CS 6530: Advanced Database Systems Fall 2023

Lecture 14
Query optimization

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SCHOOL OF COMPUTING
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So, what is query optimization and how does it work?

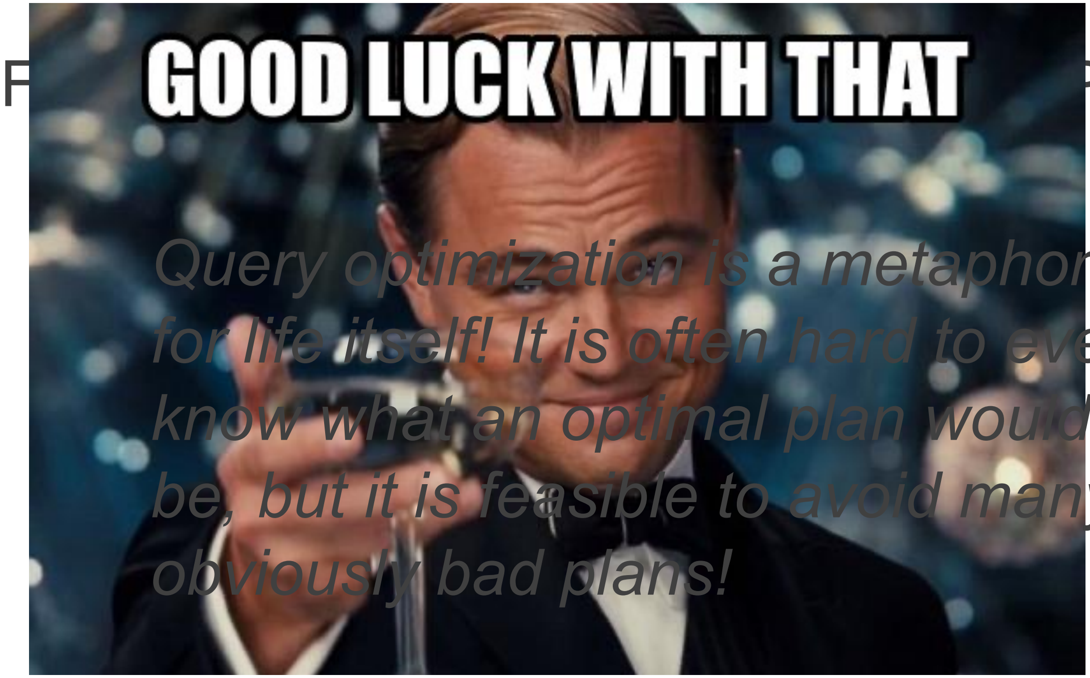
Meet Query Optimization

Basic Idea: A given LQP could have several possible PQPs with very different runtime performance

Goal (Ideal): Get the optimal (fastest) PQP for a given LQP

Goal (Realistic): F Ps!

