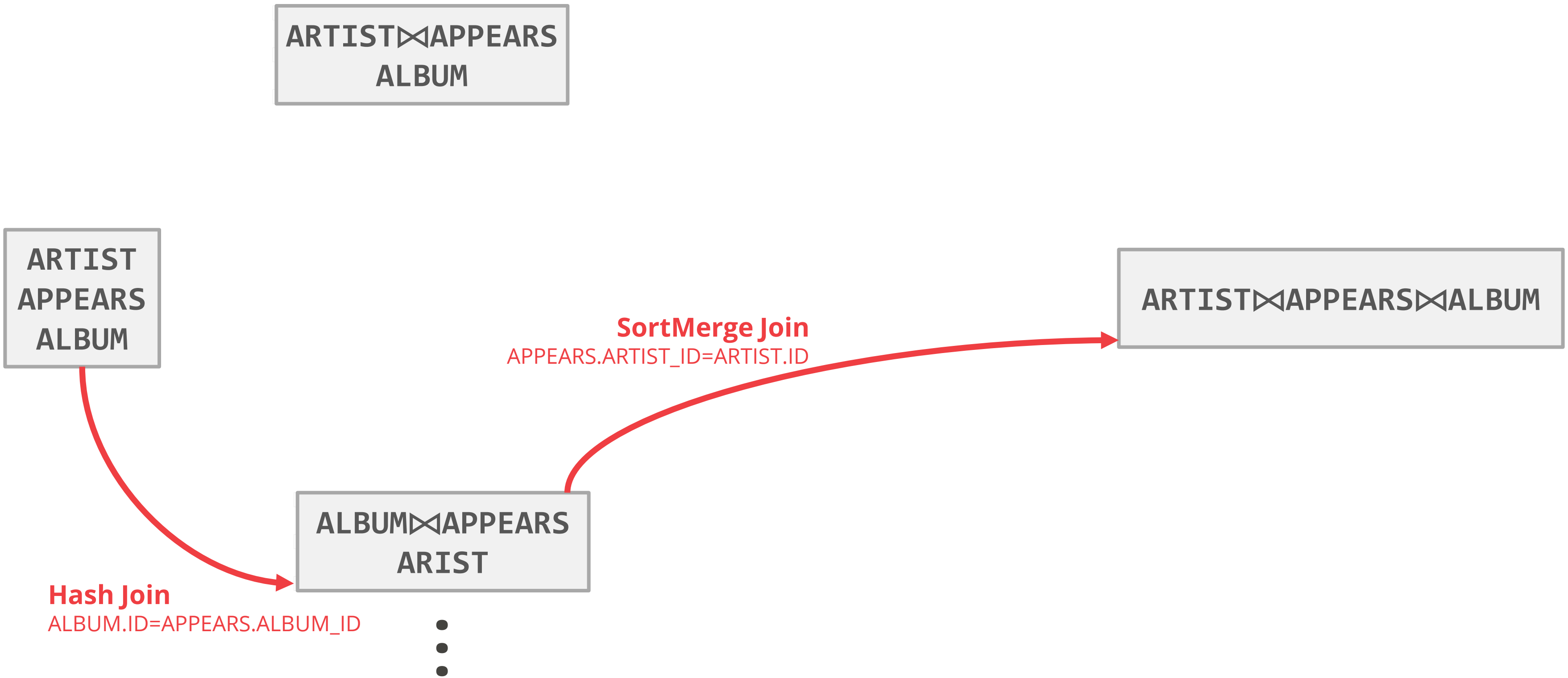


SYSTEM R OPTIMIZER



HEURISTICS + COST-BASED JOIN SEARCH

Advantages:

→ Usually finds a reasonable plan without having to perform an exhaustive search.

Disadvantages:

→ All the same problems as the heuristic-only approach.
→ Left-deep join trees are not always optimal.
→ Have to take in consideration the physical properties of data in the cost model (e.g., sort order).

RANDOMIZED ALGORITHMS

Perform a random walk over a solution space of all possible (valid) plans for a query.

Continue searching until a cost threshold is reached or the optimizer runs for a particular length of time.

Example: Postgres' genetic algorithm.

SIMULATED ANNEALING

Start with a query plan that is generated using the heuristic-only approach.

Compute random permutations of operators (e.g., swap the join order of two tables)

→ Always accept a change that reduces cost
→ Only accept a change that increases cost with some probability.
→ Reject any change that violates correctness (e.g., sort ordering)

QUERY OPTIMIZATION BY SIMULATED ANNEALING
SIGMOD 1987

POSTGRES OPTIMIZER

More complicated queries use a **genetic algorithm** that selects join orderings.

At the beginning of each round, generate different variants of the query plan.

Select the plans that have the lowest cost and permute them with other plans. Repeat.

