Data Management
08 Query Processing

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SCIENCE
PASSION
TECHNOLOGY

Announcements/Org

- **#1 Video Recording**
  - Link in **TeachCenter** & **TUbe** (lectures will be public)
  - https://tugraz.webex.com/meet/m.boehm
  - Corona traffic light **RED** → May 17: **ORANGE** (but tests required)

- **#2 Reminder Communication**
  - **Newsgroup:** news://news.tugraz.at/tu-graz.lv.dbase
  - **Office hours:** Mo 12.30-1.30pm (https://tugraz.webex.com/meet/m.boehm)

- **#3 Exercise Submissions**
  - **Grading Exercise 1:** tomorrow, **Exercise 2:** end May
  - **Exercise 3:** to be published tomorrow, discussed next lecture

Query Optimization and Query Processing

```
SELECT * FROM TopScorer
  WHERE Count>=4

  CREATE VIEW TopScorer AS
  SELECT P.Name, Count(*)
    FROM Players P, Goals G
    WHERE P.Pid=G.Pid
      AND G.GOwn=FALSE
    GROUP BY P.Name
    ORDER BY Count(*) DESC
```

WHAT →

Yes, but HOW to we get there efficiently

2014

Name	Count
James Rodríguez	6
Thomas Müller	5
Robin van Persie	4
Neymar	4

- **Goal: Basic Understanding of Internal Query Processing**
  - Query rewriting and query optimization
  - Query processing and physical plan operators
  - → **Performance debugging & reuse of concepts and techniques**
  - → Overview, detailed techniques discussed in ADBS (WS 2020)

Agenda

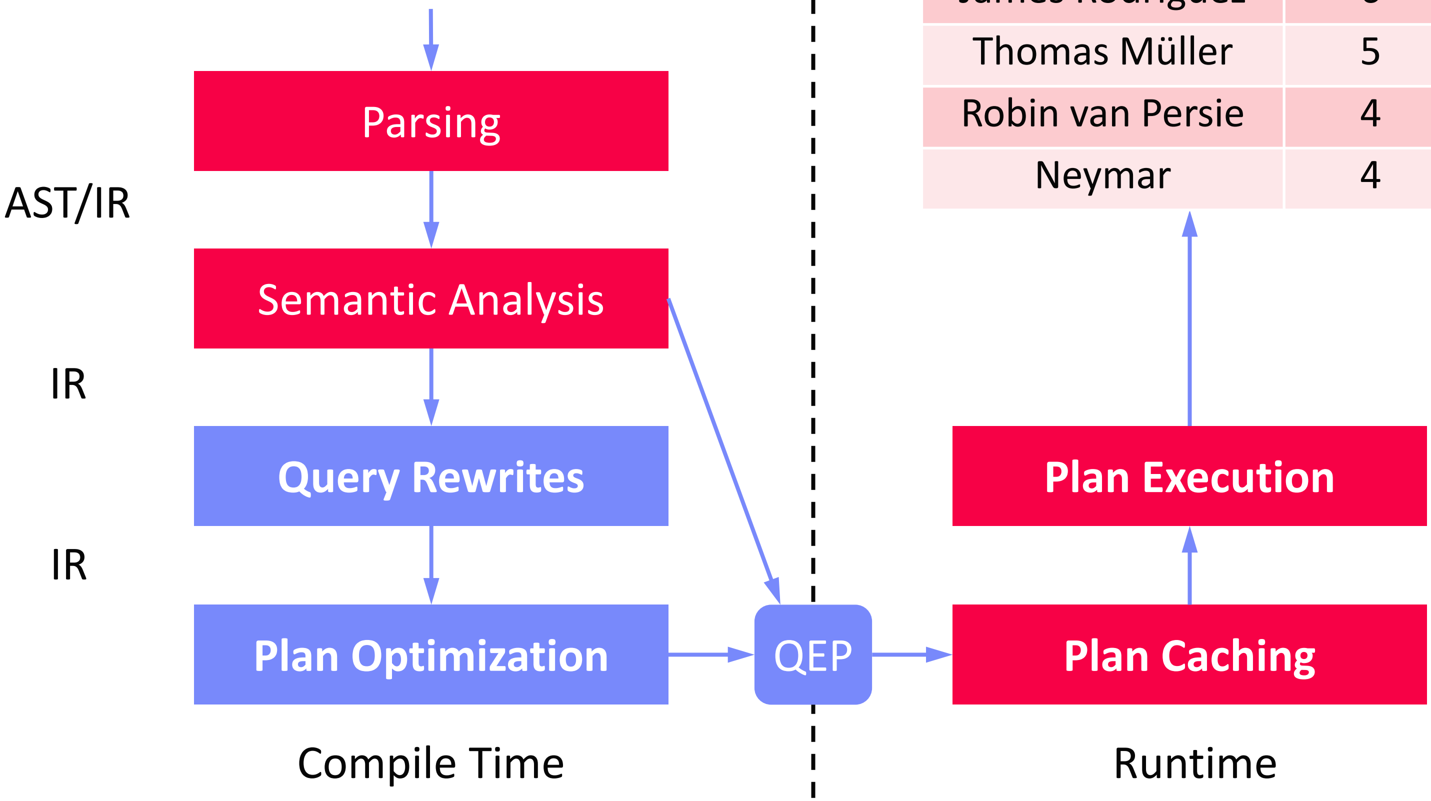
- **Query Rewriting and Optimization**
- **Plan Execution Strategies**
- **Physical Plan Operators**

Query Rewriting and Optimization

Overview Query Optimization

```
SELECT * FROM TopScorer
  WHERE Count>=4
```

Name	Count
James Rodríguez	6
Thomas Müller	5
Robin van Persie	4
Neymar	4



Query Rewrites

- **Query Rewriting**
  - Rewrite query into semantically equivalent form that may be **processed more efficiently** or **give the optimizer more freedom**
  - **#1** **Same query can be expressed differently**, avoid hand-tuning
  - **#2** **Complex queries may have redundancy**

- **A Simple Example**
  - Catalog meta data: custkey is unique

```
SELECT DISTINCT custkey, name
   FROM TPCH.Customer
```

rewrite

```
SELECT custkey, name
   FROM TPCH.Customer
```

- **25+ years of experience on query rewriting**

[Hamid Pirahesh, T. Y. Cliff Leung, Waqar Hasan: A Rule Engine for Query Transformation in Starburst and IBM DB2 C/S DBMS. **ICDE 1997**]

Standardization and Simplification

- **Normal Forms of Boolean Expressions**
  - **Conjunctive** normal form (P_{11} OR ... OR P_{1n}) **AND ... AND** (P_{m1} OR ... OR P_{mp})
  - **Disjunctive** normal form (P_{11} AND ... AND P_{1q}) **OR ... OR** (P_{r1} AND ... AND P_{rs})

- **Transformation Rules for Boolean Expressions**

Rule Name	Examples	
Commutativity rules	A OR B ⇔ B OR A A AND B ⇔ B AND A	
Associativity rules	(A OR B) OR C ⇔ A OR (B OR C) (A AND B) AND C ⇔ A AND (B AND C)	
Distributivity rules	A OR (B AND C) ⇔ (A OR B) AND (A OR C) A AND (B OR C) ⇔ (A AND B) OR (A AND C)	
De Morgan's rules	NOT (A AND B) ⇔ NOT (A) OR NOT (B) NOT (A OR B) ⇔ NOT (A) AND NOT (B)	
Double-negation rules	NOT(NOT(A)) ⇔ A	
Idempotence rules	A OR A ⇔ A A OR NOT(A) ⇔ TRUE A AND (A OR B) ⇔ A A OR FALSE ⇔ A A AND FALSE ⇔ FALSE	A AND A ⇔ A A AND NOT (A) ⇔ FALSE A OR (A AND B) ⇔ A A OR TRUE ⇔ TRUE

Standardization and Simplification, cont.

