CS525: Advanced Database Organization

Notes 6 - Part VI: Query Optimization - Physical

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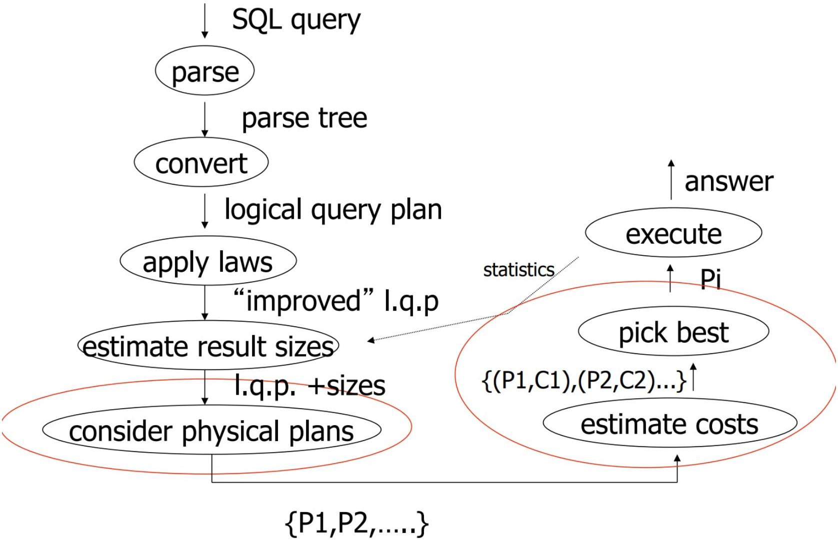
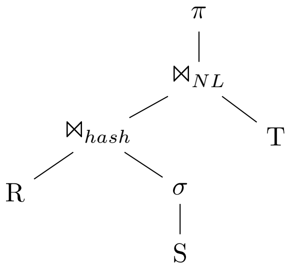
Slides: adapted from a courses taught by Hector Garcia-Molina, Stanford, T. Grust, Universitate Tuebingen & Distributed DBMS by M. Oezsu & P. Valduriez


SQL query
parse
parse tree
convert
logical query plan
apply laws
“improved” l.q.p
estimate result sizes
l.q.p. +sizes
consider physical plans
{P1,P2,…..}
estimate costs
{(P1,C1),(P2,C2)...}
pick best
Pi
execute
answer
statistics

Finding the “Best” Query Plan

```
SELECT ...
FROM   ...
WHERE  ...
```

$\xrightarrow{?}$



- We already saw that there may be more than one way to answer a given query.
  - Which one of the join operators should we pick? With which parameters (block size, buffer allocation,...)?
  - The task of finding the best execution plan is, in fact, the “holy grail” of any database implementation.

Cost of Query

- Parse + Analyze
  - Can parse SQL code in milliseconds
- Optimization - Find plan
  - Generating plans, costing plans
- Execution
  - Execute plan
- Return results to client
  - Can be expensive but not discussed here

Impact on Performance

- Finding the right plan can dramatically impact performance.

```sql
  -- Sample query over TPC-H tables
  -- Price and quantity of parts ordered by customer#1
SELECT L.L_PARTKEY, L.L_QUANTITY, L.L_EXTENDEDPRICE
FROM LINEITEM L JOIN  ORDERS O ON (L.L_ORDERKEY = O.O_ORDERKEY)
    JOIN CUSTOMER C ON (O.O_CUSTKEY = C.C_CUSTKEY)
WHERE C.C_NAME = 'Customer#1';
```

  - Above SQL syntax suggest the join order $(L \bowtie O) \bowtie C)$
  - Commutative and associativity of $\bowtie$ enable the RDBMS to reorder the joins - based on estimated evaluation costs.