Jeff Naughton

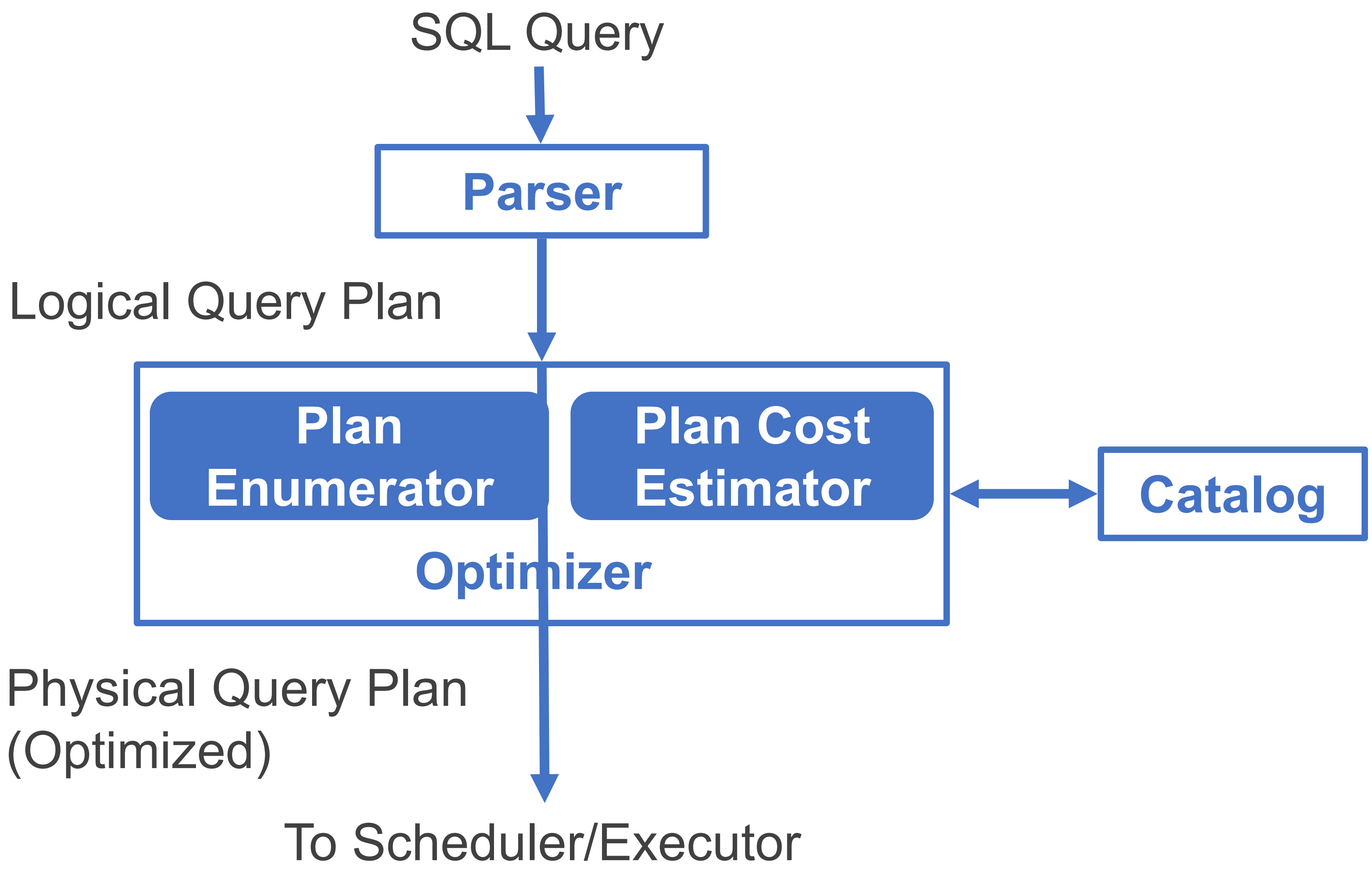


Query optimization is a metaphor for life itself! It is often hard to even know what an optimal plan would be, but it is feasible to avoid many obviously bad plans!

Query Optimization

- Overview of Query Optimizer
- Physical Query Plan (PQP)
  - Concept: Pipelining
  - Mechanism: Iterator Interface
- Enumerating Alternative PQPs
  - Logical: Algebraic Rewrites
  - Physical: Choosing Phy. Op. Impl.
- Costing PQPs
- Materialized Views

Overview of Query Optimizer



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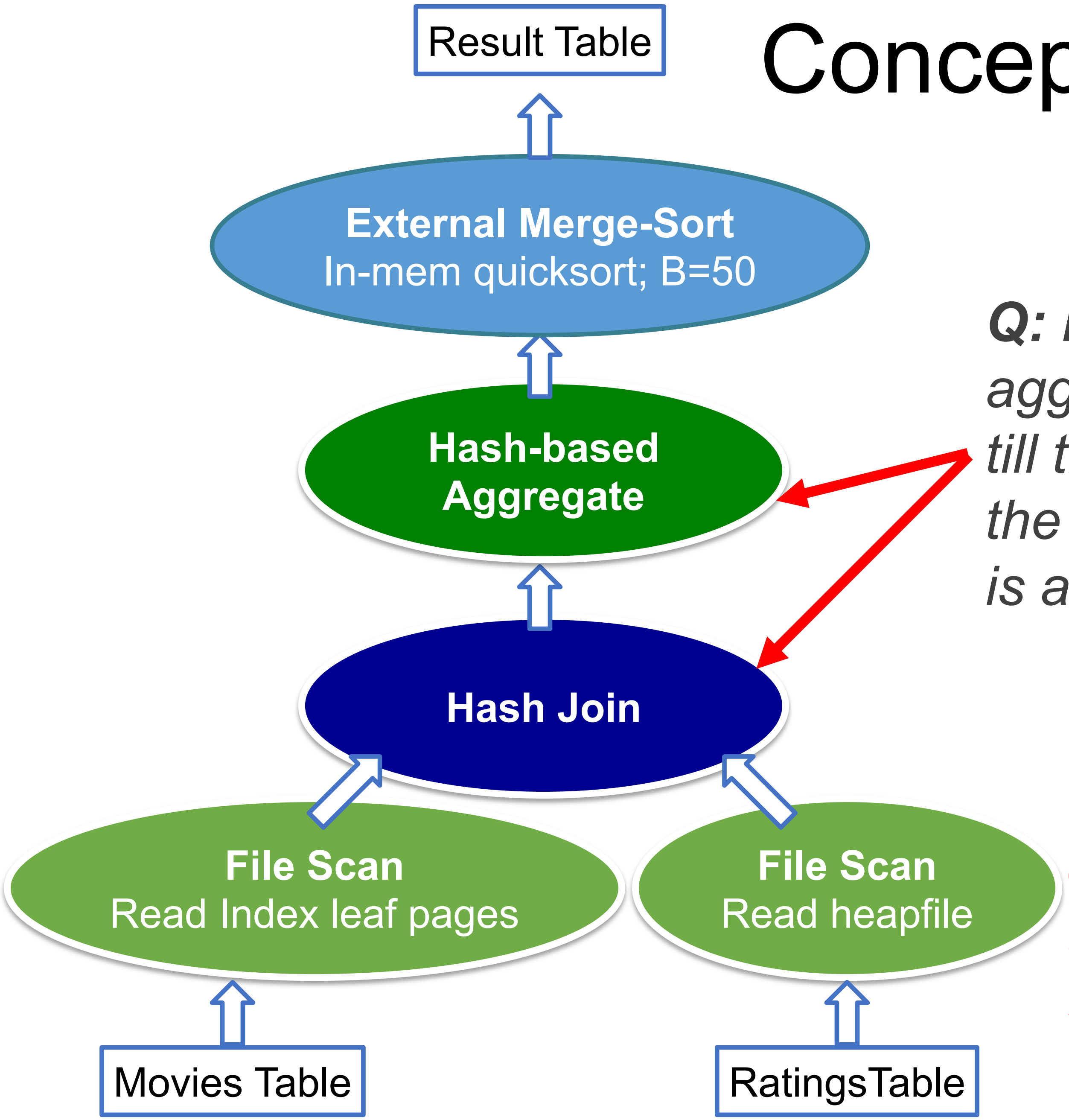
Concept: Pipelining