- **Elimination of Common Subexpressions**
  - $(A_1 = a_{11}$ **OR** $A_1 = a_{12})$ **AND** $(A_1 = a_{12}$ **OR** $A_1 = a_{11}) \rightarrow A_1 = a_{11}$ **OR** $A_1 = a_{12}$
- **Propagation of Constants**
  - $A \geq B$ **AND** $B = 7 \rightarrow A \geq 7$ **AND** $B = 7$
- **Detection of Contradictions**
  - $A \geq B$ **AND** $B > C$ **AND** $C \geq A \rightarrow A > A \rightarrow$ **FALSE**
- **Use of Constraints**
  - A is primary key/unique: $\pi_A \rightarrow$ no duplicate elimination necessary
  - Rule MAR_STATUS = 'married' → TAX_CLASS ≥ 3:
    (MAR_STATUS = 'married' **AND** TAX_CLASS = 1) → **FALSE**
- **Elimination of Redundancy** (set semantics)
  - $R \bowtie R \rightarrow R$, $R \cup R \rightarrow R$, $R - R \rightarrow \emptyset$
  - $R \bowtie (\sigma_p R) \rightarrow \sigma_p R$, $R \cup (\sigma_p R) \rightarrow R$, $R - (\sigma_p R) \rightarrow \sigma_{\neg p} R$
  - $(\sigma_{p1} R) \bowtie (\sigma_{p2} R) \rightarrow \sigma_{p1 \wedge p2} R$, $(\sigma_{p1} R) \cup (\sigma_{p2} R) \rightarrow \sigma_{p1 \vee p2} R$

Query Unnesting

[Won Kim: On Optimizing an SQL-like Nested Query. **ACM Trans. Database Syst. 1982**]

- **Case 1: Type-A Nesting**
  - Inner block is not correlated and computes an aggregate
  - Solution: Compute the aggregate once and insert into outer query

```
SELECT OrderNo FROM Order
  WHERE ProdNo =
   (SELECT MAX(ProdNo)
      FROM Product WHERE Price<100)
```

```
$X = SELECT MAX(ProdNo)
  FROM Product WHERE Price<100

SELECT OrderNo FROM Order
  WHERE ProdNo = $X
```

- **Case 2: Type-N Nesting**
  - Inner block is not correlated and returns a set of tuples
  - Solution: Transform into a symmetric form (via join)

```
SELECT OrderNo FROM Order
  WHERE ProdNo IN
   (SELECT ProdNo
      FROM Product WHERE Price<100)
```

```
SELECT OrderNo
 FROM Order O, Product P
 WHERE O.ProdNo = P.ProdNo
   AND P.Price < 100
```

Query Unnesting, cont.

[Won Kim: On Optimizing an SQL-like Nested Query. **ACM Trans. Database Syst. 1982**]

- **Case 3: Type-J Nesting**
  - Un-nesting of correlated sub-queries w/o aggregation

```
SELECT OrderNo FROM Order O
  WHERE ProdNo IN
   (SELECT ProdNo FROM Project P
    WHERE P.ProjNo = O.OrderNo
      AND P.Budget > 100,000)
```

→

```
SELECT OrderNo
  FROM Order O, Project P
  WHERE O.ProdNo = P.ProdNo
    AND P.ProjNo = O.OrderNo
    AND P.Budget > 100,000
```

- **Case 4: Type-JA Nesting**
  - Un-nesting of correlated sub-queries w/ aggregation

```
SELECT OrderNo FROM Order O
  WHERE ProdNo IN
   (SELECT MAX(ProdNo)
     FROM Project P
     WHERE P.ProjNo = O.OrderNo
       AND P.Budget > 100,000)
```

→

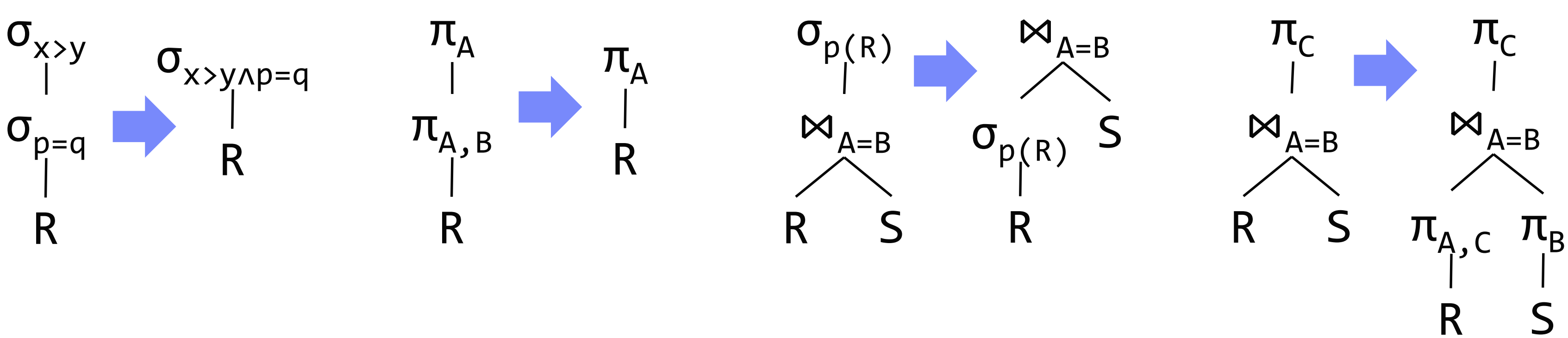
```
SELECT OrderNo FROM Order O
  WHERE ProdNo IN
   (SELECT ProdNo FROM
     (SELECT ProjNo, MAX(ProdNo)
       FROM Project
       WHERE Budget > 100.000
       GROUP BY ProjNo) P
   WHERE P.ProjNo = O.OrderNo)
```

  - Further un-nesting via case 3 and 2

Selections and Projections

- **Example Transformation Rules**

1) Grouping of Selections | 2) Grouping of Projections | 3) Pushdown of Selections | 4) Pushdown of Projections



- **Restructuring Algorithm**
  - **#1** Split n-ary joins into binary joins
  - **#2** Split multi-term selections
  - **#3** Push-down selections as far as possible
  - **#4** Group adjacent selections again
  - **#5** Push-down projections as far as possible