- Finding the right plan can dramatically impact performance.

```sql
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  -- Price and quantity of parts ordered by customer#1
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    JOIN CUSTOMER C ON (O.O_CUSTKEY = C.C_CUSTKEY)
WHERE C.C_NAME = 'Customer#1';
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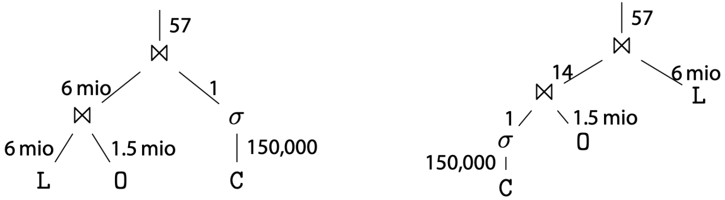


  - In terms of execution times, these differences can easily mean “seconds versus days.”

Theory vs. Implementation

- Theory
  - The join operator is (in theory) commutative: (i.e.: symmetric in behavior)
    - $R \bowtie S = S \bowtie R$
- Practice:
  - The algorithms that implement the join operation are Asymmetric
    - i.e., the role of the first input relation is different from the role of the second input relation

Ordering of join operators

- Fact:
  - The join operator is associative and communicative
    - It's just like the add (+) operator:

```
4 + 7 + 6 + 3  =  (4 + 6) + (3 + 7)  =  20
```

    - We can re-order the sequence of operations
- In general:
  - When there are ≥ 3 relations in a join operations, we must find an order of join that yields the best performance
- Note
  - Due to asymmetry in the implementation algorithms, we will need to pick an order even when there are only 2 relations:

$$R \bowtie S \quad \Longleftrightarrow \quad S \bowtie R$$

    because the running time is better when the first relation is smaller in many implementations !!!

Cost-Based Optimization: Overall idea

- The optimizer's task to come up with the optimal execution plan for the given query.
- Essentially, the optimizer
  - Apply after applying heuristics in logical optimization
  1. enumerates all possible execution plans, (if this yields too many plans, at least enumerate the "promising" plan candidates)
  2. estimates/determines the cost of each plan
  3. chooses the best one as the final execution plan.
     - i.e., picks plan with least estimated costs
- To apply pruning in the search for the best plan
  - Steps 1 and 2 have to be interleaved
  - Prune parts of the search space
    - if we know that it cannot contain any plan that is better than what we found so far
- Before we can do so, we need to answer the question
  - *What is a "good" execution plan at all?*

Cost Metrics

- Database systems judge the quality of an execution plan based on a number of cost factors, e.g.,
  - the number of disk I/Os required to evaluate the plan,
  - the plan's CPU cost,
  - the overall response time observable by the database client as well as the total execution time.
- A cost-based optimizer tries to anticipate these costs and find the cheapest plan before actually running it
  - All of the above factors depend on one critical piece of information: the size of (intermediate) query results.
  - Database systems, therefore, spend considerable effort into accurate result size estimates.

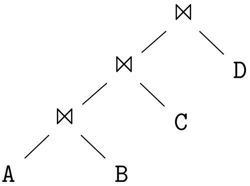
Search Space

- Search space: The set of alternative query execution plans (query trees)
  - Typically very large