***Q:** Does the hash-based aggregate have to wait till the entire output of the "upstream" hash join is available?*

No! We can "**pipeline**" the output of the join – pass on a join output tuple as soon as it is obtained!

Concept: Pipelining

Basic Idea: Do not force "downstream" physical operators to wait till the entire output is available

Benefits: Display output to the user incrementally
<u>CPU Parallelism in multi-core systems!</u>

Tuples

File Scan

Hash Join

Hash-based Aggregate

Concept: Pipelining

- Crucial for PQPs with workflow of many phy. ops.
- Common feature of almost all RDBMSs
- Works for many operators: SCAN, HASH JOIN, etc.

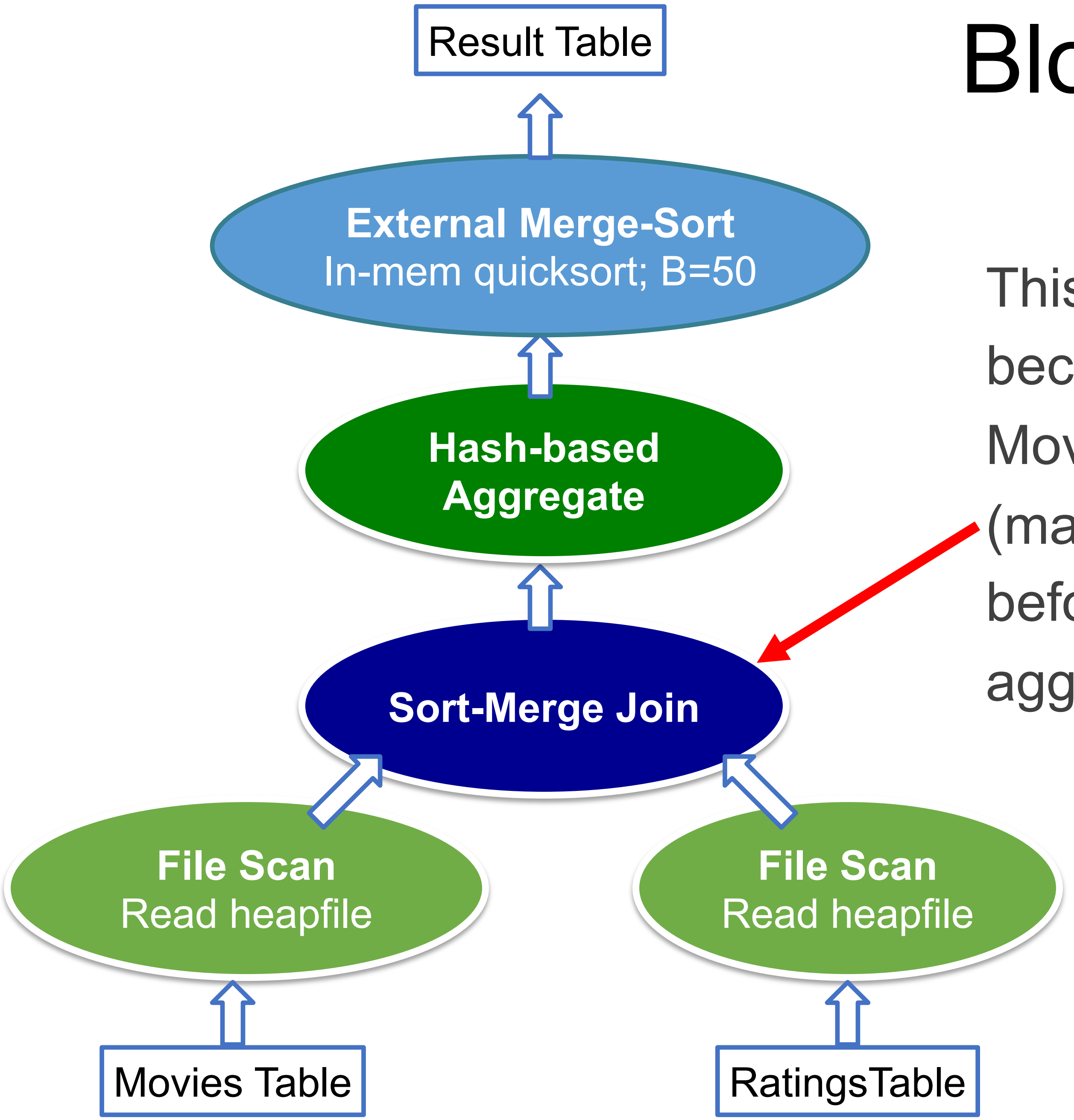
***Q:** Are all physical operators amenable to pipelining?*