Input: Standardized, simplified, and un-nested query graph

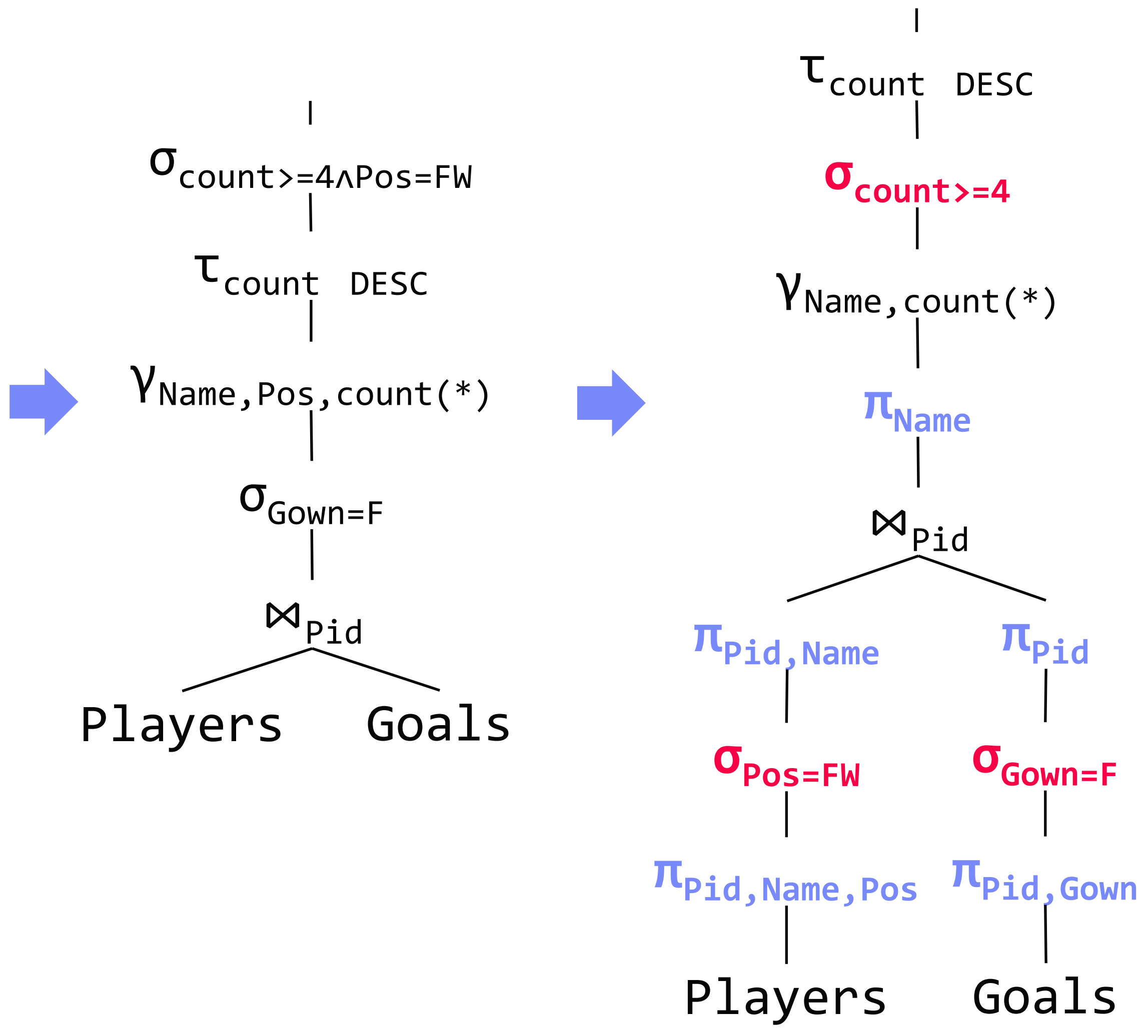
Output: Restructured query graph

Example Query Restructuring

```sql
SELECT * FROM TopScorer
  WHERE count>=4
  AND Pos='FW'
```

```sql
CREATE VIEW TopScorer AS
SELECT P.Name, P.Pos, count(*)
  FROM Players P, Goals G
  WHERE P.Pid=G.Pid
    AND G.GOwn=FALSE
  GROUP BY P.Name, P.Pos
  ORDER BY count(*) DESC
```

Additional metadata:
  P.Name is unique



Plan Optimization Overview

- **Plan Generation**
  - Selection of **physical access path and plan operators**
  - Selection of **execution order** of plan operators
  - **Input:** logical query plan → **Output:** optimal physical query plan
  - Costs of query optimization should not exceed yielded improvements

- **Different Cost Models**
  - Relies on statistics (cardinalities, selectivities via histograms + estimators)
  - Operator-specific and general-purpose cost models

$$C_{\text{out}}(T) = \begin{cases} 0 & \text{if } T \text{ is a single relation} \\ |T| + C_{\text{out}}(T_1) + C_{\text{out}}(T_2) & \text{if } T = T_1 \bowtie T_2 \end{cases}$$

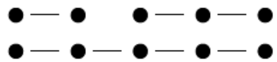
  - **I/O costs** (number of read pages, tuples)
  - **Computation costs** (CPU costs, path lengths)
  - **Memory** (temporary memory requirements)
  - **Beware assumptions of optimizers** (no skew, independence, no correlation)

	(estimated)	**(real)**
	10	**590**
$\sigma_{\text{Model= 'Golf'}}$		
	1,000	**5,000**
$\sigma_{\text{Make='VW'}}$		
Cars	10,000	10,000

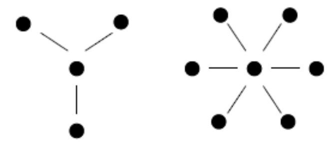
Query and Plan Types

[Guido Moerkotte, Building Query Compilers (Under Construction), **2020**, http://pi3.informatik.uni-mannheim.de/~moer/querycompiler.pdf]

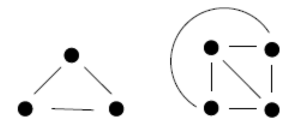
- **Query Types**
  - **Nodes:** Tables
  - **Edges:** Join conditions
  - Determine hardness of query optimization (w/o cross products)



Chains



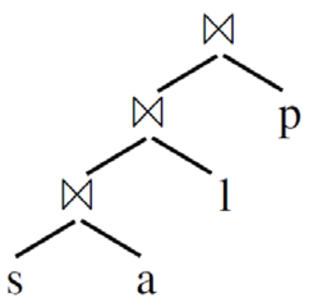
Stars



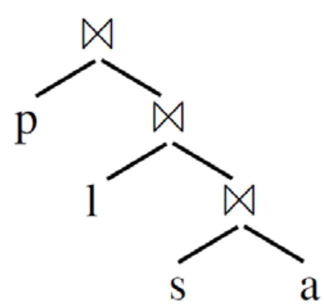
Cliques

- **Join Tree Types / Plan Types**
  - Data flow graph of tables and joins (logical/physical query trees)
  - **Edges:** data dependencies (fixed execution order: bottom-up)