  - The main issue is to optimize the joins
  - For `n` relations, there are `O(n!)` equivalent join trees that can be obtained by applying commutativity and associativity rules

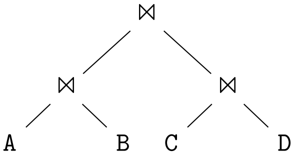
Search Space

- Restrict by means of heuristics
  - Perform unary operations before binary operations, etc.
- Restrict the shape of the join tree
  - Consider the type of trees (linear trees, vs. bushy ones)

- Linear Join Tree



- Bushy Join Tree



Plan Enumeration

- For each operator in the query
  - Several implementation options
- Binary operators (joins)
  - Changing the order may improve performance a lot!
- Consider both different implementations and order of operators in plan enumeration

Join Order

- For a query plan that contains multiple order, we often have a choice in which order we execute the different join operations.
- Notice that a particular order assumes a suitable join predicate on all pairwise joins.
- If not such predicate exists, that pairwise join is equal to a cross product and hence it is likely the particular join order does not have to be considered for query optimization.
- Q: What may be the effect of picking the wrong join order?
  - If we pick an unsuitable join order, we may end up with a slow query plan
- Q: Is join order problem only relevant for joins?
  - No, the "join order" problem exists for all binary operations that are commutative and associative, e.g., union, intersection, and cross product

Agenda : Join Optimization

- Given some query
  - How to enumerate all plans?
- Try to avoid cross-products
- Need way to figure out if equivalences can be applied
  - Data structure: Join Graph

Queries Considered

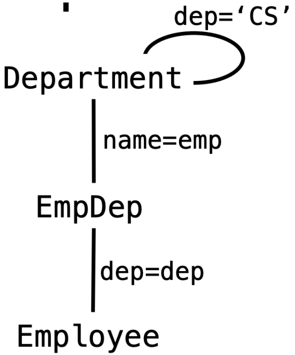
- Concentrate on join ordering, that is:
  - conjunctive queries (Only conjunctive join conditions)
  - simple predicates
  - predicates have the form $\texttt{a}_1 = \texttt{a}_2$ where $\texttt{a}_1$ is an attribute and $\texttt{a}_2$ is either an attribute or a constant
- We join relations $\texttt{R}_1, \ldots, \texttt{R}_\texttt{n}$ where $\texttt{R}_\texttt{i}$ can be
  - a base relation
  - a base relation including selections
  - a more complex building block or access path

Join Graph

- Queries of this type can be characterized by their query graph:
  - A more natural data structure for representation of a query is the query graph notation.
  - the query graph is an undirected graph with $\mathtt{R_1,\ldots,R_n}$ as nodes
  - a predicate of the form $\mathtt{a_1 = a_2}$, where $\mathtt{a_1} \in \mathtt{R_i}$ and $\mathtt{a_2} \in \mathtt{R_j}$ forms an edge between $\mathtt{R_i}$ and $\mathtt{R_j}$ labeled with the predicate
  - a predicate of the form $\mathtt{a_1 = a_2}$, where $\mathtt{a_1} \in \mathtt{R_i}$ and $\mathtt{a_2}$ is a constant forms a self-edge on $\mathtt{R_i}$ labeled with the predicate
  - most algorithms will not handle self-edges, they have to be pushed down
- *Query Graph which has the query relations as nodes and the joins between relations as undirected edges*

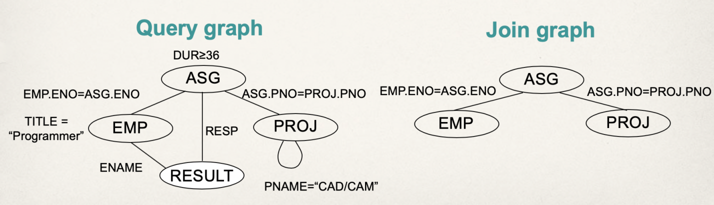
Join Graph: Example

