Lecture 22: Cascades Framework

CREATING THE NEXT®

Today's Agenda

Recap

Optimization Search 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), now IBM DB2 + Oracle
- **Choice 5: Unified Search**
  - Volcano/Cascades in 1990s, now MSSQL + Greenplum

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.

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.

Top-Down vs. Bottom-Up

- **Top-down Optimization**
  - Start with the final outcome that you want, and then work down the tree to find the optimal plan that gets you to that goal.
  - Example: Volcano, Cascades
- **Bottom-up Optimization**
  - Start with nothing and then build up the plan to get to the final outcome that you want.
  - Examples: System R, Starburst

Logical Query Optimization

Logical Query 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.

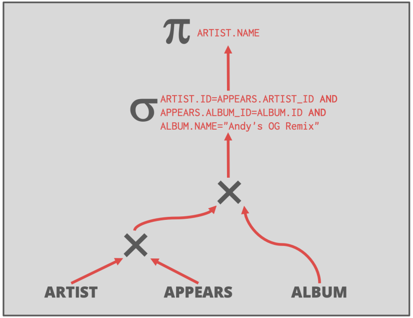
Logical Query Optimization

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

Split Conjunctive 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"
```

Decompose predicates into their simplest forms to make it easier for the optimizer to move them around.



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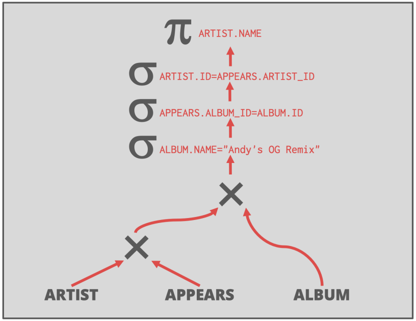

Predicate Pushdown

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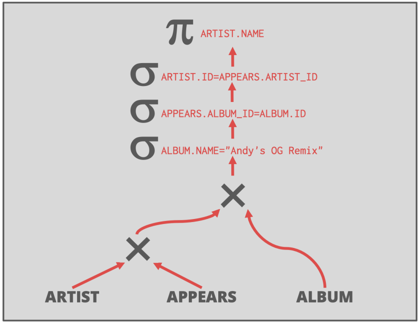
Move the predicate to the lowest point in the plan after Cartesian products.



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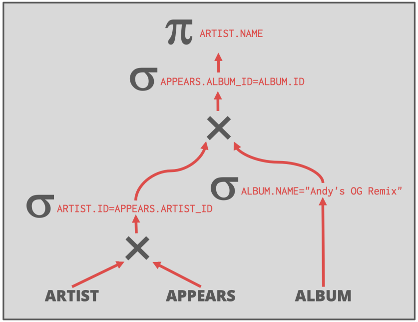

Replace Cartesian Products with Joins

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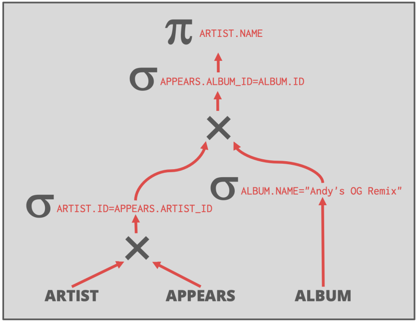
Replace all Cartesian Products with inner joins using the join predicates.



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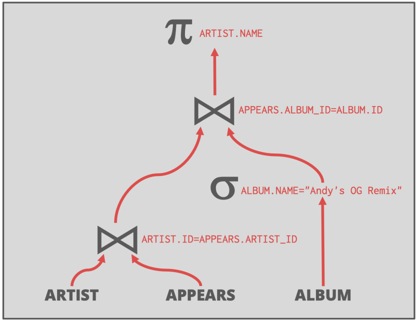

Projection Pushdown

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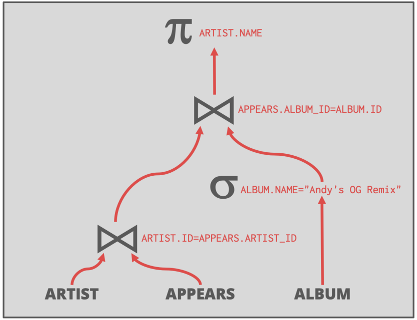
Eliminate redundant attributes before pipeline breakers to reduce materialization cost.



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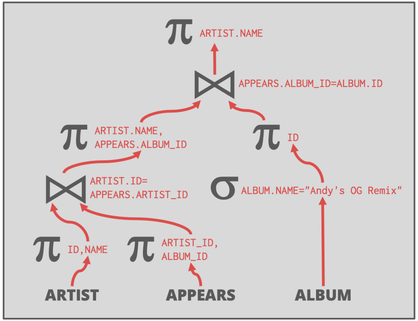

Physical Query Optimization

Physical Query Optimization

- Transform a query plan's logical operators into physical operators.
  - Add more execution information
  - Select indexes / access paths
  - Choose operator implementations
  - Choose when to materialize (*i.e.*, temp tables).
- This stage must support **cost model estimates**.

Observation

- All the queries we have looked at so far have had the following properties:
  - Equi/Inner Joins
  - Simple join predicates that reference only two tables.
  - No cross products
- Real-world queries are much more complex:
  - Outer Joins
  - Semi-joins
  - Anti-joins

Reordering: Limitations

- No valid reordering is possible.
- The A⟕B operator is not commutative with B⟗C.
  - The DBMS does not know the value of B.val (may be *NULL*) until after computing the join with A.
- Reference