No! Some may “stall” the pipeline: “**Blocking Op**”

A blocking op. requires its output to be **Materialized** as a temporary table

Usually, any phy. op. involving <u>sorting</u> is blocking!

Blocking Op



This phy. op. is blocking because we need to sort Movies and sort Ratings (materialize the output) before we can start any aggregate computations!

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Mechanism: Iterator Interface

- Software API to process PQP; makes pipelining easy to impl.
- Enables us to abstract away individual phy. op. impl. details
- Three main functions in usage interface of each phy. op.:

Open():	**Initialize the phy. op. "state", get arguments**
	Allocate input and output buffers
GetNext():	**Ask the phy. op. impl. to "deliver" next output tuple; pass it on; if blocking, wait**
Close():	**Clear phy. op. state, free up space**

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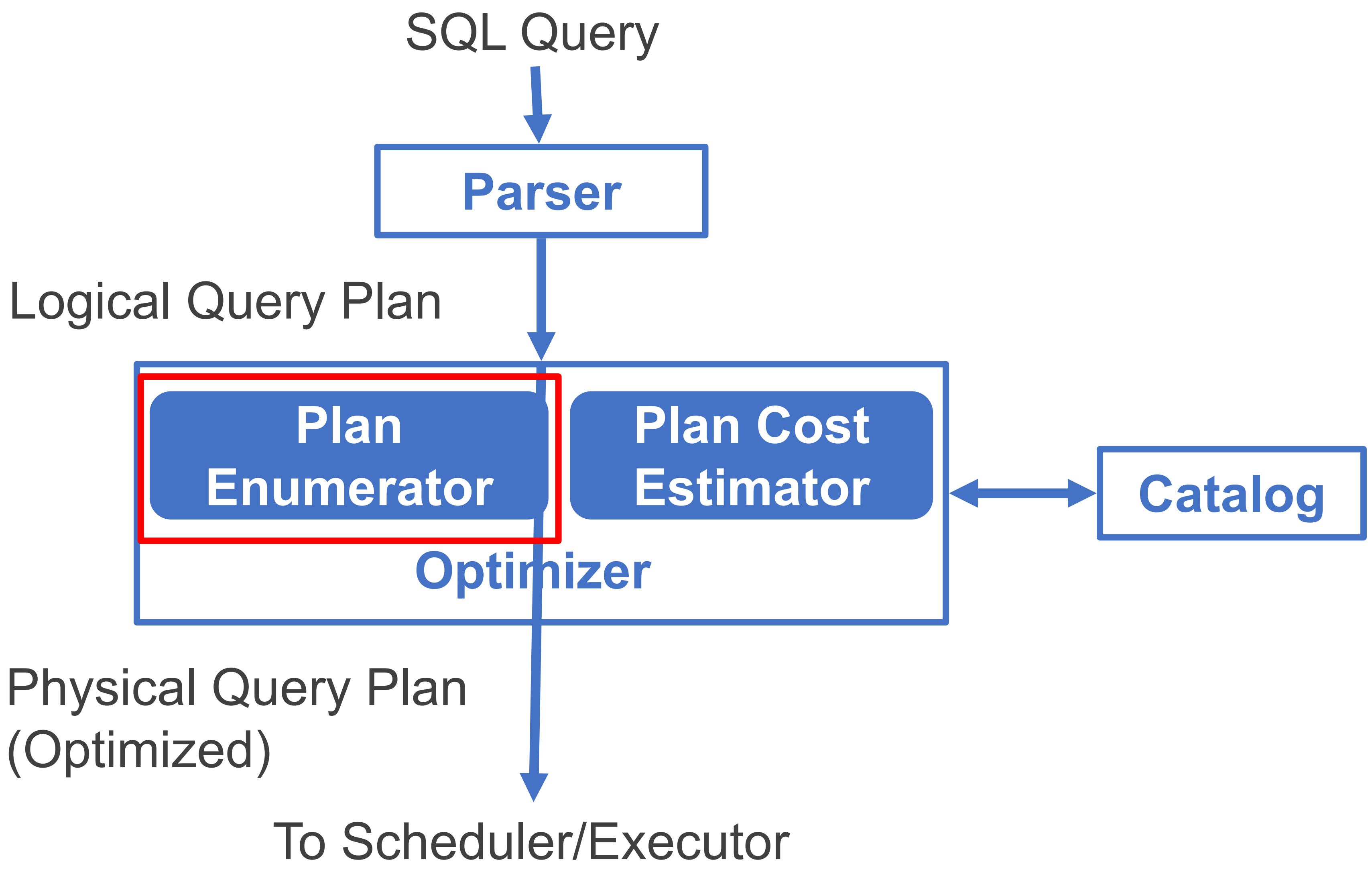