```
SELECT e.name
FROM Employee e,
     EmpDep ed,
     Department d
WHERE e.name = ed.emp
      AND ed.dep = d.dep
      AND d.dep = 'CS'
```



Query Graph: Example

```
SELECT ENAME,RESP
FROM   EMP, ASG, PROJ
WHERE  EMP.ENO = ASG.ENO AND  ASG.PNO = PROJ.PNO AND PNAME = "CAD/CAM"
       AND DUR >= 36 AND   TITLE = "Programmer"
```

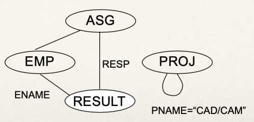


- Join graph: A subgraph of query graph for join operation.

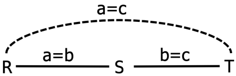
Notes on Join Graph

- If the query graph is not connected, the query may be wrong or use Cartesian product

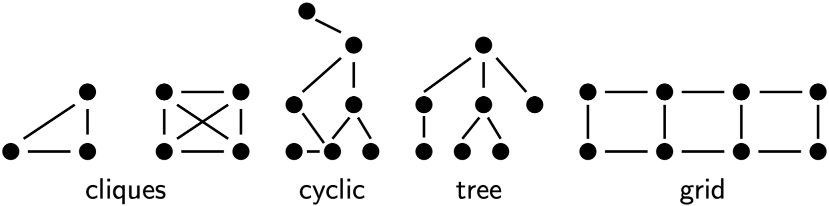
```sql
SELECT ENAME,RESP
FROM   EMP, ASG, PROJ
WHERE  EMP.ENO = ASG.ENO AND  PNAME = "CAD/CAM"
       AND DUR >= 36 AND TITLE = "Programmer"
```



- Join Graph tells us in which ways we can join without using cross products
- However, ...
  - Only if transitivity is considered



Shapes of Join Graphs



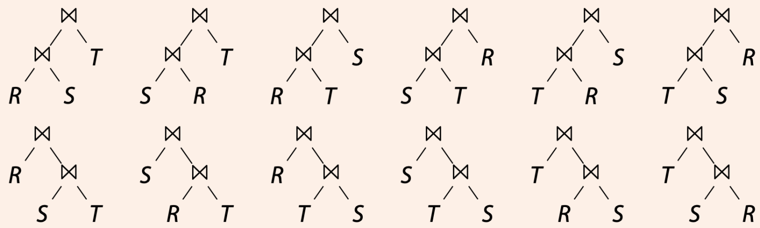
- real world queries are somewhere in-between
- chain, cycle, star and clique are interesting to study
- they represent certain kind of problems and queries

Join Ordering and Join Trees

- A join tree is a binary tree where the internal nodes are are join operators and the leaf nodes are relations
- Algorithms will produce different kinds of join trees
- Shape of Join Trees
  - Commonly used classes of join trees:
    - left-deep tree
    - right-deep tree
    - zigzag tree
    - bushy tree
  - The first three are summarized as linear trees
- A join tree will represent a unique ordering of join operations
  - We will use join trees to represent the join order explicitly

How many join orders?

- Assumption
  - Joins are binary operations
    - Two inputs
    - Each input either join result or relation access
- Example: 3 relations `R,S,T`: Ways of building a 3-way join from two 2-way joins
  - 12 orders



- How many join orders? How Many Such Combinations Are There?

Finding the optimal join-tree: search space analysis

- Consider the possible join ordering when there are 3 relations:

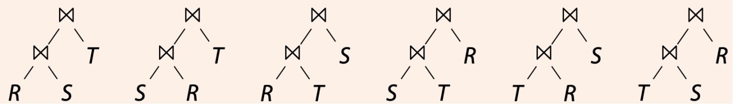
```
Form 1:
   ( R ⋈ S ) ⋈ T       ( S ⋈ R ) ⋈ T
   ( R ⋈ T ) ⋈ S       ( T ⋈ R ) ⋈ S
   ( S ⋈ T ) ⋈ R       ( T ⋈ S ) ⋈ R