→ The mutator function only generates valid plans.

Source: Postgres Documentation

RANDOMIZED ALGORITHMS

Advantages:

→ Jumping around the search space randomly allows the optimizer to get out of local minimums.
→ Low memory overhead (if no history is kept).

Disadvantages:

→ Difficult to determine why the DBMS may have chose a particular plan.
→ Have to do extra work to ensure that query plans are deterministic.
→ Still have to implement correctness rules.

OBSERVATION

Writing query transformation rules in a procedural language is hard and error-prone.

→ No easy way to verify that the rules are correct without running a lot of fuzz tests.

→ Generation of physical operators per logical operator is decoupled from deeper semantics about query.

A better approach is to use a declarative DSL to write the transformation rules and then have the optimizer enforce them during planning.

OPTIMIZER GENERATORS

Use a rule engine that allows transformations to modify the query plan operators.

The physical properties of data is embedded with the operators themselves.

Choice #1: Stratified Search

→ Planning is done in multiple stages

Choice #2: Unified Search

→ Perform query planning all at once.

STRATIFIED SEARCH

First rewrite the logical query plan using transformation rules.

→ The engine checks whether the transformation is allowed before it can be applied.
→ Cost is never considered in this step.

Then perform a cost-based search to map the logical plan to a physical plan.

STARBURST OPTIMIZER

Better implementation of the System R optimizer that uses declarative rules.

Stage #1: Query Rewrite

→ Compute a SQL-block-level, relational calculus-like representation of queries.

Stage #2: Plan Optimization

→ Execute a System R-style dynamic programming phase once query rewrite has completed.

Example: Latest version of IBM DB2

Lohman

GRAMMAR-LIKE FUNCTIONAL RULES FOR REPRESENTING QUERY OPTIMIZATION ALTERNATIVES
SIGMOD 1988

STARBURST OPTIMIZER

Advantages:

→ Works well in practice with fast performance.

Disadvantages:

→ Difficult to assign priorities to transformations

→ Some transformations are difficult to assess without computing multiple cost estimations.

→ Rules maintenance is a huge pain.

UNIFIED SEARCH

Unify the notion of both logical-logical and logical-physical transformations.

→ No need for separate stages because everything is transformations.

This approach generates a lot more transformations so it makes heavy use of memoization to reduce redundant work.

VOLCANO OPTIMIZER

General purpose cost-based query optimizer, based on equivalence rules on algebras.

→ Easily add new operations and equivalence rules.

→ Treats physical properties of data as first-class entities during planning.

→ **Top-down approach** (backward chaining) using branch-and-bound search.

Graefe

Example: NonStop SQL

THE CASCADES FRAMEWORK FOR QUERY OPTIMIZATION
IEEE Data Engineering Bulletin 1995

VOLCANO OPTIMIZER

VOLCANO OPTIMIZER

Start with a logical plan of what we want the query to be.