Enumerating Alternative PQPs

- Plan Enumerator explores various PQPs for a given LQP
- **Challenge: Space of plans is huge! How to make it feasible?**
- RDBMS Plan Enumerator has **Rules** to help determine what plans to enumerate, and also consults **Cost models**
- Two main sources of Rules for enumerating plans:

  Logical: Algebraic Rewrites:

  Use relational algebra <u>equivalence</u> to rewrite LQP itself!

  Physical: Choosing Phy. Op. Impl.:

  Use different phy. op. impl. for a given log. op. in LQP

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Algebraic Rewrite Rules

- Rewrite a given RA query in to another that is <u>equivalent</u> (a logical property) but might be <u>faster</u> (a physical property)
- RA operators have some formal properties we can exploit
- We will cover only a few rewrite rules:

  Single-operator Rewrites

    Unary operators

    Binary operators

  Cross-operator Rewrites

Unary Operator Rewrites

- Key unary operators in RA: σ π
- Commutativity of σ

$$\sigma_{p_1}(\sigma_{p_2}(\mathbf{R})) = \sigma_{p_2}(\sigma_{p_1}(\mathbf{R}))$$

- Cascading of σ

$$\sigma_{p_1}(\sigma_{p_2}(\ldots\sigma_{p_n}(\mathbf{R})\ldots)) = \sigma_{p_1 \wedge p_2 \wedge \cdots \wedge p_n}(\mathbf{R})$$

- Cascading of π $\quad A_i \subseteq A_{i+1} \forall i = 1 \ldots (n-1)$

$$\pi_{A_1}(\pi_{A_2}(\ldots\pi_{A_n}(\mathbf{R})\ldots)) = \pi_{A_1}(\mathbf{R})$$

***Q:** Why are cascading rewrites beneficial?*

Binary Operator Rewrites

- Key binary operator in RA: $\bowtie$
- Commutativity of $\bowtie$ $\quad R \bowtie S = S \bowtie R$
- Associativity of $\bowtie$ $\quad (R \bowtie S) \bowtie T = R \bowtie (S \bowtie T)$

Q: *Why are these properties beneficial?*

Q: *What other binary operators in RA satisfy these?*

Cross-Operator Rewrites

- Commuting σ and π $\quad A \subseteq B$

$$\sigma_{p(A)}(\pi_B(R)) = \pi_B(\sigma_{p(A)}(R))$$

- Combining σ and $\times$

$$\sigma_p(R \times S) = R \bowtie_p S$$

- "Pushing the select" $\quad A \subseteq R.*$

$$\sigma_{p(A)}(R \bowtie S) = \sigma_{p(A)}(R) \bowtie S$$

$$\sigma_{p(A)}(R \times S) = \sigma_{p(A)}(R) \times S$$

- Commuting π with $\times$ and $\bowtie$

$$\pi_A(R \times S) = \pi_{A \cap R.*}(R) \times \pi_{A \cap S.*}(S) \qquad B \subseteq A$$

$$\pi_A(R \bowtie_{p(B)} S) = \pi_{A \cap R.*}(R) \bowtie_{p(B)} \pi_{A \cap S.*}(S)$$

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Choosing Phy. Op. Impl.

- Given a (rewritten) LQP, pick phy. op. impl. for each log. op.
- Recall various RA op. impl. with their I/O (and CPU costs)

σ	File scan vs Indexed (B+ Tree vs Hash)
π	Hashing-based vs Sorting-based vs Indexed
$\bowtie$	BNLJ vs INLJ vs SMJ vs HJ
	etc.

$$\pi_B(\sigma_{p(A)}(R) \bowtie S)$$

3 options 3 options 4 options = **36** PQPs!