Form 2:
   R ⋈ ( S ⋈ T )       R ⋈ ( T ⋈ S )
   S ⋈ ( R ⋈ T )       S ⋈ ( T ⋈ R )
   T ⋈ ( R ⋈ S )       T ⋈ ( S ⋈ R )
```

- The number of different join orderings of `n` relations is exponentially large
- Because the number of permutations is exponentially large
  - The number of possible join trees to consider is just too large
  - We need to reduce the search space.
- Some type of trees in better than others: the left-deep tree

Search space for left-Deep trees

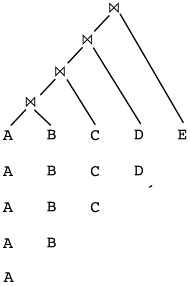
- Left-Deep Tree
  - Given a sequence of input relations $R_1, R_2, \ldots, R_n$, a left-deep tree starts by a binary join on R_1 and R_2. Then it iteratively adds binary joins $R_3, \ldots, R_n$.
- Example: 3 way join: $R \bowtie S \bowtie T$
  - The possible left-deep join trees are:



  - `# left deep tree = 6 (= 3!)`
- *Number of possible left-deep join trees for n input relations is $n!$ (factorial)*

Search space for left-Deep trees: Example

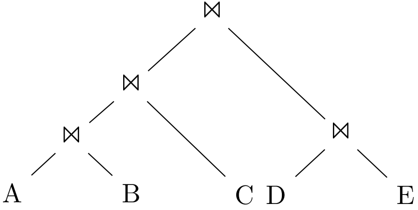
- Starting by joining two relations `A ⋈ B` then the result joining with the next relation, and so on



- `# of options in terms of structure (# of unlabeled trees (varies)) = 1`
- `# different order (# of leaf combinations) = n!=5!=120`
- `# of join left-deep trees = # of leaf combinations` $\times$ `# of unlabeled trees (varies) = n!`$\times$ `1 = n!`

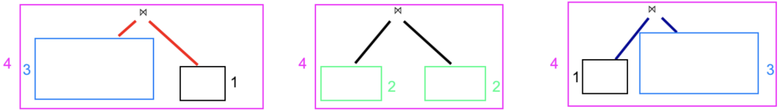
Search space for not a left-Deep trees: Bushy Tree

- Bushy Tree
  - Tree that is not left-deep, i.e., at least for one of the joins in that plan its right input is not an input relation but another join operation.
  - Notice that the union of the set of bushy trees and the set of left-deep tress forms the set of all possible trees.

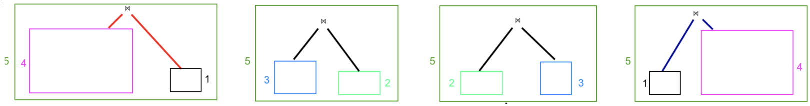


Search space for not a left-Deep trees: Bushy Tree

$\Rightarrow$ 2 options



$\Rightarrow$ 5 options



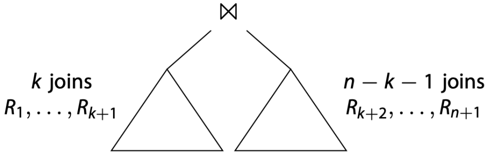
$\Rightarrow$ 14

options

- This can be expressed mathematically by `Catalan Numbers`
- *Catalan numbers C_n, the number of orders binary tress with $n + 1$ leaves. C_0=1*

How Many Such Combinations Are There?

1. A join over `n+1` relations $R_1, \ldots, R_{n+1}$ requires `n` binary joins.
   - The root join combines subtrees of `k` and `n-k-1` join operators ($0 \leq k \leq n-1$):



   - Let C_i be the number of possibilities to construct a binary tree of `i` inner nodes (join operators):

$$C_n = \sum_{k=0}^{n-1} C_k \; C_{n-k-1}$$