VOLCANO OPTIMIZER

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```
ARTIST⋈APPEARS⋈ALBUM
ORDER-BY(ARTIST.ID)
```

VOLCANO OPTIMIZER

Start with a logical plan of what we want the query to be.

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)

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ARTIST⋈APPEARS⋈ALBUM
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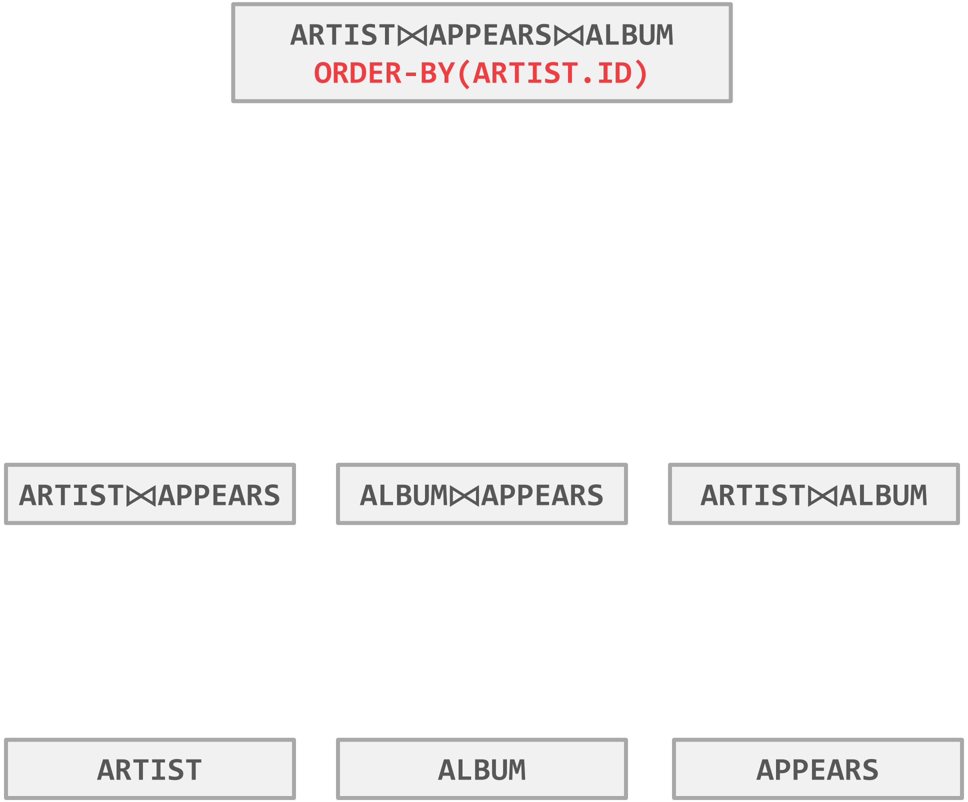

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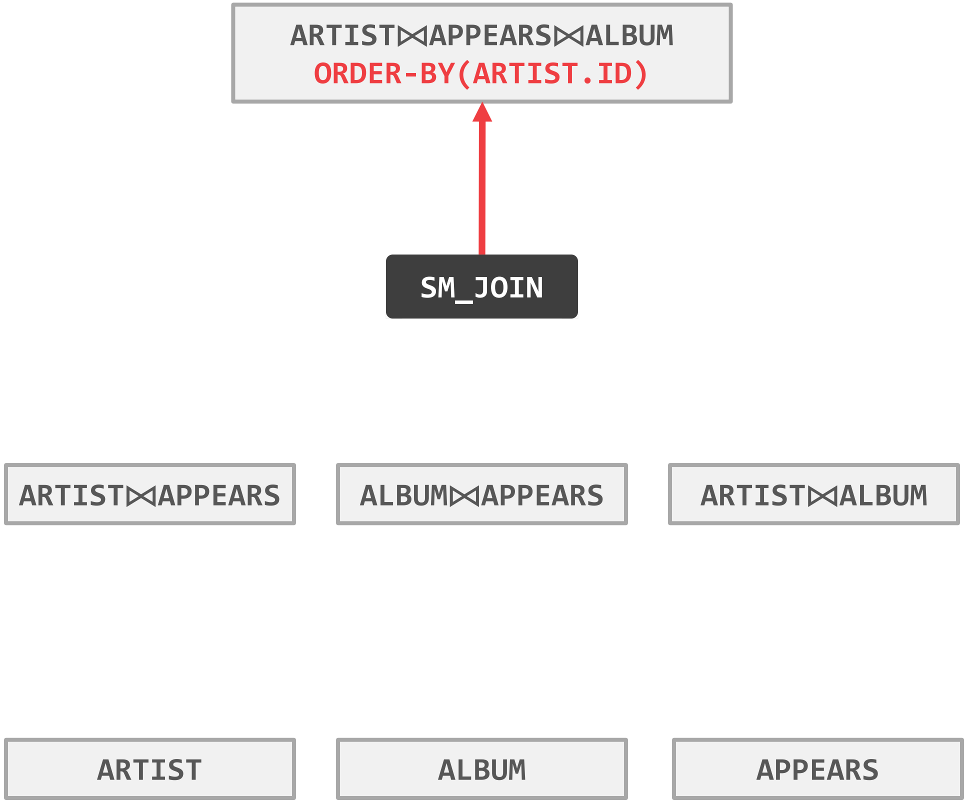

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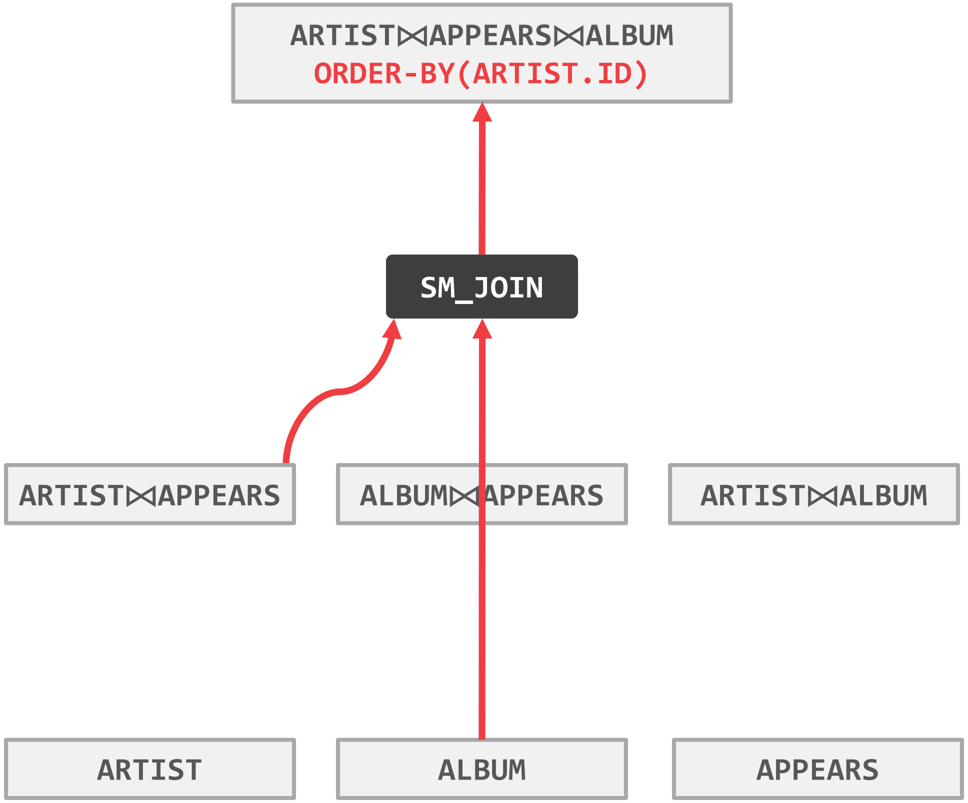