***Q:** With algebraic rewrites?!*

Phy. Op. Impl.: Other Factors

- Are the indexes clustered or unclustered?
- Are there multiple matching indexes? Use multiple?
- Are index-only access paths possible for some ops?
- Are there “interesting orderings” among the inputs?
- Would sorted outputs benefit downstream ops?
- Estimation of <u>cardinality</u> of intermediate results!
- How best to reorder multi-table joins?

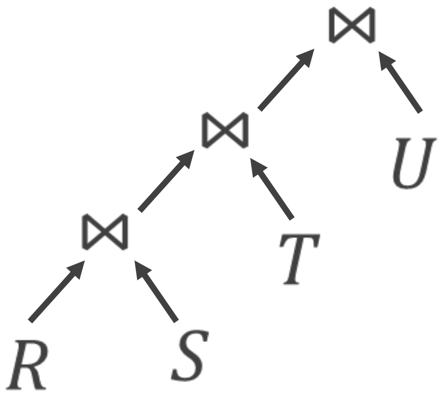
Query optimizers are complex beasts!

Still a hard, open research problem!

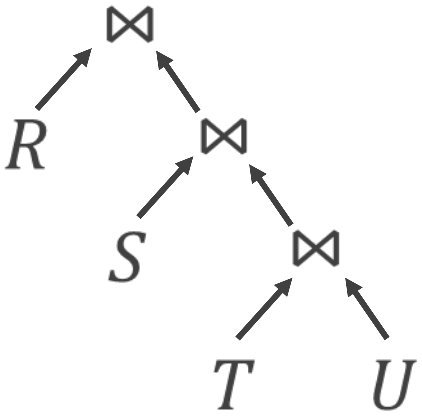
Phy. Op. Impl.: Join Orderings

- Since joins are associative, exponential number of orderings!

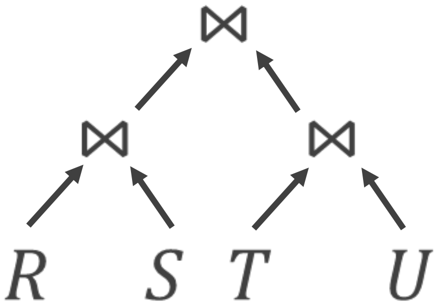
$$R \bowtie S \bowtie T \bowtie U$$



Left Deep tree



Right Deep tree



"Bushy" tree

- Almost all RDBMSs consider only left deep join trees

  Enables easy pipelining! Why?

- "Interesting orderings" idea from System R optimizer paper
- Dynamic program to combine enumeration and costing