2. Orderings of the input relations at the join tress leaf level: $(n+1)!$
3. Join algorithm choices (a available algorithms): a^n

Catalan Numbers

- This recurrence relation is satisfied by Catalan numbers:

$$\mathtt{C_n} = \begin{cases} 1, & \texttt{if n=0} \\ \sum_{k=0}^{n-1} C_k C_{n-k-1}, & \texttt{n>0} \end{cases}$$

- describing the number of ordered binary trees with `n + 1` leaves.
- It can be written in a closed form as $C_n = \frac{1}{n+1}\binom{2n}{n} = \frac{(2n)!}{(n+1)!n!}$
- For **each** of these trees, we can **permute** the input relations `(n+1)!` permutations, leading to:

Number of possible join trees for an (n+1)-way relational join

- $\frac{(2n)!}{(n+1)!n!} \times (n+1)! = \frac{(2n)!}{n!}$

Search Space

- The resulting search space is enormous:
- Possible bushy join trees joining `n` relations

number of relations n	C_{n-1}	join trees
2	1	2
3	2	12
4	5	120
5	14	1,680
6	42	30,240
7	132	665,280
8	429	17,297,280
10	4,862	17,643,225,600

- And we haven't yet even considered the use of `a` different join algorithms (yielding another factor of $\mathtt{a}^{(\mathtt{n-1})}$)

Sample Numbers, with Cross Products

n	Left-Deep $n!$	Bushy $n!\mathcal{C}(n-1)$
1	1	1
2	2	2
3	6	12
4	24	120
5	120	1680
6	720	30240
7	5040	665280
8	40320	17297280
9	362880	518918400
10	3628800	7643225600

How many join orders?

- If for each join we consider `a` join algorithms then for `n` relations we have
  - Multiply with a factor $\mathtt{a}^{\mathtt{n-1}}$
- Example consider
  - Nested loop
  - Merge
  - Hash

How many join orders?

#relations	#join trees
2	6
3	108
4	3240
5	136,080
6	7,348,320
7	484,989,120
8	37,829,151,360
9	115,757,203,161,600
10	13,196,321,160,422,400
11	1,662,736,466,213,222,400

Too many join orders?

- How to deal with excessive number of combinations?
  - Prune parts based on optimality
    - Dynamic programming
  - Only consider certain types of join trees
    - Left-deep, Right-deep, zig-zag, bushy
  - Heuristic and random algorithms

What is dynamic programming?

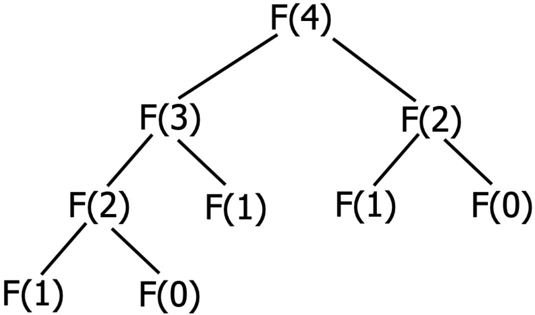
- Recall data structures and algorithms
- Consider a Divide-and-Conquer problem
  - Solutions for a problem of size `n` can be build from solutions for sub-problems of smaller size (e.g., $\frac{\mathtt{n}}{\mathtt{2}}$ or `n-1`)
- Memoize
  - Store solutions for sub-problems
  - Each solution has to be only computed once
  - Needs extra memory

Example Fibonacci Numbers

- F(n) = F(n-1) + F(n-2)
- F(0) = F(1) = 1