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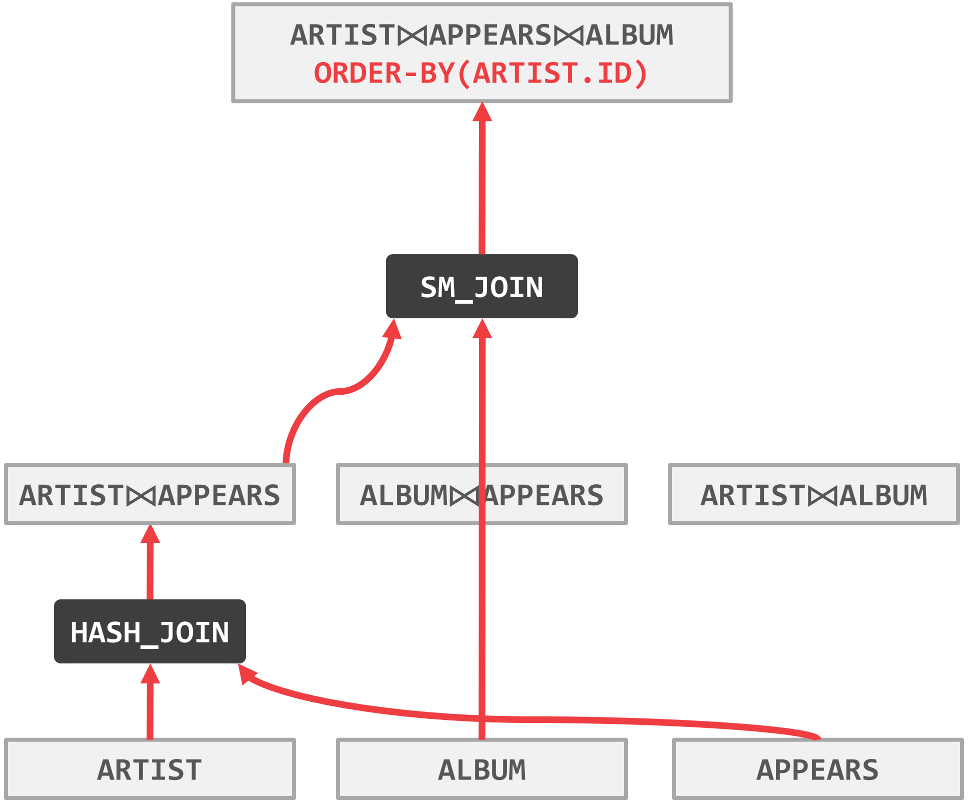

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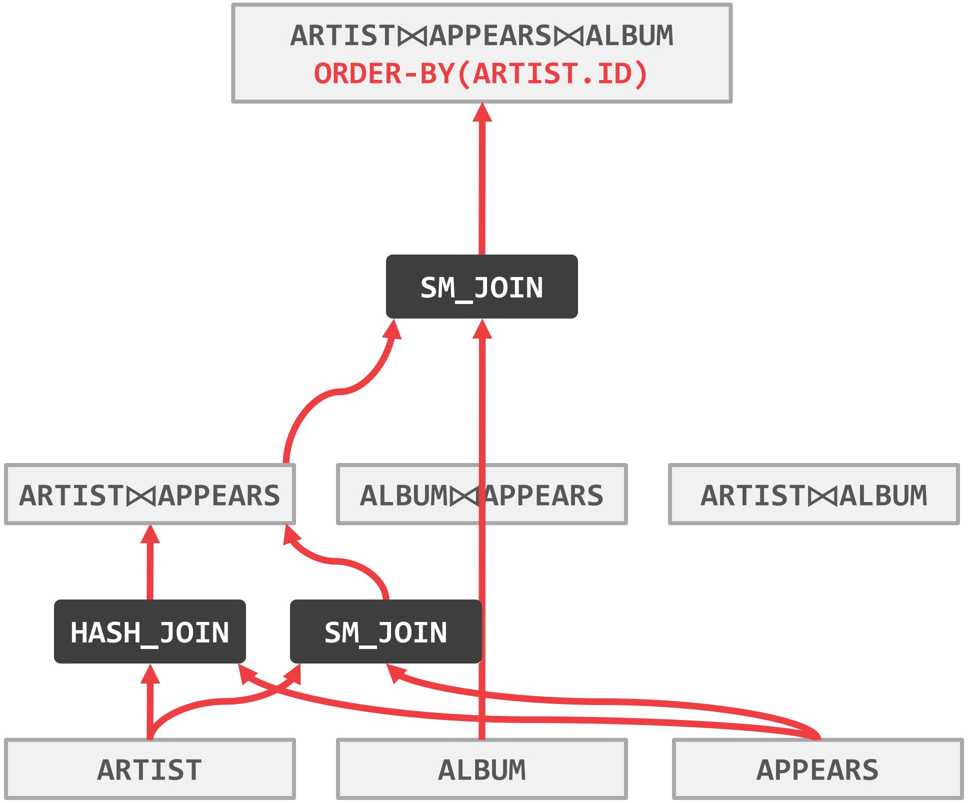

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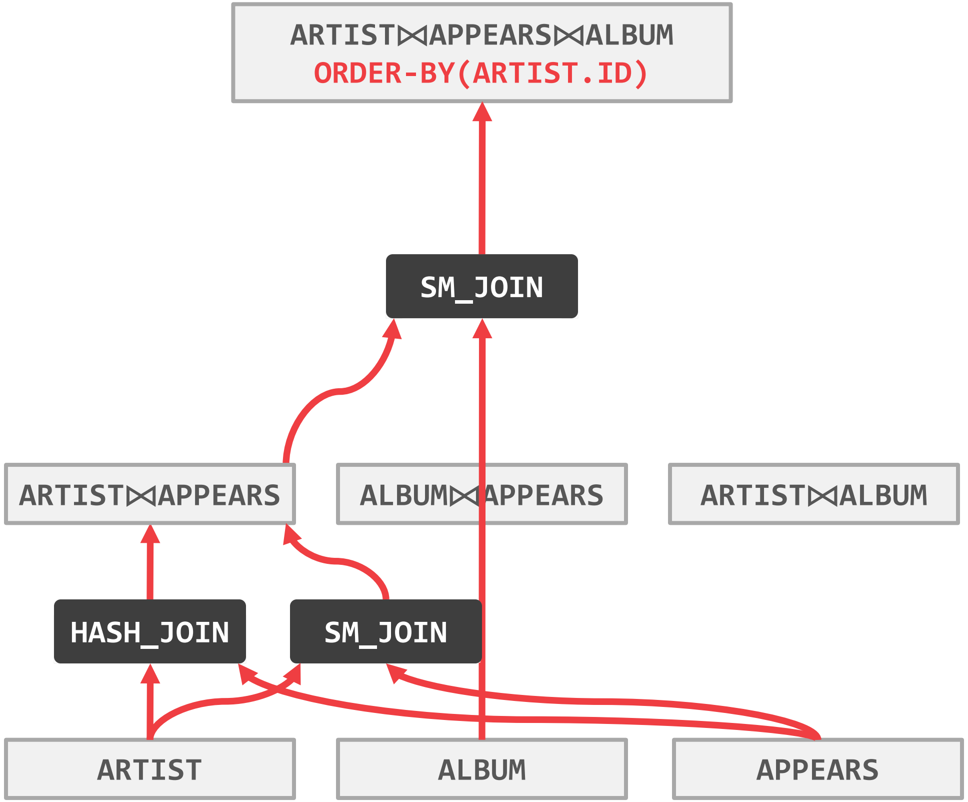
Can create "enforcer" rules that require input to have certain properties.



VOLCANO OPTIMIZER

Start with a logical plan of what we want the query to be.

Invoke rules to create new nodes and traverse tree.

→ **Logical-Logical:**