```
SELECT * FROM
  A LEFT OUTER JOIN B
  ON A.id = B.id
  FULL OUTER JOIN C
  ON B.val = C.id;
```

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Plan Enumeration

- **Approach 1: Transformation**
  - Modify some part of an existing query plan to transform it into an alternative plan that is equivalent.
- **Approach 2: Generative**
  - Assemble building blocks to generate a query plan (similar to dynamic programming).
- Reference

Dynamic Programming Optimizer

- Model the query as a hypergraph and then incrementally expand to enumerate new plans.
- Algorithm Overview:
  - Iterate connected sub-graphs and incrementally add new edges to other nodes to complete query plan.
  - Use rules to determine which nodes the traversal is allowed to visit and expand.
- Reference

Cascades Optimizer

- Object-oriented implementation of the Volcano query optimizer.
- Materialize transformations on the fly (rather than pre-generate them all at once).
- Unlike Volcano, restricts the set of transformations to constrain the search space.
- Supports simplistic expression re-writing through a direct mapping function rather than an **exhaustive search**.

Cascades Optimizer

Cascades Optimizer: Design Decisions

- Optimization tasks as data structures.
- Rules to place **property enforcers** (*e.g.*, sorting order).
- Ordering of transformations by priority. Dynamically adjust ordering as we traverse the search tree.
- Predicates are first class citizens (same as logical/physical operators).

Cascades – Expressions

- An **expression** is an **operator** with zero or more input expressions.
- **Logical Expression**: $(A \bowtie B) \bowtie C$
- **Physical Expression**: $(A_{Seq} \bowtie_{HJ} B_{Seq}) \bowtie_{NL} C_{Idx}$