"Access Path Selection in a Relational Database Management System" SIGMOD'79

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- $\boxed{\text{Costing PQPs}}$
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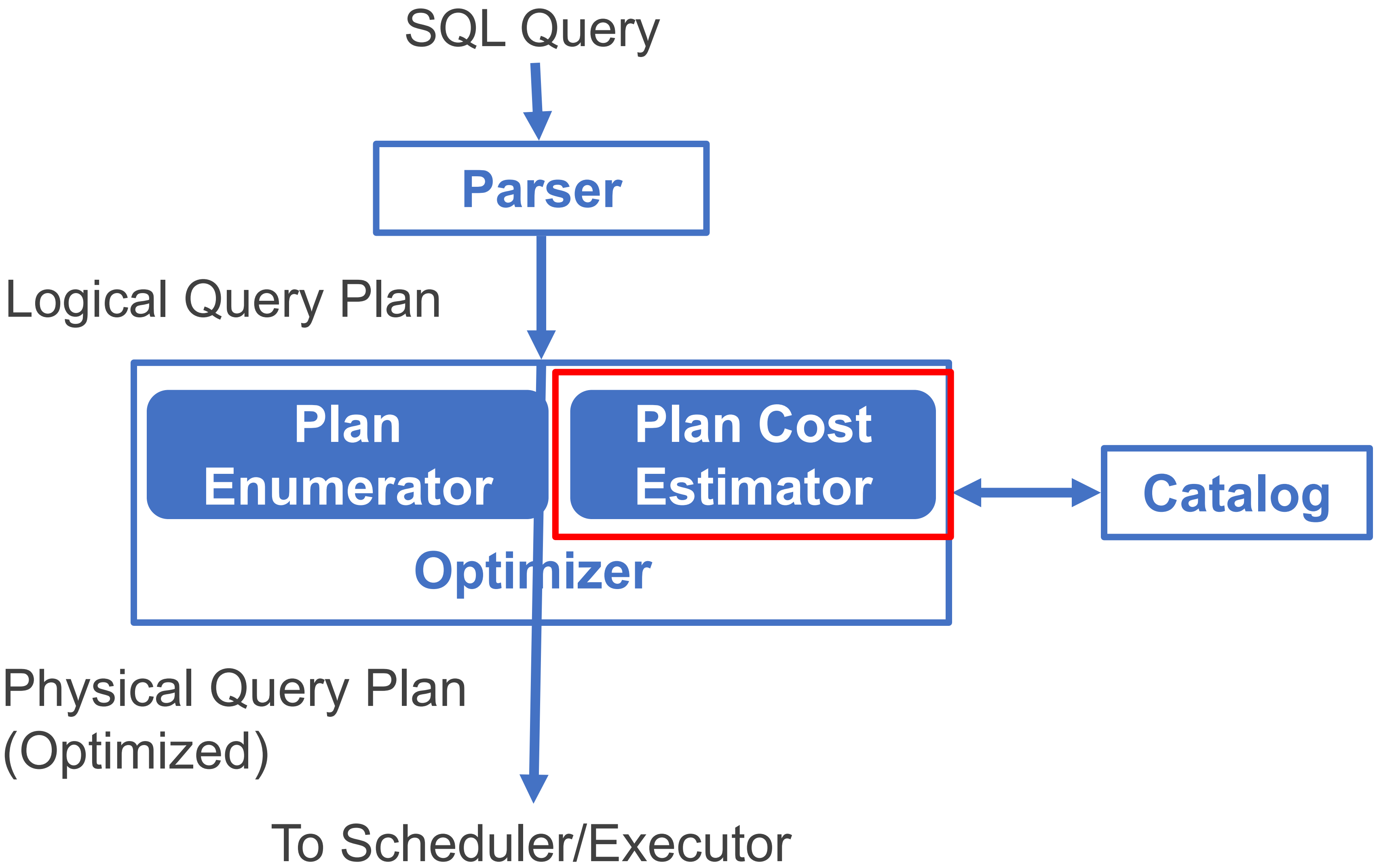
Overview of Query Optimizer



Costing PQPs

- For each PQP considered by the Plan Enumerator, the Plan Cost Estimator computes “**Cost**” of the PQP
  - Weighted sum of I/O cost and CPU cost
  - (Distributed RDBMSs also include Network cost)
- **Challenge: Given a PQP, compute overall cost**
- **Issues to consider:**
  - Pipelining vs. blocking ops; cannot simply add costs!
  - **Cardinality estimation** for intermediate tables!
  - ***Q:*** *What statistics does the catalog have to help?*

Costing PQPs

- Most RDBMSs use various heuristics to make costing tractable; so, it is approximate!
- **Example: Complex predicates**

$$\sigma_{p_1 \wedge p_2}(R)$$

Suppose selectivity of p_1 is 5%
and selectivity of p_2 is 10%

Q. What is the selectivity of $p_1 \wedge p_2$*?*

Not enough info!

But, most RDBMSs use the **independence** heuristic!

Selectivity of conjunction = Product of selectivities

Thus, ≈ 0.05 * 0.1 = 0.005, i.e., 0.5%

Query Optimization: Summary

- Plan Enumerator and Cost Estimator work in lock step:
  - **Rules** determine what PQPs are enumerated
    - Logical: Algebraic rewrites of LQP
    - Physical: Op. Impl. and ordering alternatives
  - **Cost models** and **heuristics** help cost the PQPs
- Still an active research area!
  - Parametric Q.O., Multi-objective Q.O.,
  - Multi-objective parametric Q.O., Multiple Q.O.,
  - Online/Adaptive Q.O., Dynamic re-optimization, etc.

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Introducing Materialized Views

- A **View** is a "virtual table" created with an SQL query
- A **Materialized View** is a physically instantiated/stored view

Example:

<u>RatingID</u>	Stars	RateDate	UID	MID

<u>UID</u>	Name	Age	JoinDate

<u>MID</u>	Name	Year	Director

```
SELECT  AVG(Stars)
FROM    Ratings R, Movies M, Users U
WHERE   R.MID = M.MID AND R.UID = U.UID
        M.Director = "Christopher Nolan" AND
        U.Age >= 20 AND U.Age < 30;
```

$$\gamma_{AVG(Stars)}(R \bowtie \sigma_{Director=\text{“}Christopher\ \ Nolan\text{”}}(M) \bowtie \sigma_{20 \le Age < 30}(U))$$

Requires file scans of R, M, and U and, say, hash joins

Materialized Views Example

Example:

