CS 525: Advanced Database Organization

11: Query Optimization Physical

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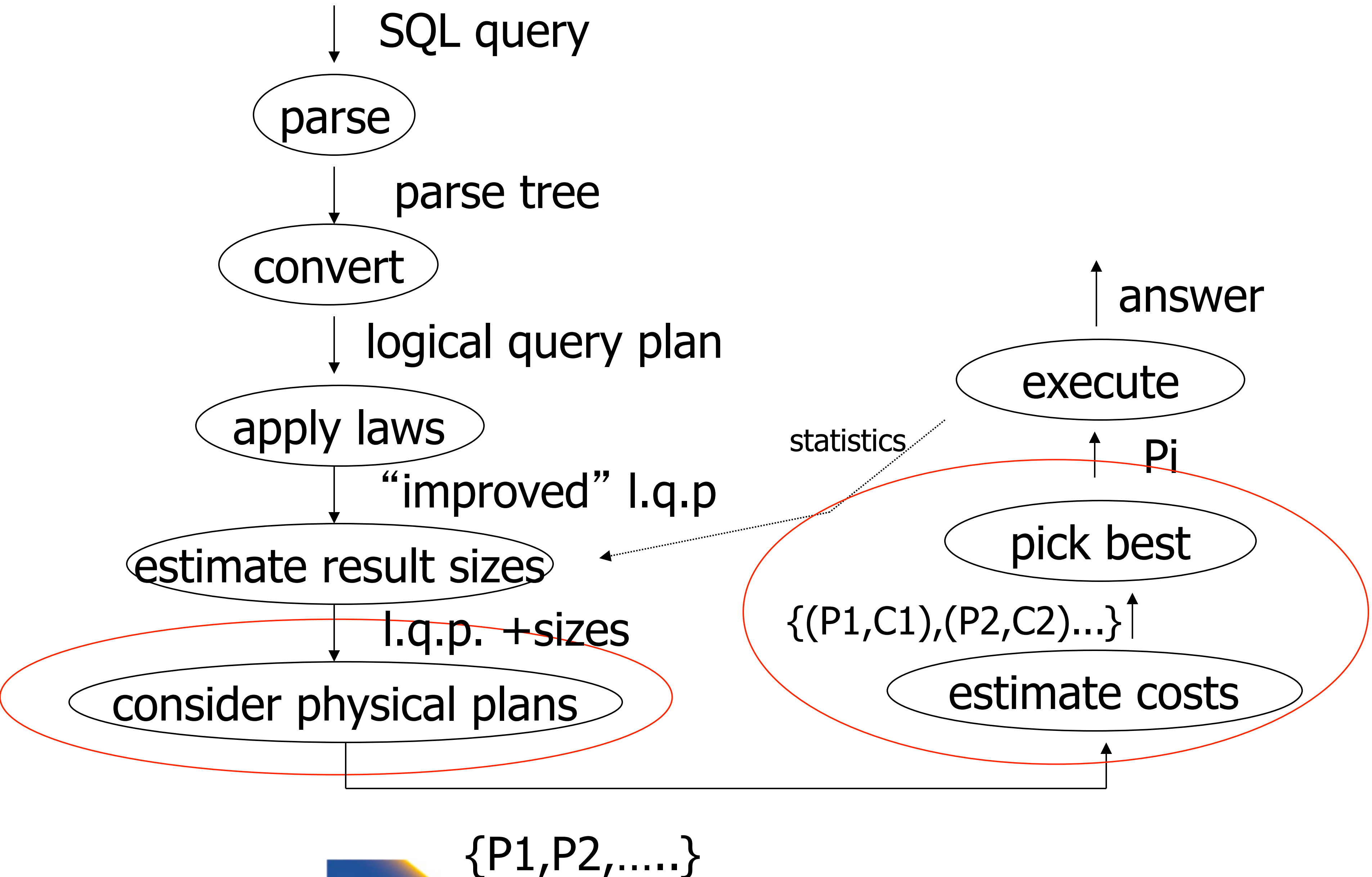
Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab


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

Cost of Query

- Parse + Analyze
- Optimization – Find plan
- Execution
- Return results to client