```
SELECT * FROM A
  JOIN B ON A.id = B.id
  JOIN C ON C.id = A.id;
```

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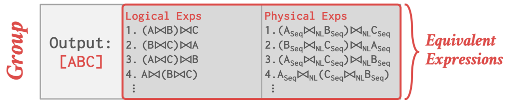
Cascades – Groups

- A **group** is a set of **logically equivalent** logical and physical expressions that produce the same output.
  - All logical forms of an expression.
  - All physical expressions that can be derived from selecting the allowable physical operators for the corresponding logical forms.



Cascades – Multi-Expression

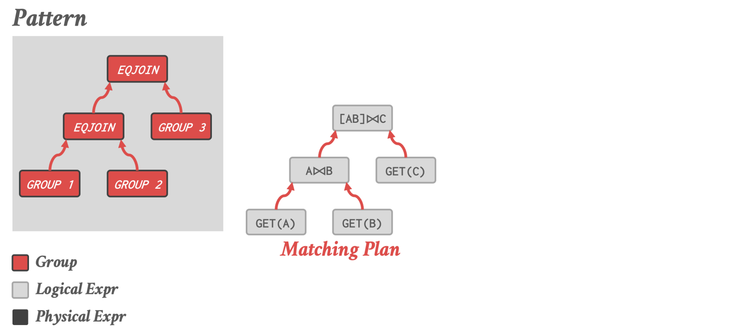
- Instead of explicitly instantiating all possible expressions in a group, the optimizer implicitly represents redundant expressions in a group as a **multi-expression**.
  - This reduces the number of transformations, storage overhead, and repeated cost estimations.
  - We can make decisions about whether to traverse [AB] first vs. [C] first.

Output: [ABC]	Logical Multi-Exps	Physical Multi-Exps
	1. $[AB]\bowtie[C]$	1. $[AB]\bowtie_{SM}[C]$
	2. $[BC]\bowtie[A]$	2. $[AB]\bowtie_{HJ}[C]$
	3. $[AC]\bowtie[B]$	3. $[AB]\bowtie_{NL}[C]$
	4. $[A]\bowtie[BC]$	4. $[BC]\bowtie_{SM}[A]$
	⋮	⋮

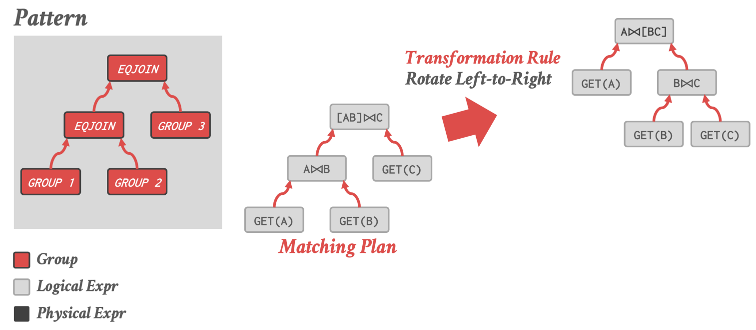
Cascades – Rules

- A **rule** is a transformation of an expression to a logically equivalent expression.
  - **Transformation Rule:** Logical to Logical
  - **Implementation Rule:** Logical to Physical
- Each rule is represented as a pair of attributes:
  - **Pattern:** Defines the structure of the logical expression that can be applied to the rule.
  - **Substitute:** Defines the structure of the result after applying the rule.

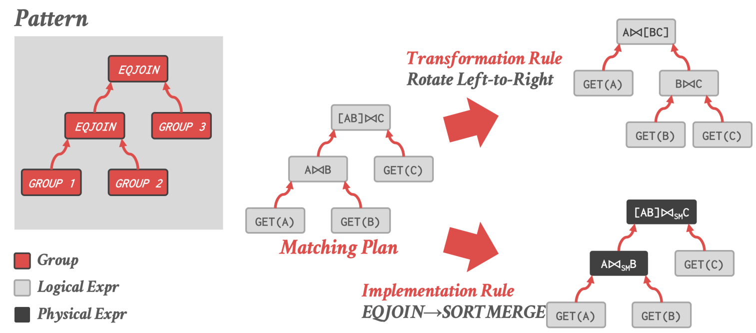
Cascades – Rules



Cascades – Rules



Cascades – Rules



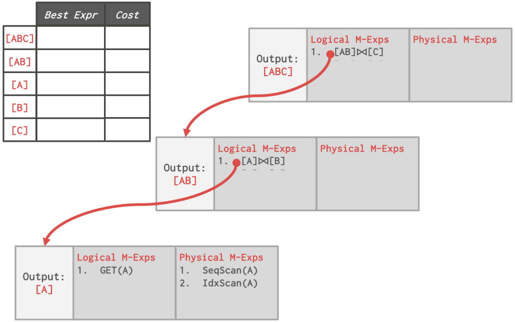
Cascades – Memo Table

- Stores all previously explored alternatives in a compact graph structure / hash table.
- Equivalent operator trees and their corresponding plans are stored together in groups.