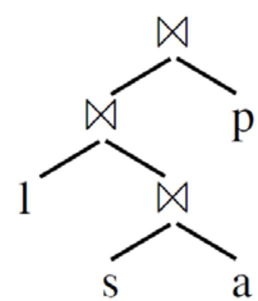
Left-Deep Tree



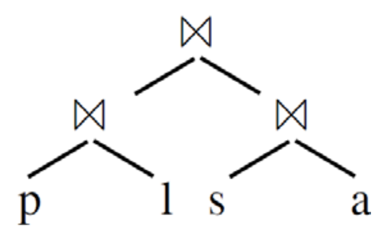
Right-Deep Tree



Zig-Zag Tree



Bushy Tree



Join Ordering Problem

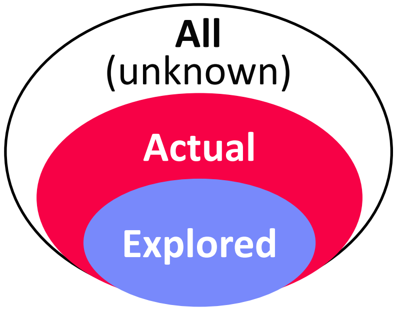
- **Join Ordering**
  - Given a join query graph, find the optimal join ordering
  - In general, **NP-hard**; but polynomial algorithms exist for special cases

- **Search Space**
  - Dependent on query and plan types
  - **Note:** if we allow cross products similar to cliques (fully connected)

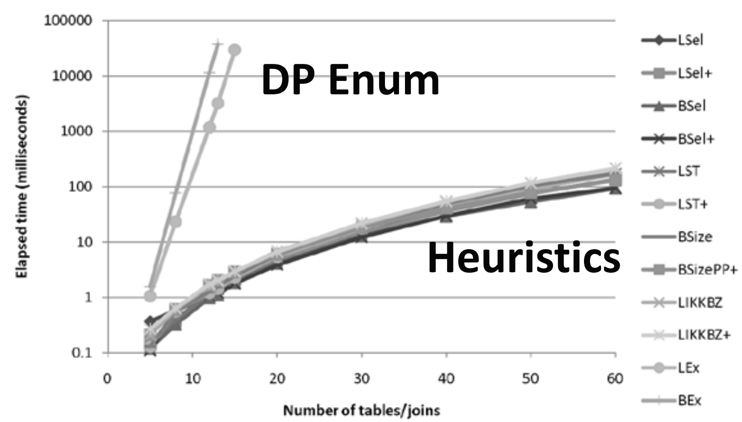
	Chain (no CP)			Star (no CP)		Clique / CP (cross product)		
	left-deep	**zig-zag**	**bushy**	**left-deep**	**zig-zag/ bushy**	**left-deep**	**zig-zag**	**bushy**
n	2^{n-1}	2^{2n-3}	$2^{n-1}C(n-1)$	$2(n-1)!$	$2^{n-1}(n-1)!$	$n!$	$2^{n-2}n!$	$n!\,C(n-1)$
5	16	128	224	48	384	120	960	1,680
10	512	~131K	~2.4M	~726K	~186M	~3.6M	~929M	~17.6G

C(n) … Catalan Numbers

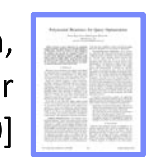
Join Order Search Strategies



- **Tradeoff: Optimal (or good)** plan vs **compilation time**
- **#1 Naïve Full Enumeration**
  - Infeasible for reasonably large queries (long tail up to 1000s of joins)
- **#2 Exact Dynamic Programming**
  - Guarantees optimal plan, often too expensive (beyond 20 relations)
  - Bottom-up vs top-down approaches
- **#3 Greedy / Heuristic Algorithms**
- **#4 Approximate Algorithms**
  - E.g., Genetic algorithms, simulated annealing
- **Example PostgreSQL**
  - Exact optimization (DPSize) if < 12 relations (geqo_threshold)
  - Genetic algorithm for larger queries
  - Join methods: NLJ, SMJ, HJ

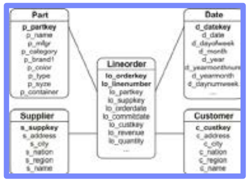


[Nicolas Bruno, César A. Galindo-Legaria, Milind Joshi: Polynomial heuristics for query optimization. **ICDE 2010**]



Greedy Join Ordering

Star Schema Benchmark



- **Example**
  - Part ⋈ Lineorder ⋈ Supplier ⋈ σ(Customer) ⋈ σ(Date), **left-deep plans**

#	Plan	Costs
1	Lineorder ⋈ Part	30M
	Lineorder ⋈ Supplier	20M
	Lineorder ⋈ σ(Customer)	90K
	Lineorder ⋈ σ(Date)	**40K**
	~~Part ⋈ Customer~~	N/A
	…	…
2	(Lineorder ⋈ σ(Date)) ⋈ Part	150K
	(Lineorder ⋈ σ(Date)) ⋈ Supplier	100K
	(Lineorder ⋈ σ(Date)) ⋈ σ(Customer)	**75K**

#	Plan	Costs
3	((Lineorder ⋈ σ(Date)) ⋈ σ(Customer)) ⋈ Part	120M
	((Lineorder ⋈ σ(Date)) ⋈ σ(Customer)) ⋈ Supplier	**105M**
4	**(((Lineorder ⋈ σ(Date)) ⋈ σ(Customer)) ⋈ Supplier) ⋈ Part**	**135M**

Note: Simple $O(n^2)$ algorithm for left-deep trees; $O(n^3)$ algorithms for bushy trees existing (e.g., GOO)

Dynamic Programming Join Ordering

- **Exact Enumeration via Dynamic Programming**
  - **#1: Optimal substructure** (Bellman's Principle of Optimality)
  - **#2: Overlapping subproblems** allow for memoization
  - ➔ Approach DPSize: Split in independent subproblems (optimal plan per set of quantifiers and interesting properties), solve subproblems, combine solutions
- **Example**

Q1	Plan
{C}	Tbl, IX
{D}	Tbl, IX
{L}	…
{P}	…
{S}	…

Q1+Q1

Q2	Plan
{C,L}	L⋈C, ~~C⋈L~~
{D,L}	L⋈D, ~~D⋈L~~
{L,P}	~~L⋈P~~, P⋈L
{L,S}	~~L⋈S~~, S⋈L
~~{C,D}~~	~~N/A~~
…	…

Q1+Q2, Q2+Q1

Q3	Plan
{C,D,L}	(L⋈C)⋈D, ~~D⋈(L⋈C)~~, ~~(L⋈D)⋈C~~, ~~C⋈(L⋈D)~~
{C,L,P}	~~(L⋈C)⋈P~~, P⋈(L⋈C), ~~(P⋈L)⋈C~~, ~~C⋈(P⋈L)~~
{C,L,S}	…
{D,L,P}	…
{D,L,S}	…
{L,P,S}	…

Q1+Q3, Q2+Q2, Q3+Q1

Q4	Plan
{C,D,L,P}	~~((L⋈C)⋈D)⋈P~~, P⋈((L⋈C)⋈D)
{C,D,L,S}	…
{C,L,P,S}	…
{D,L,P,S}	…

Q1+Q4, Q2+Q3, Q3+Q2, Q4+Q1

Q5	Plan
{C,D,L,P,S}	…

BREAK (and Test Yourself)

- **Rewrite the following RA expressions – assuming two relations R(a, b, c) and S(d, e, f) – into equivalent expressions with lower costs.** (5 points)
  - $\sigma_{b=7}(R \bowtie S)$ → $\sigma_{b=7}(R) \bowtie S$
  - $(\sigma_{e>3}(S)) \cap (\sigma_{f<7}(S))$ → $\sigma_{e>3 \wedge f<7}(S)$
  - $\pi_{a,b}(R \bowtie_{a=d} S)$ → $\pi_{a,b}(R) \ltimes_{a=d} S$
  - $R \cup (\sigma_{d<e \wedge e<f \wedge f<d}(S))$ → $R \cup \emptyset$ → R
  - $\sigma_{b=3}(\gamma_{b,max(c)}(R))$ → $\gamma_{3,max(c)}(\sigma_{b=3}(R))$

BREAK (and Test Yourself), cont.