Cost of Query

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

Physical Optimization

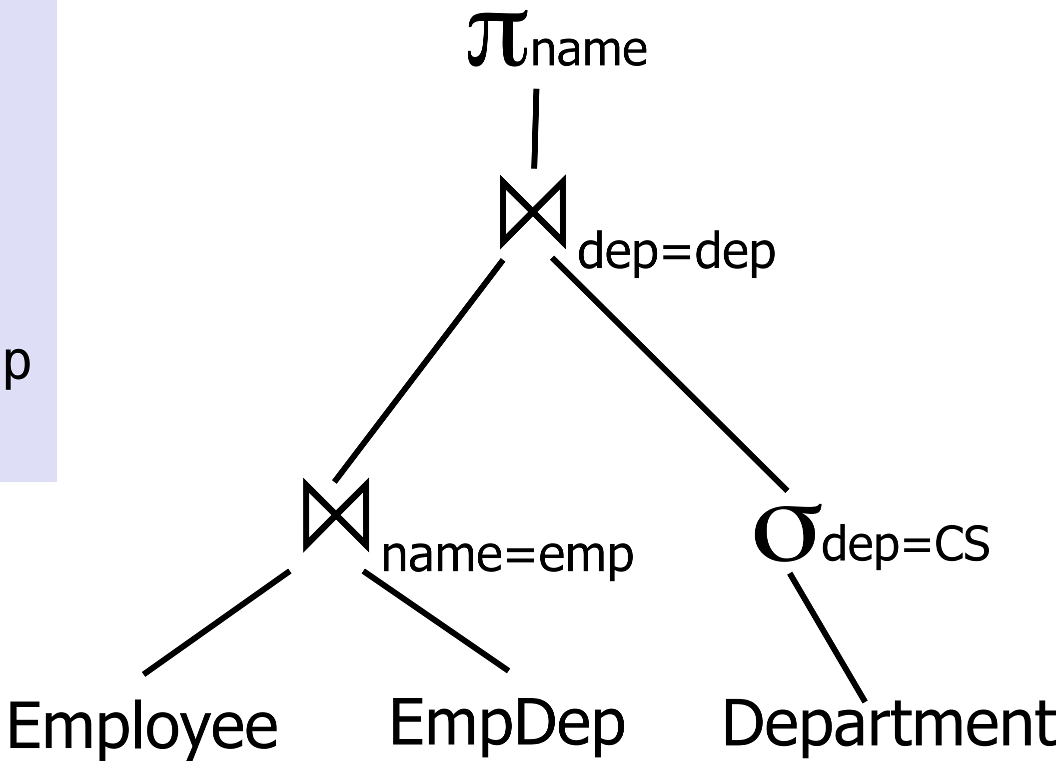
- Apply after applying heuristics in logical optimization
- 1) Enumerate potential execution plans
  - All?
  - Subset
- 2) Cost plans
  - What cost function?