```
 // nth Fibonacci number
 Fib(n){
   if (n <= 1) return n
   else return Fib(n-1) + Fib(n-2)
}
```

Example Fibonacci Numbers

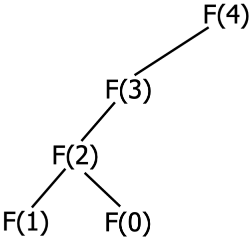


- Complexity
  - Number of calls
    - `T(n) = T(n-1) + T(n-2) +` θ`(1)`
    - `T(n) = O(`2^n`)`

Using dynamic programming

```
Fib(n)
{
   int[] fib; // Declare an array to store Fibonacci numbers.
   fib[0] = 0; // 0th and 1st number of the series are 0 and 1
   fib[1] = 1;
   for(i = 2; i <= n; i++)
       fib[i] = fib[i-1] + fib[i-2]
   return fib[n];
}
```

Example Fibonacci Numbers



What do we gain?

- `O(n)` instead of `O(2^n)`

Dynamic Programming for Join Enumeration

- The traditional approach to master this search space is the use of dynamic programming
- **Problem:** Find optimal query plan `opt[{`R_1`,...,`R_n`}]` that joins `n` inputs $R_1,\ldots,R_n$.
  1. **Iteration 1**:
     For each R_j, find and memorize `best 1-input plan` `opt[{`R_j`}]` that access R_j only.
  2. **Iteration `k>1`**:
     Find and memorize the `best` k`-input plans` that joins `k`$\leq$ `n` inputs by combining (`for 1`$\leq$`i`$\leq$`k`)
     - the `best i-input plans`
     - the `best (k-i)-input plans`
       (simple lookups in `opt[.]` memo)

DP: Example (Four-way join of tables $R_1, \ldots, R_4$)

- **Pass 1** (best 1-relation plans)
  - Find the best **access path** to each of the R_i individually (considers index scans, full table scans).
- **Pass 2** (best 2-relation plans)
  - For each **pair** of tables R_i and R_j, determine the best order to join R_i and R_j (use $R_i \bowtie R_j$ or $R_j \bowtie R_i$?):

    $$\mathit{optPlan}(\{R_i, R_j\}) \leftarrow \text{best of } R_i \bowtie R_j \text{ and } R_j \bowtie R_i$$

    $\Rightarrow$ 12 plans to consider
- **Pass 3** (best 3-relation plans)
  - For each **triple** of tables R_i and R_j, and R_k, determine the best three-table join plan, using sub-plans obtained so far:

    $$\mathit{optPlan}(\{R_i, R_j, R_k\}) \leftarrow \text{best of } R_i \bowtie \mathit{optPlan}(\{R_j, R_k\}),\ \mathit{optPlan}(\{R_j, R_k\}) \bowtie R_i,\ R_j \bowtie \mathit{optPlan}(\{R_i, R_k\}), \ldots$$

    $\Rightarrow$ 24 plans to consider.

DP: Example-Four-way join of tables $R_1, \ldots, R_4$) cont'd

- **Pass 4** (best 4-relation plans)
  - For each **four** of tables R_i and R_j, R_k, and R_l, determine the best four-table join plan, using sub-plans obtained so far:

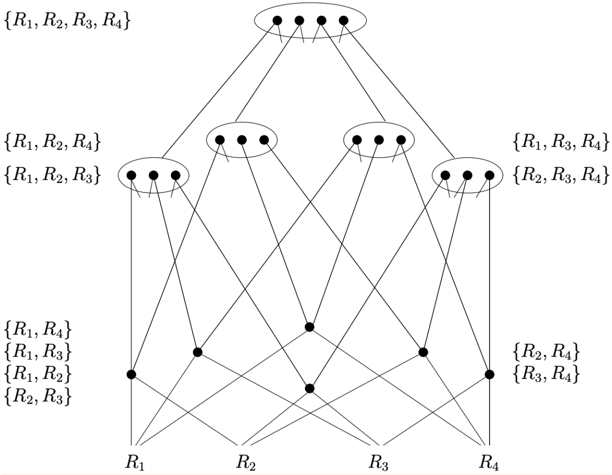
    $optPlan(\{R_i, R_j, R_k, R_l\}) \leftarrow$ best of
    $R_i \bowtie optPlan(\{R_j, R_k, R_l\}), optPlan(\{R_j, R_k, R_l\}) \bowtie R_i,$
    $R_j \bowtie optPlan(\{R_i, R_k, R_l\}), \ldots, optPlan(\{R_i, R_j\}) \bowtie optPlan(\{R_k, R_l\})$

    $\Rightarrow$ 14 plans to consider.

- Overall, we looked at only 50 (sub-)plans (instead of the possible 120 four-way join plans
- All decisions required the evaluation of **simple** sub-plans only (**no need to re-evaluate** ***optPlan(.)*** for already known relation combinations $\Rightarrow$ use lookup table).
- And we haven't considered the use of different join algorithms

Sharing Under the Optimality Principle

- Sharing optimal sub-plans



Dynamic Programming Algorithm

Find optimal *n*-way bushy join tree via dynamic programming

Function: `find_join_tree_dp` ($q(R_1, \ldots, R_n)$)

for $i = 1$ **to** n **do**
- $\mathit{optPlan}(\{R_i\}) \leftarrow$ `access_plans` (R_i) ;
- `prune_plans` $(\mathit{optPlan}(\{R_i\}))$;

for $i = 2$ **to** n **do**
- **foreach** $S \subseteq \{R_1, \ldots, R_n\}$ **such that** $|S| = i$ **do**