- **Assume relations R(a,b,c) and S(d,e), and indicate in the table below whether or not the two RA expressions per row are equivalent in bag semantics. For non-equivalent expressions briefly explain why.** (5 points)

Expression 1	Expression 2	Equivalent?
$\sigma_{c=3}(\sigma_{b=7}(R))$	$\sigma_{c=3}(\sigma_{c=3 \vee b=7}(R))$	✗
$R \bowtie_{a=e} S$	$\sigma_{a=e}(R \times S)$	✓
$(\sigma_{b<3}(R)) \cap (\sigma_{b \geq 3}(R))$	R	✗
$\pi_{b,d}(R \bowtie_{a=e} S)$	$(\pi_{a,b}(R)) \bowtie_{a=e} (\pi_{d,e}(S))$	✗
$\pi_{a,b}(\sigma_{c=3}(\sigma_{b=7}(R)))$	$\sigma_{b=7}(\pi_{a,b}(\sigma_{c=3}(R)))$	✓

Plan Execution Strategies

Overview Query Processing

```
SELECT * FROM TopScorer
  WHERE Count>=4
```

Name	Count
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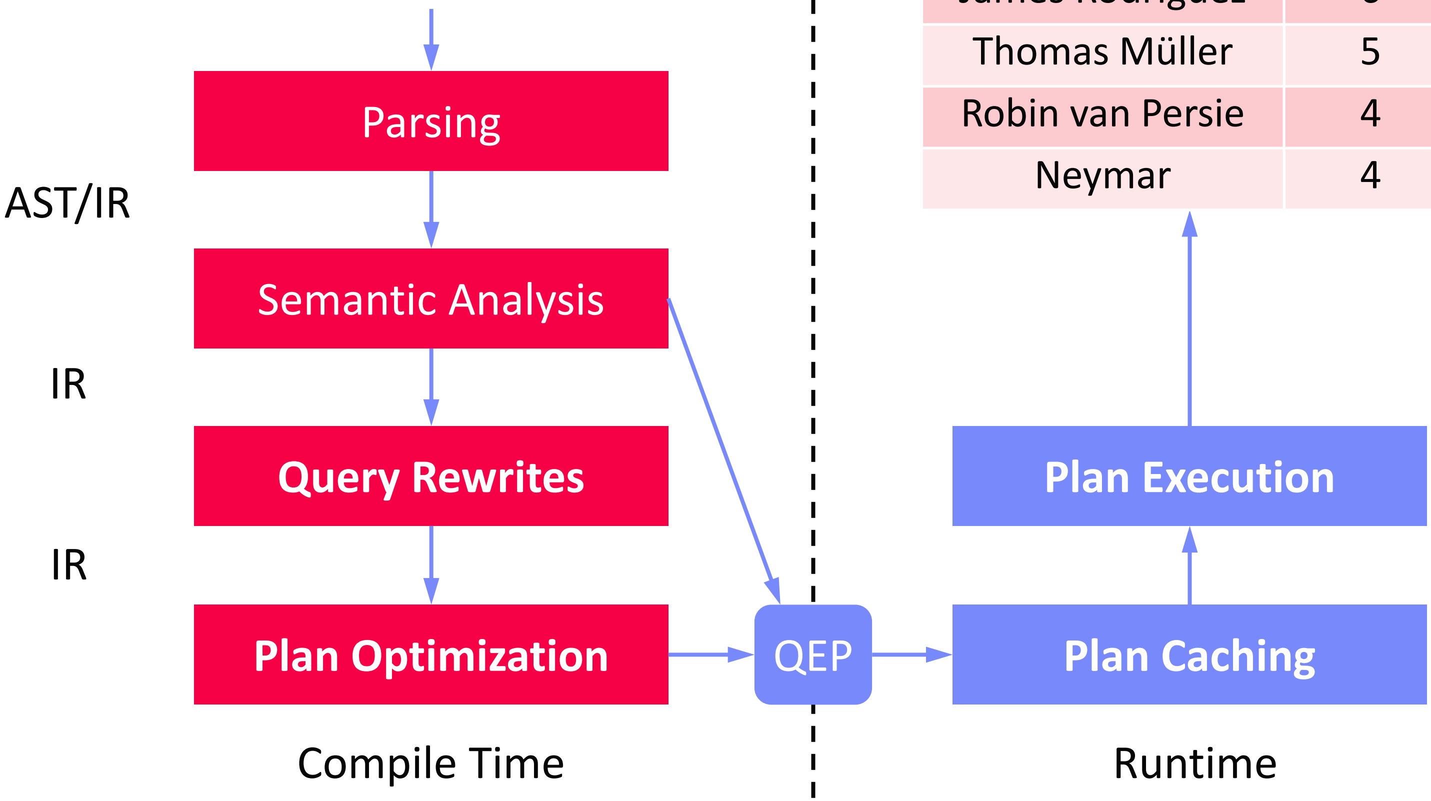


Overview Execution Strategies

- **Different execution strategies (processing models) with different pros/cons** (e.g., memory requirements, DAGs, efficiency, reuse)

- **#1 Iterator Model** (mostly row stores)

- **#2 Materialized Intermediates** (mostly column stores)

- **#3 Vectorized (Batched) Execution** (row/column stores)

- **#4 Query Compilation** (row/column stores)

High-level overview, details in **ADBS**

Iterator Model

Scalable (small memory)
High CPI measures

- **Volcano Iterator Model**
  - **Pipelined & no global knowledge**
  - **Open-Next-Close** (ONC) interface
  - Query execution from root node (pull-based)

[Goetz Graefe: Volcano - An Extensible and Parallel Query Evaluation System. **IEEE Trans. Knowl. Data Eng. 1994**]

- **Example $\sigma_{A=7}(R)$**

```
void open() { R.open(); }

void close() { R.close(); }

Record next() {
  while( (r = R.next()) != EOF )
    if( p(r) ) //A==7
      return r;
  return EOF;
}
```

```
open()
 next()
  next() → EOF
   close()
      |
open()
next()
next()        σA=7  → EOF
close()
      |
open()
next()
next()          R
next()
next()                → EOF
close()
```

- **Blocking Operators**
  - Sorting, grouping/aggregation, build-phase of (simple) hash joins