Physical Optimization

- 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

Example Query

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



Example Query – Possible Plan

```
SELECT e.name
FROM Employee e,
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WHERE e.name = ed.emp
      AND ed.dep = d.dep
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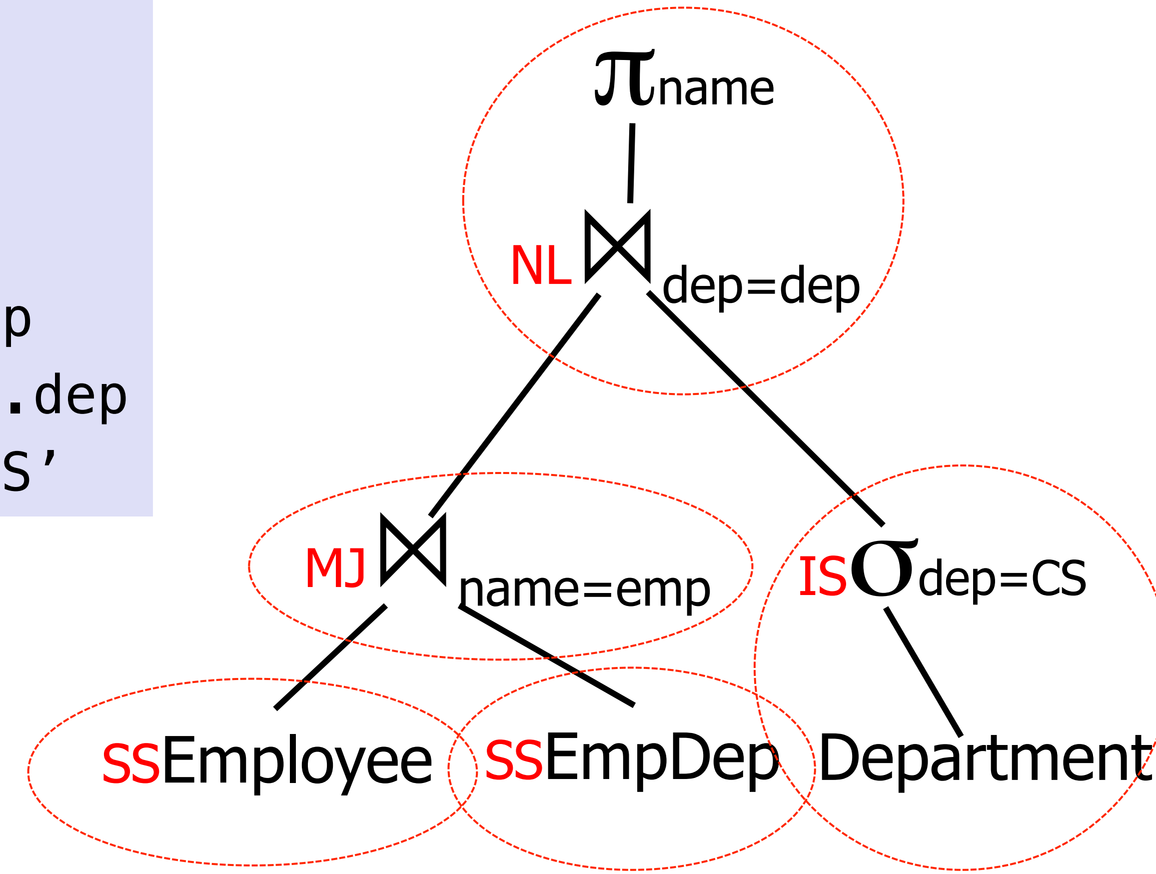


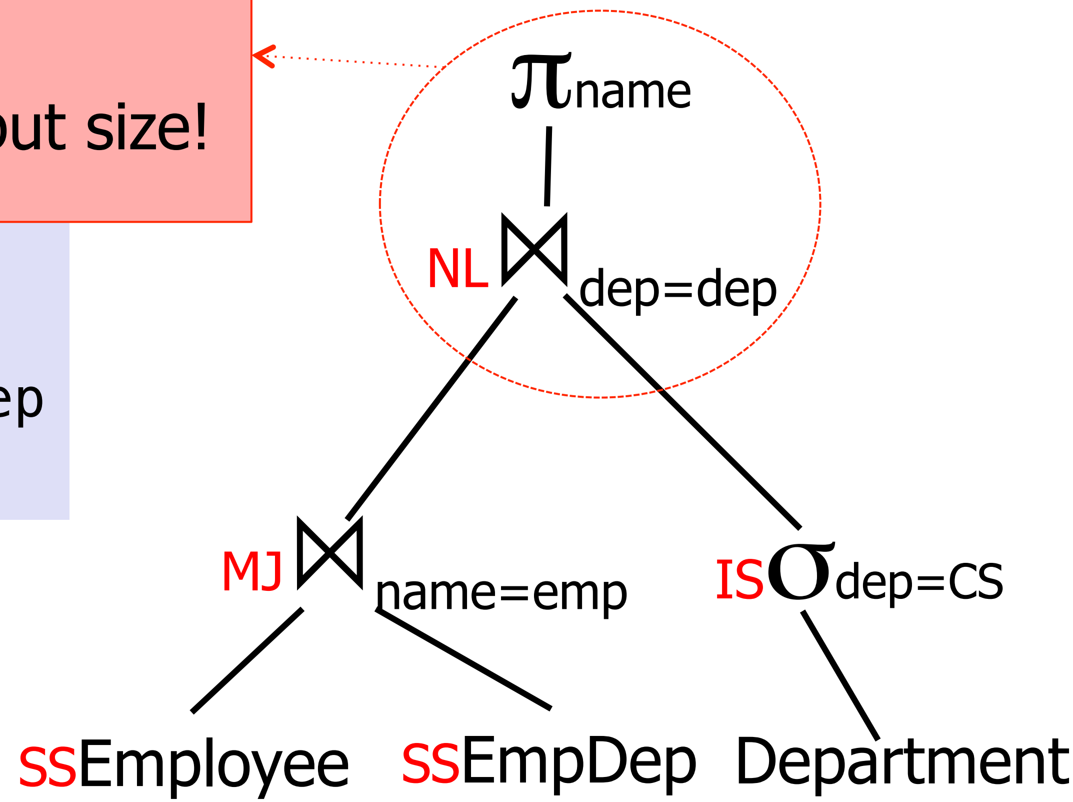
Cost Model

- Cost factors
  - **#disk I/O**
  - **CPU cost**
  - Response time
  - Total **execution time**
- Cost of operators
  - I/O as discussed in query execution (part 10)
  - Need to know **size of intermediate results** (part 09)

Example Query – Possible Plan