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→ **Logical-Physical:**
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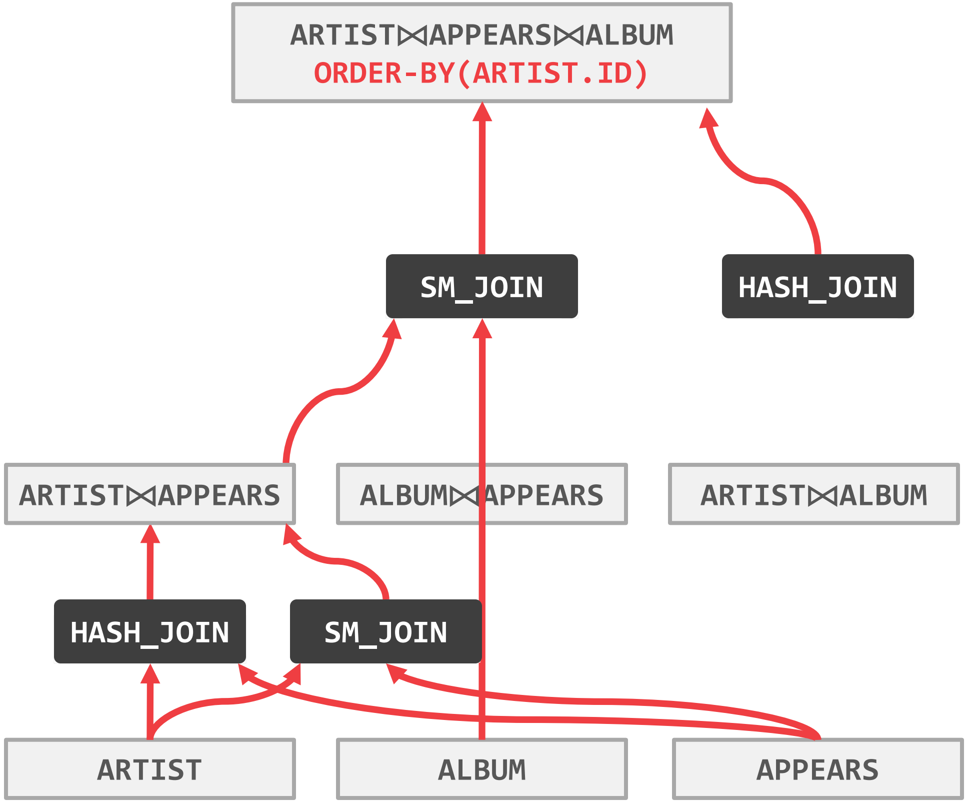

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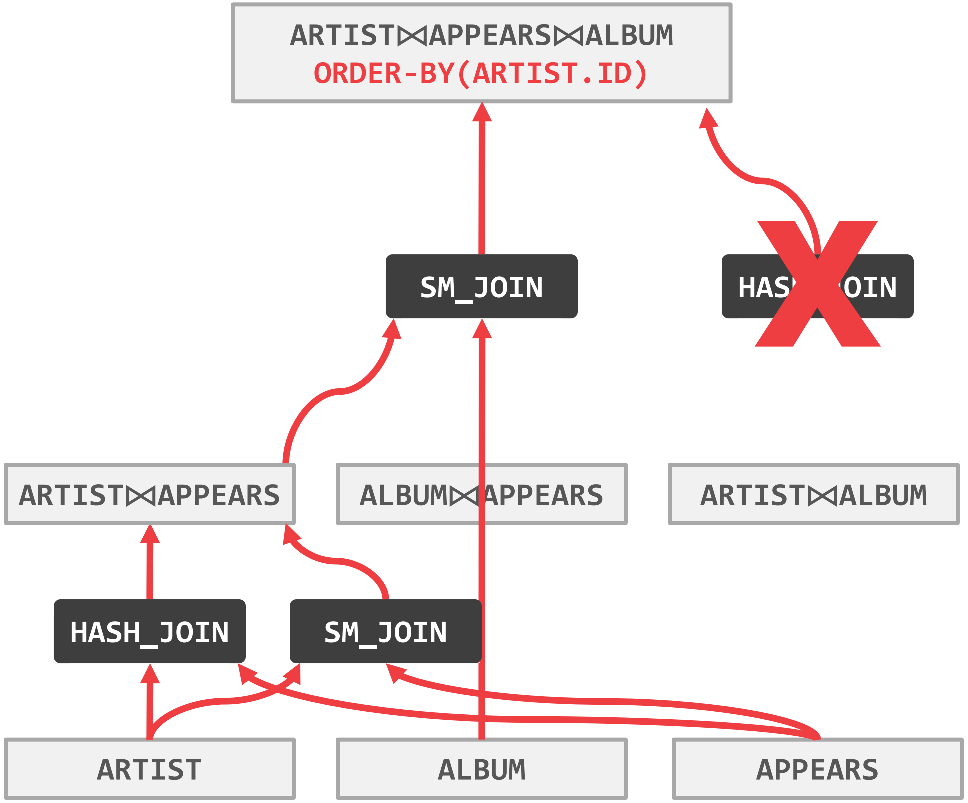

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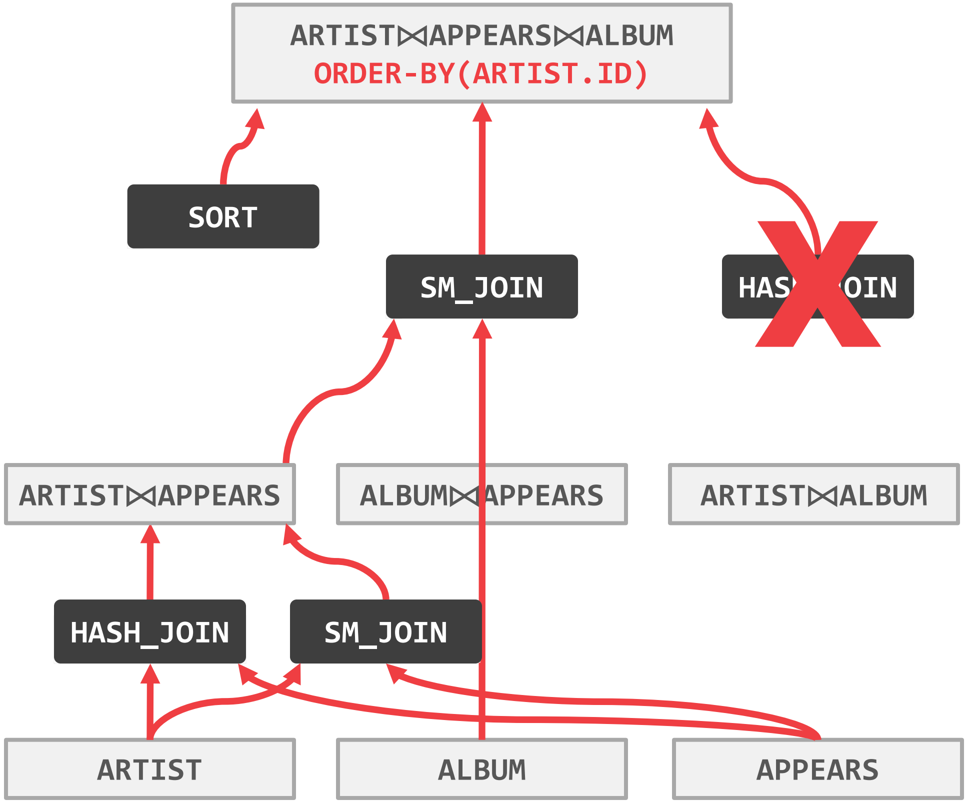

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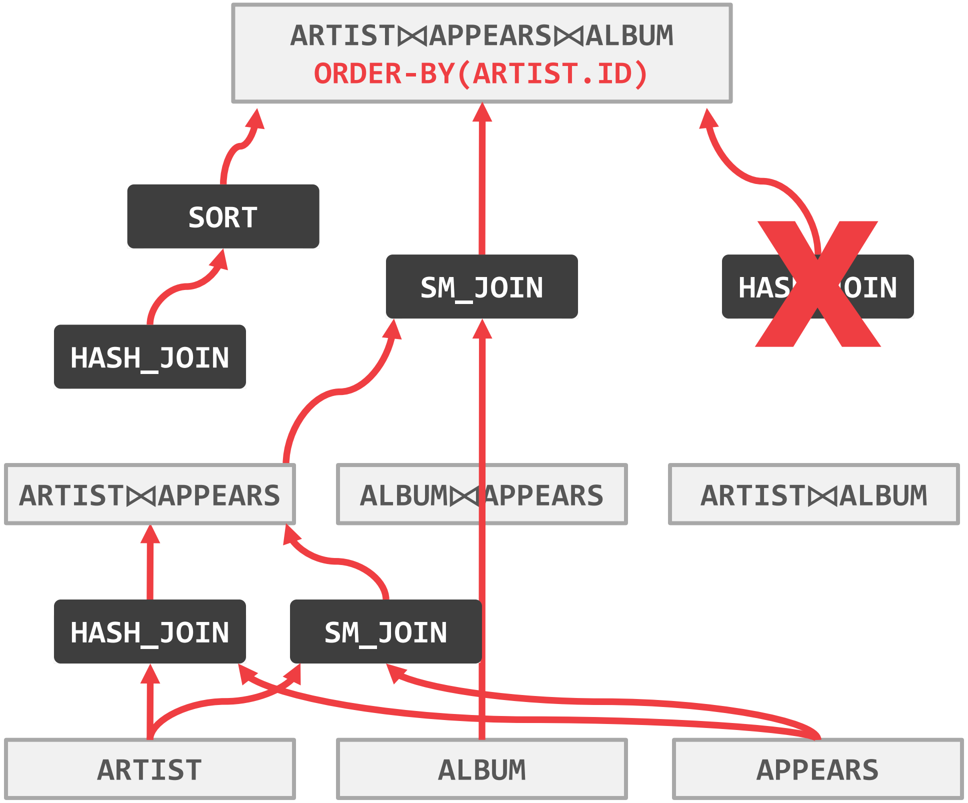

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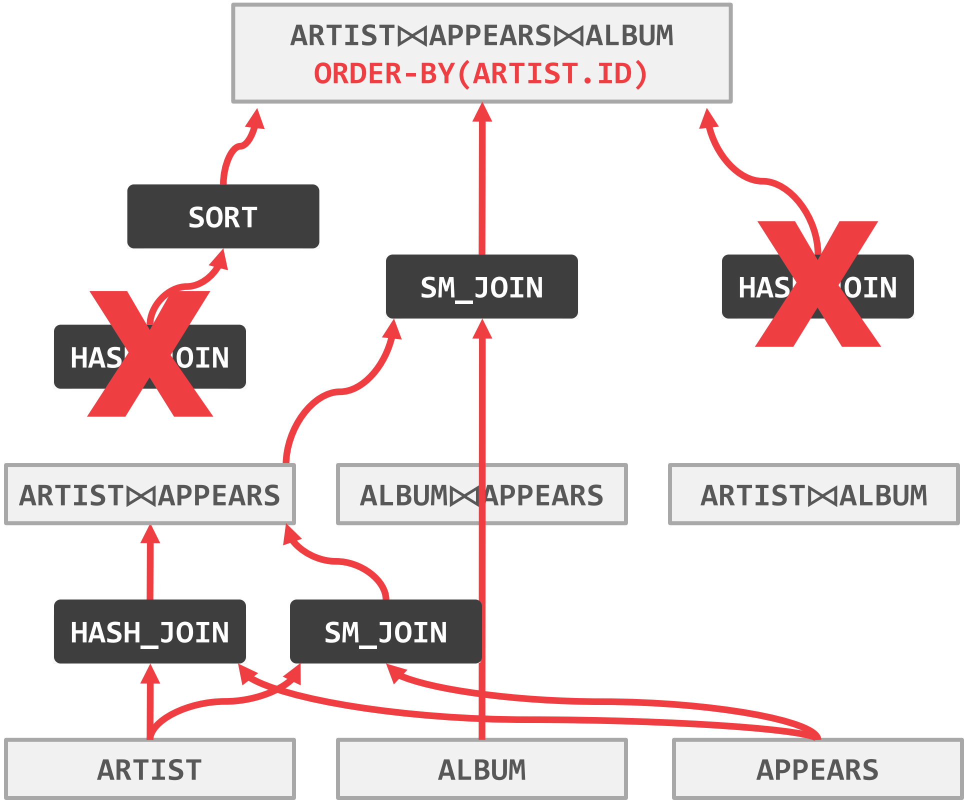

VOLCANO OPTIMIZER