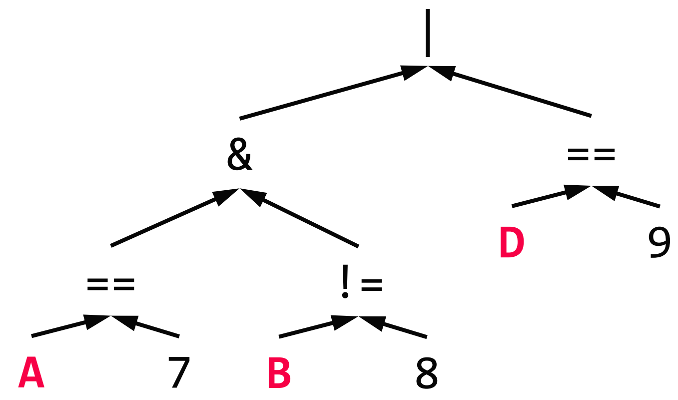
PostgreSQL: Init(), GetNext(), ReScan(), MarkPos(), RestorePos(), End()

Iterator Model – Predicate Evaluation

- **Operator Predicates**
  - Examples: arbitrary selection predicates and join conditions
  - Operators parameterized **with in-memory expression trees/DAGs**
  - **Expression evaluation engine** (interpretation)

- **Example Selection σ**
  - $(A = 7 \land B \neq 8) \lor D = 9$

A	B	C	D
7	8	Product 1	10
14	8	Product 3	11
7	3	Product 7	7
3	3	Product 2	1



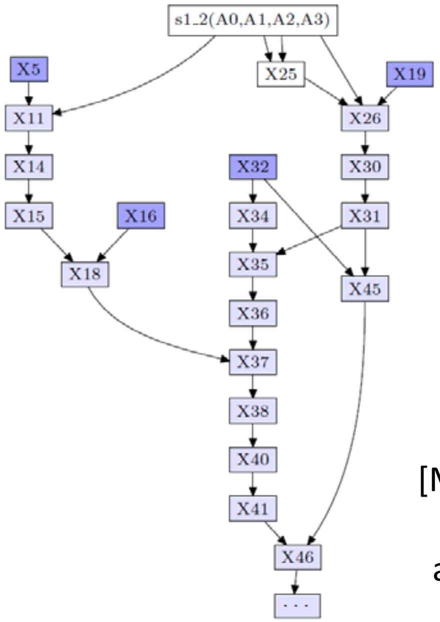
Materialized Intermediates (column-at-a-time)

```
SELECT count(DISTINCT o_orderkey)
  FROM orders, lineitem
  WHERE l_orderkey = o_orderkey
    AND o_orderdate >= date '1996-07-01'
    AND o_orderdate < date '1996-07-01'
      + interval '3' month
    AND l_returnflag = 'R';
```

```
function user.s1_2(A0:date,A1:date,A2:int,A3:str):void;
  X5 := sql.bind("sys","lineitem","l_returnflag",0);
  X11 := algebra.uselect(X5,A3);
  X14 := algebra.markT(X11,0@0);
  X15 := bat.reverse(X14);
  X16 := sql.bindIdxbat("sys","lineitem","l_orderkey_fkey");
  X18 := algebra.join(X15,X16);
  X19 := sql.bind("sys","orders","o_orderdate",0);
  X25 := mtime.addmonths(A1,A2);
  X26 := algebra.select(X19,A0,X25,true,false);
  X30 := algebra.markT(X26,0@0);
  X31 := bat.reverse(X30);
  X32 := sql.bind("sys","orders","o_orderkey",0);
  X34 := bat.mirror(X32);
  X35 := algebra.join(X31,X34);
  X36 := bat.reverse(X35);
  X37 := algebra.join(X18,X36);
  X38 := bat.reverse(X37);
  X40 := algebra.markT(X38,0@0);
  X41 := bat.reverse(X40);
  X45 := algebra.join(X31,X32);
  X46 := algebra.join(X41,X45);
  X49 := algebra.selectNotNil(X46);
  X50 := bat.reverse(X49);
  X51 := algebra.kunique(X50);
  X52 := bat.reverse(X51);
  X53 := aggr.count(X52);
  sql.exportValue(1,"sys.orders","L1","wrd",32,0,6,X53);
end s1_2;
```

Binary Association Tables

(BATs:=OID/Val)

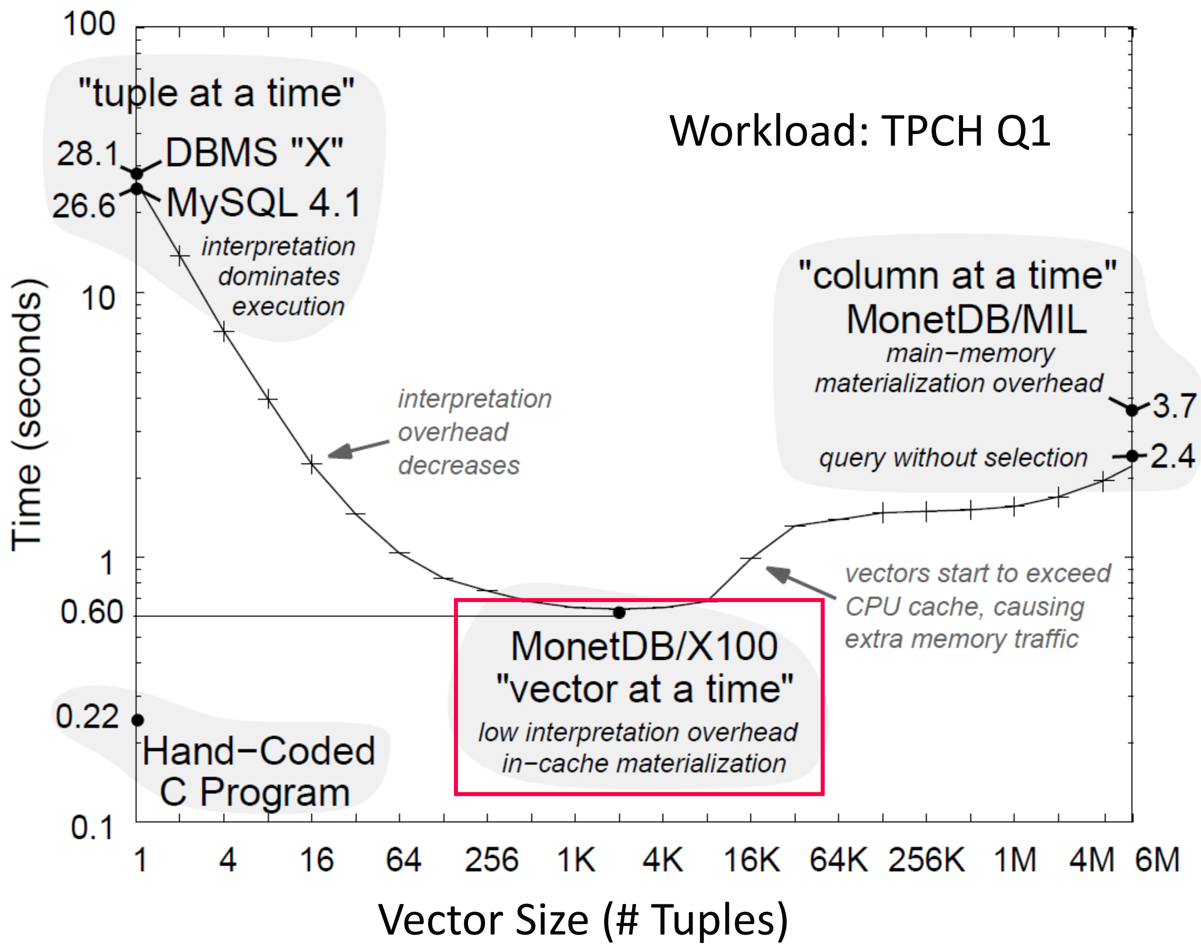


Column-oriented storage
Efficient array operations
DAG processing
Reuse of intermediates
Memory requirements
Unnecessary read/write from and to memory