  - $\mathit{optPlan}(S) \leftarrow \varnothing$;
  - **foreach** $O \subset S$ with $O \neq \varnothing$ **do**
    - $\mathit{optPlan}(S) \leftarrow \mathit{optPlan}(S) \cup$ `possible_joins` $\left[\mathit{optPlan}(O) \bowtie \mathit{optPlan}(S \setminus O) \right]$;
  - `prune_plans` $(\mathit{optPlan}(S))$;

return $\mathit{optPlan}(\{R_1, \ldots, R_n\})$;

- *possible_joins* `[R ⋈ S]` enumerates the possible joins between `R` and `S` (nested loops join, merge join, etc.).
- *prune_plans* `(set)` discards all but the best plan from `set`.

Dynamic Programming - Discussion

- *find_join_tree_dp* () draws its advantage from **filtering** plan candidates early in the process.
  - In our example, pruning in Pass 2 reduced the search space by a factor of 2, and another factor of 6 in Pass 3.
- Some **heuristics** can be used to prune even more plans:
  - Try to avoid **Cartesian products**.
  - Produce **left-deep plans** only (see next slides).

Left/Right-Deep vs. Bushy Join Trees

- The algorithm on slide 43 explores all possible shapes a join tree could take
- Actual systems often prefer left-deep join trees.
  - The **inner** (rhs) relation always is a **base relation**.
  - Easier to implement in a **pipelined** fashion.

Revisiting the assumption

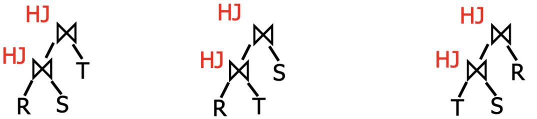
- Is it really sufficient to only look at the best plan for every sub-query?
- Cost of merge join depends whether the input is already sorted
  - A sub-optimal plan may produce results ordered in a way that reduces cost of joining above
  - Keep track of interesting orders
  - i.e., the notion of interesting orders allowed query optimizers to consider plans that could be locally sub-optimal, but produce ordered output beneficial for other operators, and thus be part of a globally optimal plan.

Interesting Orders

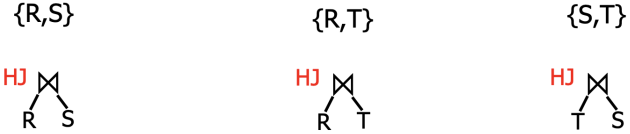
- Number of interesting orders is usually small
- Extend DP join enumeration to keep track of interesting orders
  - Determine interesting orders
  - For each sub-query store best-plan for each interesting order
- In *prune_plans*(), retain
  - the cheapest "unordered" plan and
  - the cheapest plan for each interesting order.

Example Interesting Orders

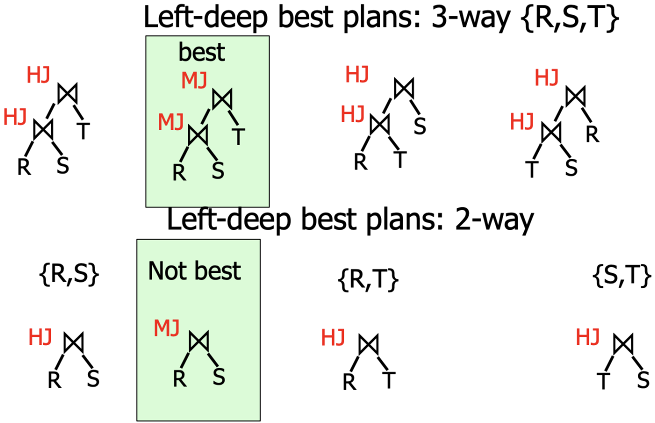
Left-deep best plans: 3-way {R,S,T}



Left-deep best plans: 2-way



Example Interesting Orders



Joining Many Relations

- Dynamic programming still has exponential resource requirements[1]:
  - time complexity: $O(3^n)$
  - space complexity: $O(2^n)$
- This may still be too expensive
  - for joins involving many relations ($\sim$ 10-20 and more),
  - for simple queries over well-indexed data (where the right plan choice should be easy to make).
- The greedy join enumeration algorithm jumps into this gap.

[1] K. Ono, G.M. Lohman, Measuring the Complexity of Join Enumeration in Query Optimization, VLDB 1990

Greedy Join Enumeration

- Heuristic method
  - Not guaranteed that best plan is found
- Start from single relation plans
- In each iteration greedily join to plans with the minimal cost
- Until a plan for the whole query has been generated

Other join enumeration techniques

- Randomized algorithms
  - randomly rewrite the join tree one rewrite at a time; use **hill-climbing** or **simulated annealing** strategy to find optimal plan.
- Genetic algorithms

Summary: (Join) Optimization

- Find "best" query execution plan based on a cost model (considering I/O cost, CPU cost,...); data statistics (histograms); dynamic programming, greedy join enumeration; physical plan properties (interesting orders).