- Provides memoization, duplicate detection, and property + cost management.

Principle of Optimality

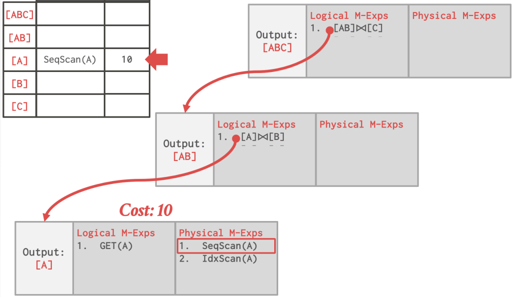
- Every sub-plan of an optimal plan is itself optimal.
- This allows the optimizer to restrict the search space to a smaller set of expressions.
  - The optimizer never has to consider a plan containing sub-plan $P1$ that has a greater cost than equivalent plan $P2$ with the same physical properties.
  - Reference

Cascades – Memo Table



Cascades – Memo Table

	Best Expr	Cost
[ABC]		
[AB]		
[A]	SeqScan(A)	10
[B]		
[C]		



Cascades – Memo Table

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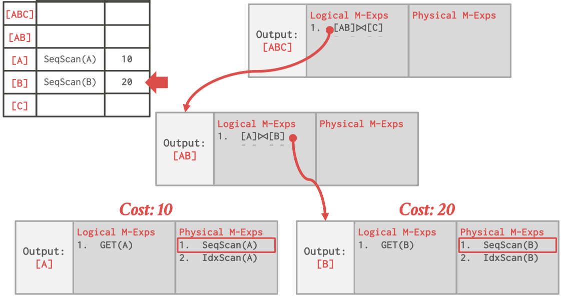

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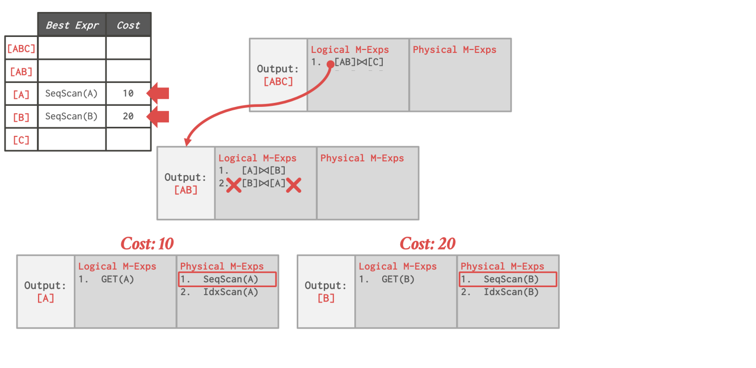

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Cascades – Memo Table

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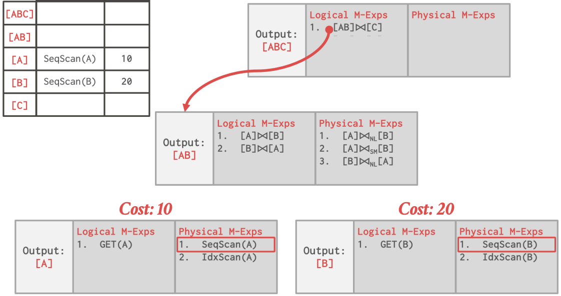
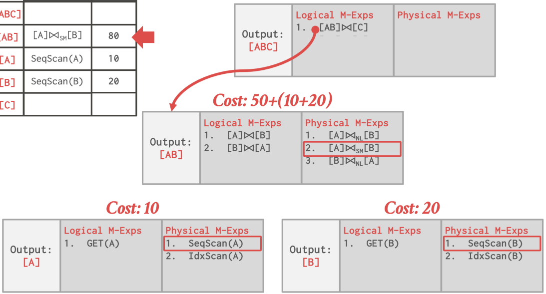


Cascades – Memo Table

	Best Expr	*Cost*
[ABC]		
[AB]	$[A]\bowtie_{SM}[B]$	80
[A]	SeqScan(A)	10
[B]	SeqScan(B)	20
[C]		



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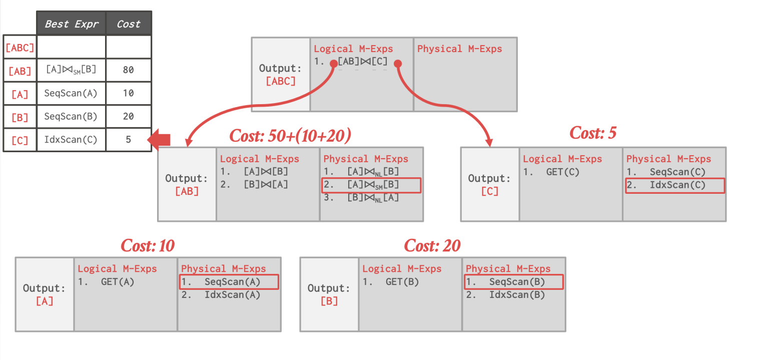
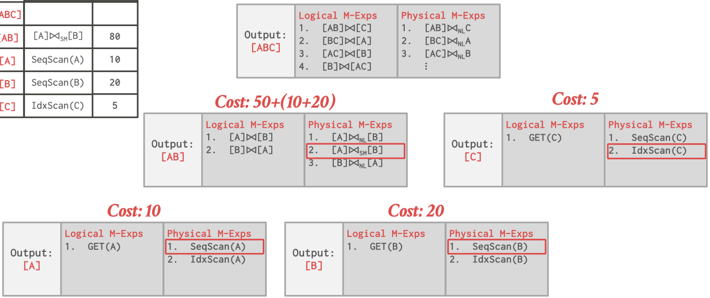


Cascades – Memo Table

	Best Expr	*Cost*
[ABC]		
[AB]	[A]$\bowtie_{SM}$[B]	80
[A]	SeqScan(A)	10
[B]	SeqScan(B)	20
[C]	IdxScan(C)	5



Search Termination

- **Approach 1: Wall-clock Time**
  - Stop after the optimizer runs for some length of time.
- **Approach 2: Cost Threshold**
  - Stop when the optimizer finds a plan that has a lower cost than some threshold.
- **Approach 3: Transformation Exhaustion**
  - Stop when there are no more ways to transform the target plan. Usually done per group.

Case Studies

Cascades: Implementations

- **Approach 1: Standalone Optimizer Generator**
  - Wisconsin OPT++ (1990s)
  - Portland State Columbia (1990s)