[Milena Ivanova, Martin L. Kersten, Niels J. Nes, Romulo Goncalves: An architecture for recycling intermediates in a column-store. **SIGMOD 2009**]

Vectorized Execution (vector-at-a-time)

- **Idea: Pipelining of vectors (sub columns) s.t. vectors fit in CPU cache**



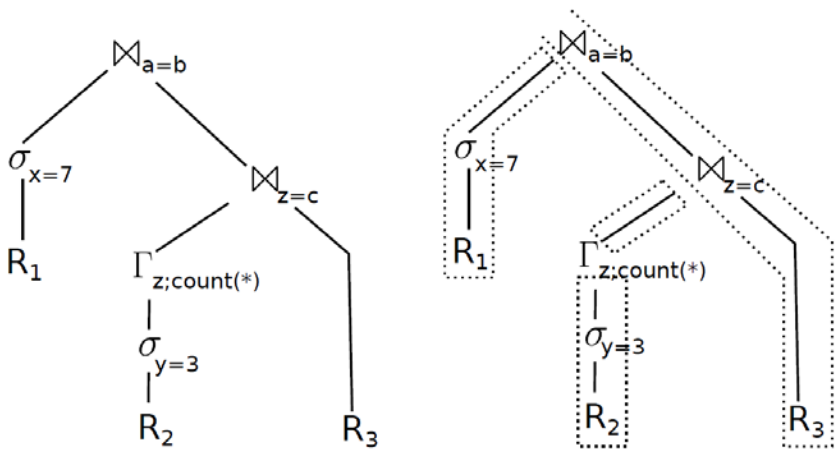
Column-oriented storage
Efficient array operations
Memory/cache efficiency
DAG processing
Reuse of intermediates


[Peter A. Boncz, Marcin Zukowski, Niels Nes: MonetDB/X100: Hyper-Pipelining Query Execution. **CIDR 2005**]

Query Compilation

- **Idea: Data-centric, not op-centric processing + LLVM code generation**

Operator Trees
(w/o and w/ pipeline boundaries)



Compiled Query
(conceptual, not LLVM)

initialize memory of $\bowtie_{a=b}$, $\bowtie_{c=z}$, and Γ_z
for each tuple t in R_1
  if $t.x = 7$
    materialize t in hash table of $\bowtie_{a=b}$
for each tuple t in R_2
  if $t.y = 3$
    aggregate t in hash table of Γ_z
~~**for each** tuple t in Γ_z~~
  ~~materialize t in hash table of $\bowtie_{z=c}$~~
for each tuple t_3 in R_3
  for each match t_2 in $\bowtie_{z=c}[t_3.c]$
    for each match t_1 in $\bowtie_{a=b}[t_3.b]$
      output $t_1 \circ t_2 \circ t_3$

[Thomas Neumann: Efficiently Compiling Efficient Query Plans for Modern Hardware. **PVLDB 2011**]

Physical Plan Operators

Overview Plan Operators

- **Multiple Physical Operators**
  - **Different physical operators** for different data and query characteristics
  - Physical operators can have vastly different costs

- **Examples** (supported in most DBMS)

	Selection	Projection	Grouping	Join
Logical Plan Operators	$\sigma_p(R)$	$\pi_A(R)$	$\gamma_{G:agg(A)}(R)$	$R \bowtie_{R.a=S.b} S$

Physical Plan Operators	`TableScan`
	`IndexScan`
	ALL
		ALL	`SortGB`
			`HashGB`
				`NestedLoopJN`
				`SortMergeJN`
				`HashJN`

	Lecture 07		**This Lecture** **Exercise 3**	

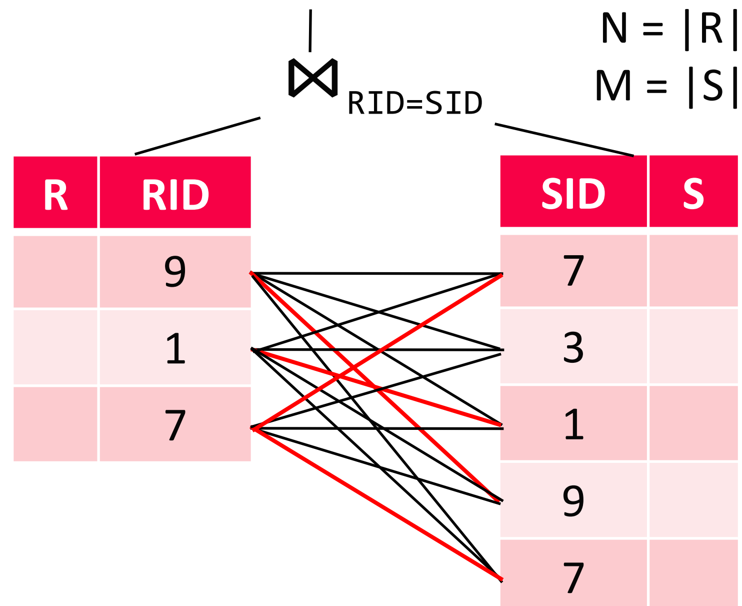
Nested Loop Join

- **Overview**
  - **Most general join operator** (no order, no indexes, arbitrary predicates θ)
  - **Poor asymptotic behavior** (very slow)

- **Algorithm** (pseudo code)

```
for each s in S
  for each r in R
    if( r.RID θ s.SID )
      emit concat(r, s)
```

How to implement **next()**?