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

Cost?
Need input size!



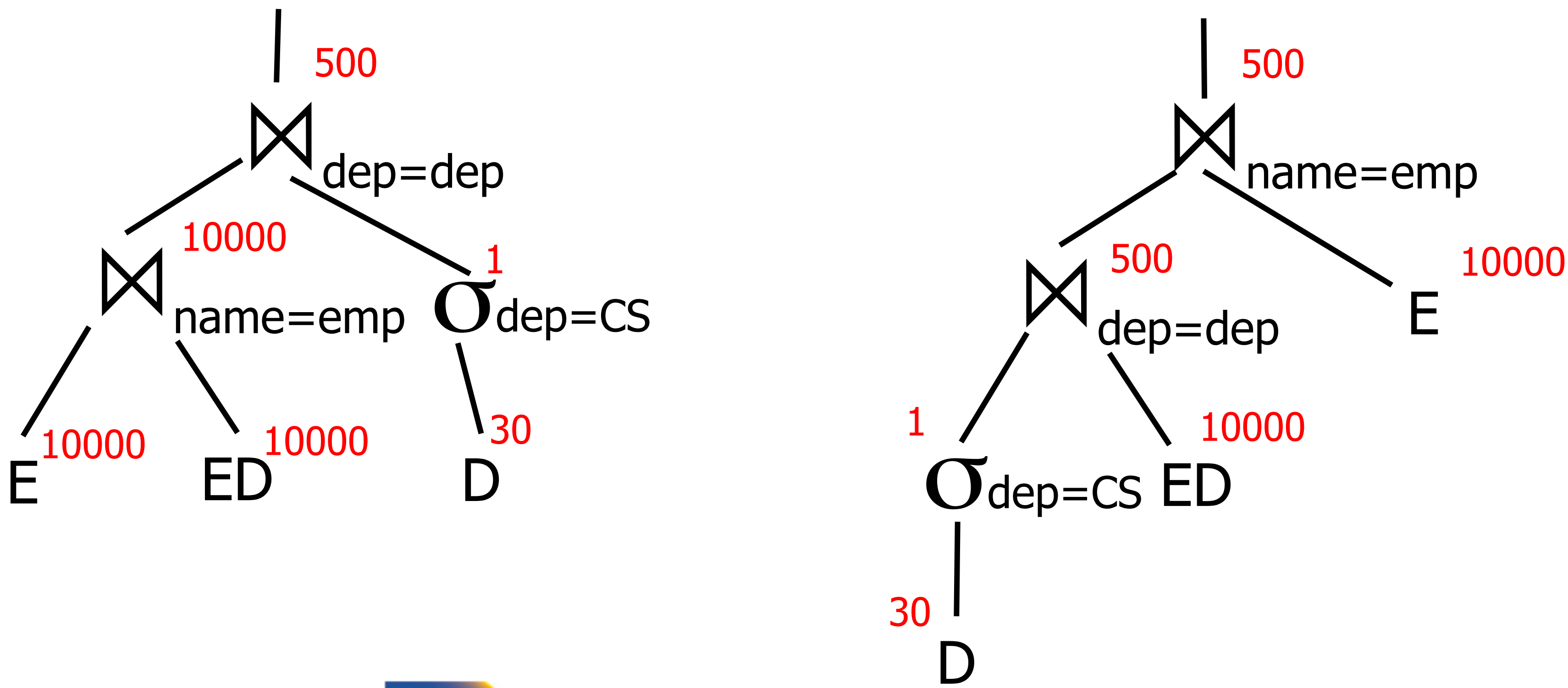
Cost Model Trade-off

- **Precision**
  - Incorrect cost-estimation -> choose suboptimal plan
- **Cost of computing cost**
  - Cost of costing a plan
    - We may have to cost millions or billions of plans
  - Cost of maintaining statistics
    - Occupies resources needed for query processing

Plan Enumeration

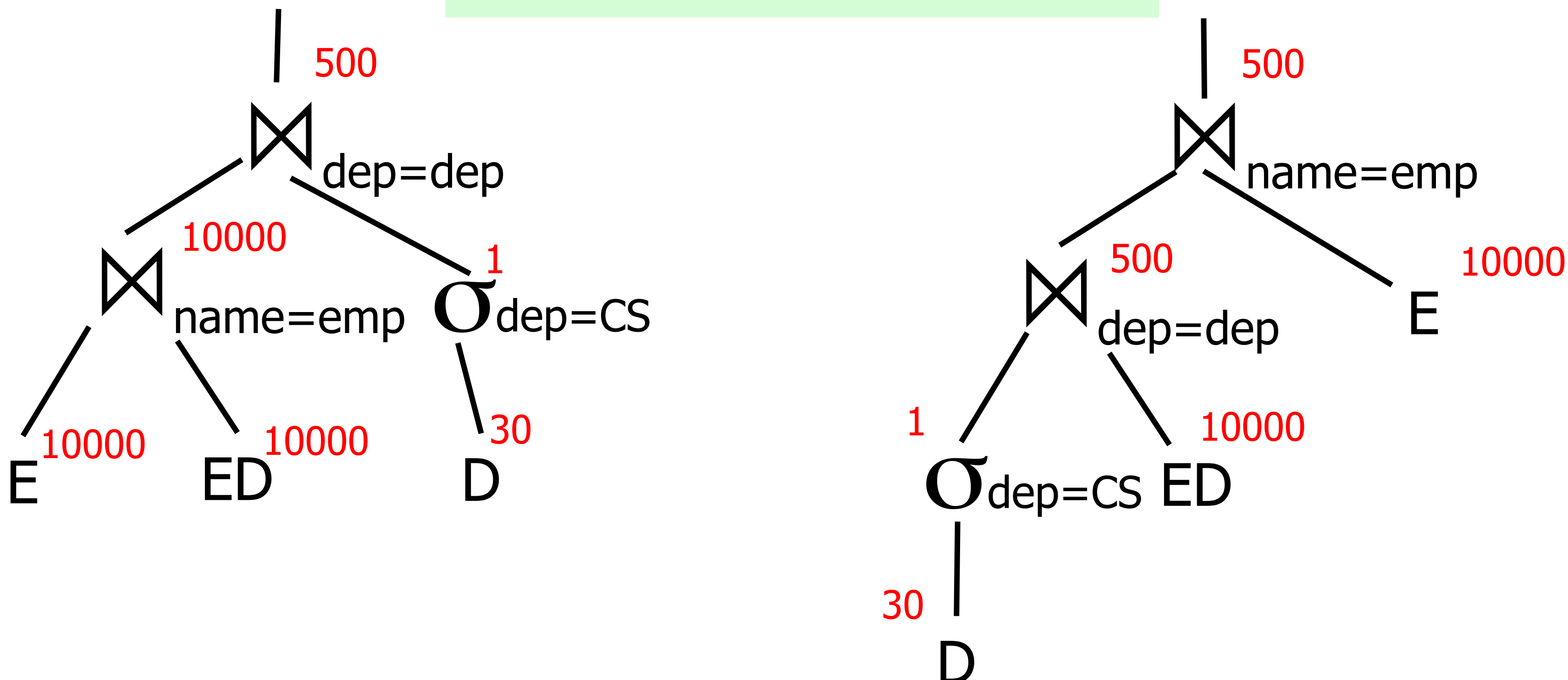
- For each operator in the query
  - Several implementation options
- Binary operators (joins)
  - Changing the order may improve performance a lot!
- -> consider both **different implementations** and **order of operators** in plan enumeration