  - Pivotal Orca (2010s)
  - Apache Calcite (2010s)
- **Approach 2: Integrated**
  - Microsoft SQL Server (1990s)
  - Tandem NonStop SQL (1990s)
  - Clustrix (2000s)
  - CMU Peloton (2010s – RIP)

Pivotal Orca

- Standalone Cascades (Optimization-as-a-service).
- Reference
  - Originally written for Greenplum.
  - Extended to support HAWQ.
- A DBMS can use Orca by implementing API to send catalog + stats + logical plans and then retrieve physical plans.
- Supports multi-threaded search.

Orca – Engineering

- **Issue 1: Remote Debugging**
  - Automatically dump the state of the optimizer (with inputs) whenever an error occurs.
  - The dump is enough to put the optimizer back in the exact same state later for further debugging.
- **Issue 2: Optimizer Accuracy**
  - Automatically check whether the ordering of the estimate cost of two plans matches their actual execution cost.

Apache Calcite

- Standalone extensible query optimization framework for data processing systems.
  - Support for pluggable query languages, cost models, and rules.
  - Does not distinguish between logical and physical operators. Physical properties are provided as annotations.
- Reference
- Originally part of LucidDB.

MemSQL Optimizer

- **Rewriter**
  - Logical-to-logical transformations with access to the cost-model.
- **Enumerator**
  - Logical-to-physical transformations.
  - Mostly join ordering.
- **Planner**
  - Convert physical plans back to SQL.
  - Contains MemSQL-specific commands for moving data.
- Reference

Conclusion

Parting Thoughts

- Cascades
  - Optimization tasks as data structures.
  - Rules to place **property enforcers** (*e.g.*, sorting order).
  - Ordering of transformations by priority.
  - Predicates are first class citizens (same as logical/physical operators).
- All of this relies on a good **cost model**.
- A good cost model needs good statistics.

Next Class

- Non-Traditional Query Optimization Techniques