- **Complexity**
  - Complexity: Time: **O(N * M)**, Space: **O(1)**
  - Pick smaller table as inner if it fits entirely in memory (buffer pool)

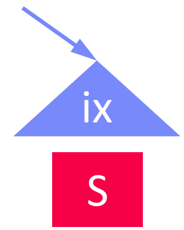
Block Nested Loop / Index Nested Loop Joins

- **Block Nested Loop Join**
  - Avoid I/O by blocked data access
  - Read blocks of b_R and b_S R and S pages
  - Complexity unchanged but potentially much fewer scans

```
for each block b_R in R
  for each block b_S in S
    for each r in b_R
      for each s in b_S
        if( r.RID θ s.SID )
          emit concat(r, s)
```

- **Index Nested Loop Join**
  - Use index to locate qualifying tuples (==, >=, >, <=, <)
  - Complexity (for equivalence predicates): Time: **O(N * log M)**, Space: **O(1)**

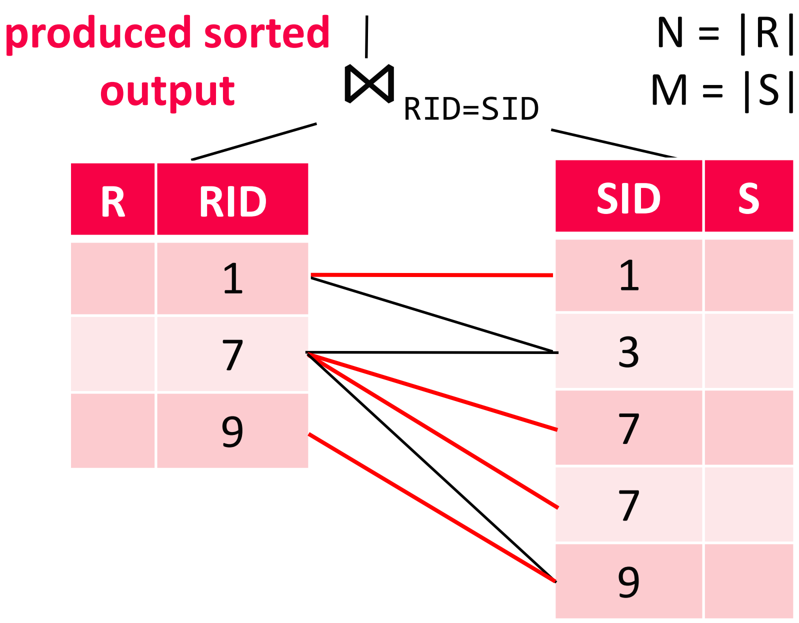
```
for each r in R
  for each s in S.IX(θ,r.RID)
    emit concat(r,s)
```



Sort-Merge Join

- **Overview**
  - **Sort Phase:** sort the input tables R and S (w/ external sort algorithm)
  - **Merge Phase:** step-wise merge with lineage scan
- **Algorithm** (Merge, PK-FK)

```
Record next() {
  while( curR!=EOF && curS!=EOF ) {
    if( curR.RID < curS.SID )
      curR = R.next();
    else if( curR.RID > curS.SID )
      curS = S.next();
    else if( curR.RID == curS.SID ) {
      t = concat(curR, curS);
      curS = S.next(); //FK side
      return t;
  } }
  return EOF;
}
```



- **Complexity**
  - Time (unsorted vs sorted): O(N log N + M log M) vs O(N + M)
  - Space (unsorted vs sorted): O(N + M) vs O(1)

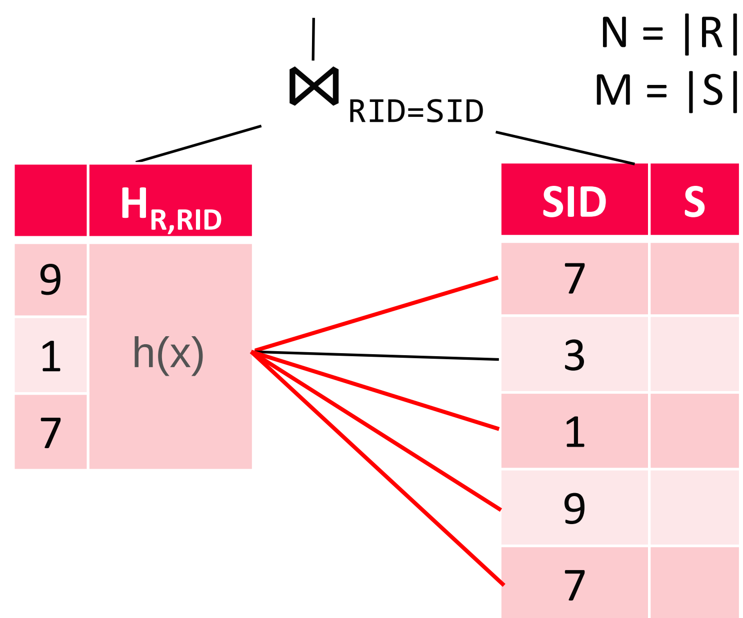
Hash Join

- **Overview**
  - **Build Phase:** read table S and build a hash table H_S over join key
  - **Probe Phase:** read table R and probe H_S with the join key
- **Algorithm** (Build+Probe, PK-FK)

```
Record next() {
  // build phase (first call)
  while( (r = R.next()) != EOF )
    Hr.put(r.RID, r);

  // probe phase
  while( (s = S.next()) != EOF )
    if( Hr.containsKey(s.SID) )
      return concat(Hr.get(s.SID), s);

  return EOF;
}
```



- **Complexity**
  - Time: O(N + M), Space: O(N)
  - Classic hashing: p in-memory partitions of Hr w/ p scans of R and S

Sort-GroupBy and Hash-GroupBy

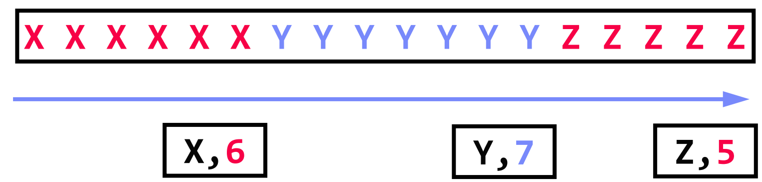
- **Recap: Classification of Aggregates (04 Relational Algebra)**
  - Additive, semi-additive, additively-computable, others

$\gamma_{A,\mathtt{count(*)}}(R)$

- **Sort Group-By**
  - Similar to sort-merge join (`Sort`, `GroupAggregate`)
  - Sorted group output

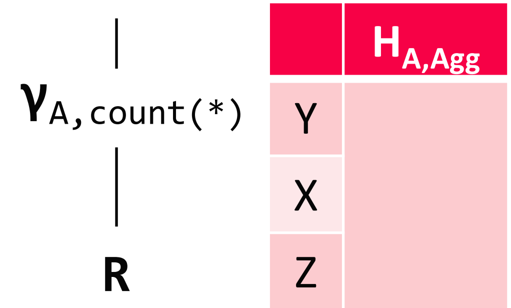
sort O(N log N)

aggregate O(N)



- **Hash Group-By**
  - Similar to hash join (`HashAggregate`)
  - Higher temporary memory consumption
  - Unsorted group output
  - **#1** w/ **tuple grouping**
  - **#2** w/ **direct aggregation** (e.g., count)
  - **Beware:** cache-unfriendly if many groups (size(H) > L2/L3 cache)

build & agg O(N)



Summary and Q&A

- **Query Rewriting and Optimization**
- **Plan Execution Strategies**
- **Physical Plan Operators**

- **Next Lectures**
  - **09 Transaction Processing and Concurrency** [May 10]

  - **10 NoSQL (key-value, document, graph)** [May 31]
  - **11 Distributed Storage and Data Analysis** [Jun 07]
  - **12 Data Stream Processing Systems and Q&A** [Jun 14]