<u>RatingID</u>	Stars	RateDate	UID	MID

<u>UID</u>	Name	Age	JoinDate	<u>MID</u>	Name	Year	Director

$$\gamma_{AVG(Stars)}(R \bowtie \sigma_{Director=\text{“}Christopher\ \ Nolan\text{”}}(M) \bowtie \sigma_{20 \leq Age < 30}(U))$$

```
CREATE MATERIALIZED VIEW NolanRatings AS
SELECT RatingID, Stars, UID, MID
FROM   Ratings R, Movies M
WHERE  R.MID = M.MID AND
       M.Director = "Christopher Nolan";
```

Creates a subset of R with ratings for only Nolan’s movies

$$V \leftarrow \pi_{RatingID,Stars,UID,MID}(R \bowtie \sigma_{Director=\text{“}Christopher\ \ Nolan\text{”}}(M))$$

Materialized Views Example

Example:

<u>RatingID</u>	Stars	RateDate	UID	MID

<u>UID</u>	Name	Age	JoinDate	<u>MID</u>	Name	Year	Director

$$\gamma_{AVG(Stars)}(R \bowtie \sigma_{Director=\text{``}Christopher\ \ Nolan\text{''}}(M) \bowtie \sigma_{20 \leq Age < 30}(U))$$

Given the materialized view V, RDBMS optimizer can automatically *rewrite* to use V to avoid scans of R and M

$$V \leftarrow \pi_{RatingID,Stars,UID,MID}(R \bowtie \sigma_{Director=\text{``}Christopher\ \ Nolan\text{''}}(M))$$

$$\gamma_{AVG(Stars)}(V \bowtie \sigma_{20 \leq Age < 30}(U))$$

Likely much faster since V is likely much smaller than R, but this depends on data statistics; leave it to optimizer!

Q: *How did DBA know to materialize a view for Nolan ratings?*

Materialized View Maintenance

Example:

<u>RatingID</u>	Stars	RateDate	UID	MID

<u>UID</u>	Name	Age	JoinDate

<u>MID</u>	Name	Year	Director

We are given this materialized view V over R and M

$$V \leftarrow \pi_{RatingID, Stars, UID, MID}(R \bowtie \sigma_{Director=\text{``}Christopher\ \ Nolan\text{''}}(M))$$

***Q:** What if new ratings are inserted to R for Nolan's movies?*

- RDBMS will automatically "trigger" updates to V
- Such updates are called **Materialized View Maintenance**
- 2 alternatives: Recompute whole view from scratch vs **Incremental View Maintenance** (IVM)

Incremental View Maintenance (IVM)

Basic Idea: Recomputing V from scratch may be an overkill
Try to *incrementally* update parts that change

$$V = Q(D) \qquad V' = Q(D')$$

- D' can be the outcome of inserts and/or deletes to D
- Q can be a unary query or involve multiple tables
- Computing V' may require inserts and/or deletes to V; realized as ***algebraic rewrite rules*** at LQP level
- Whether or not IVM of V is feasible and/or efficient depends on form of Q, nature of updates to D, data statistics, etc.
- We will focus only on inserts to D triggering inserts to V

Incremental View Maintenance (IVM)

Unary IVM for insertions:

$$R' = R \cup \Delta R$$ ← Newly inserted tuples

Select:

$$V \leftarrow \sigma_{SelectCondition}(R)$$

$$V' = V \cup \sigma_{SelectCondition}(\Delta R)$$

Can be just an *append* (union with “bag” semantics)

Project:

$$V \leftarrow \pi_{ProjectionList}(R)$$

$$V' = V \cup \pi_{ProjectionList}(\Delta R)$$

Requires full set union with V for deduplication

Select and Project can be composed and reordered as before

Incremental View Maintenance (IVM)

Unary IVM for insertions:

$$R' = R \cup \Delta R$$ ← Newly inserted tuples

Group By Agg: $V \leftarrow \gamma_{AggList,Agg(Y)}(R)$

Feasibility of IVM Depends on Agg() function!

Rewrite rules exist for SUM, COUNT, and MIN/MAX over bags

AVG not possible in general; needs deeper system changes

$$V' = \gamma_{AggList,SUM(Y)}(V \cup \gamma_{AggList,SUM(Y)}\Delta R)$$

$$V' = \gamma_{AggList,SUM(Y)}(V \cup \gamma_{AggList,COUNT(Y)}\Delta R)$$

$$V' = \gamma_{AggList,MIN(Y)}(V \cup \gamma_{AggList,MIN(Y)}\Delta R)$$

Incremental View Maintenance (IVM)

Join IVM for insertions:

Assume no duplicate inserts

$$V \leftarrow A \bowtie B$$

$$A' = A \cup \Delta A$$
$$B' = B \cup \Delta B$$

$$V' = V \cup (\Delta A \bowtie B') \cup (A' \bowtie \Delta B)$$

Alternatively, we can just append the output of the following query to V (union below is just append too):

$$(\Delta A \bowtie B') \cup (A' \bowtie \Delta B) - (\Delta A \bowtie \Delta B)$$

IVM for complex queries compose such op-level rewrites

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