The optimizer needs to enumerate all possible transformations without repeating.

Go from logical to physical plan as fast as possible, then try alternative plans.

→ Use a top-down rules engine that performs branch-and-bound pruning.
→ Use memoization to cache equivalent operators.

CASCADES OPTIMIZER

Object-oriented implementation of the Volcano query optimizer.

Simplistic expression re-writing can be through a direct mapping function rather than an exhaustive search.

Graefe

Example: SQL Server, Greenplum’s Orca, and Apache Calcite.

THE CASCADES FRAMEWORK FOR QUERY OPTIMIZATION
IEEE Data Engineering Bulletin 1995

QUERY OPTIMIZATION STRATEGIES

Choice #1: Heuristics
→ INGRES, Oracle (until mid 1990s)

Choice #2: Heuristics + Cost-based Join Search
→ System R, early IBM DB2, most open-source DBMSs

Choice #3: Randomized Search
→ Academics in the 1980s, current Postgres

Choice #4: Stratified Search
→ IBM's STARBURST (late 1980s), current IBM DB2 + Oracle

Choice #5: Unified Search
→ Volcano/Cascades in 1990s, now SQL Server + Greenplum

ADAPTIVE QUERY PROCESSING

INGRES could modify a query plan on a per tuple basis.

→ Each tuple could join with relations in a different order and using a different algorithm.

Adaptive processing removes the distinction between planning and execution phases.

→ But I don't think any DBMS actually does this...

PARTING THOUGHTS

Query optimization is **hard**.

→ This is why it wasn't implemented in any of the NoSQL systems.

The research literature suggests that there is no difference in quality between bottom-up vs. top-down search strategies.

All of this hinges on a good cost model.
A good cost model needs good statistics.

NEXT CLASS

Cost Models
Working in a large code base