Example Join Ordering Result Sizes



Example Join Ordering Cost (only NL)

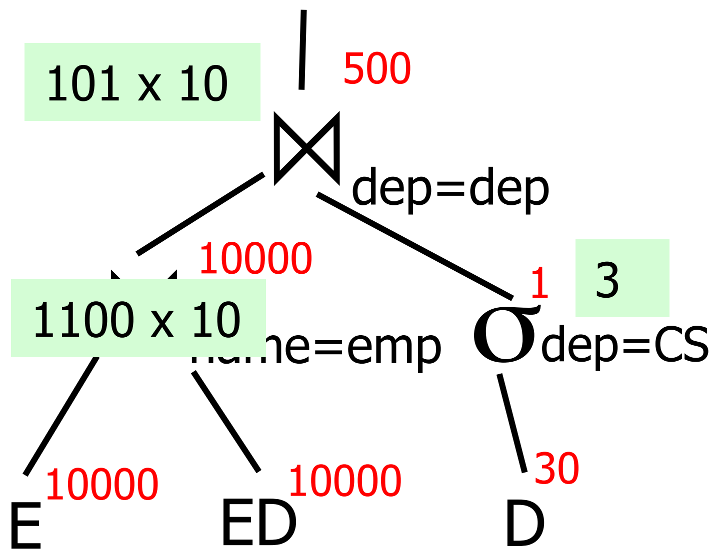
S(E) = S(ED) = S(D) = 1/10 block
M = 101

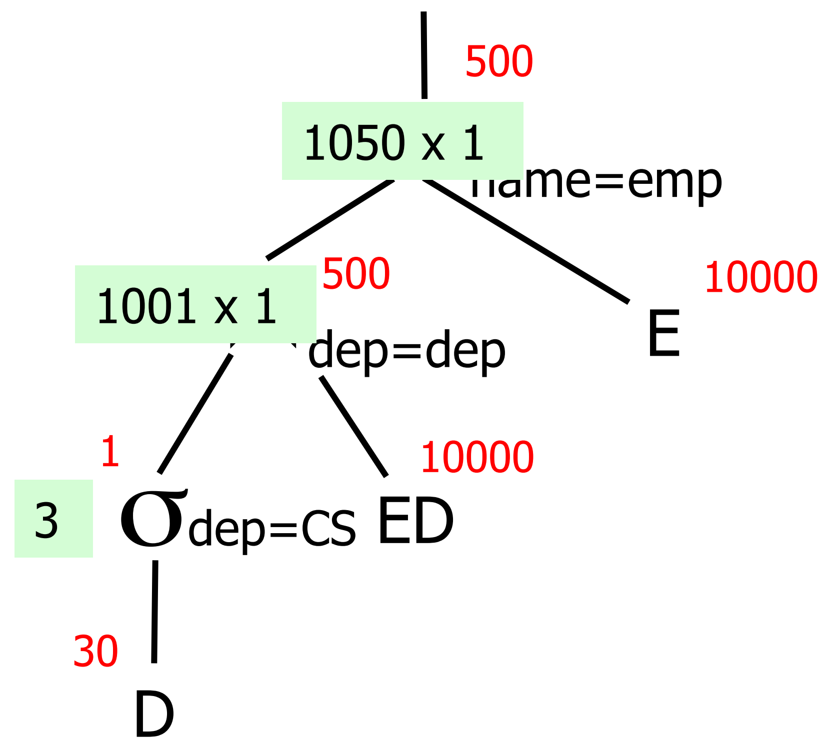


S(E) = S(ED) = S(D) = 1/10 block
M = 101
I/O costs only
No pipelining, write all results to disk

1100 x 10 + 101 x 10 + 3 (operator costs)
+ 1000 + 1 + 50 (write results)
= 13064 I/Os

1001 + 1050 + 3 (operator costs)
+ 1 + 50 + 50
= 2155 I/Os





Plan Enumeration

- All
  - Consider all potential plans of a certain type (discussed later)
  - Prune only if sure
- Heuristics
  - Apply heuristics to prune search space
- Randomized Algorithms

Plan Enumeration Algorithms

- All
  - Dynamic Programming (System R)
  - A* search
- Heuristics
  - Minimum Selectivity, Intermediate result size, …
  - KBZ-Algorithm, AB-Algorithm
- Randomized
  - Genetic Algorithms
  - Simulated Annealing

Reordering Joins Revisited

- Equivalences (Natural Join)
  1. $R \bowtie S \equiv S \bowtie R$
  2. $(R \bowtie S) \bowtie T \equiv R \bowtie (S \bowtie T)$
- Equivalences Equi-Join
  1. $R \bowtie_{a=b} S \equiv S \bowtie_{a=b} R$
  2. $(R \bowtie_{a=b} S) \bowtie_{c=d} T \equiv R \bowtie_{a=b} (S \bowtie_{c=d} T)$?
  3. $\sigma_{a=b} (R \text{ X } S) \equiv R \bowtie_{a=b} S$?

Equi-Join Equivalences

- $(R \bowtie_{a=b} S) \bowtie_{c=d} T \equiv R \bowtie_{a=b} (S \bowtie_{c=d} T)$
  - What if c is attribute of R?

$(R \bowtie_{a=b} S) \bowtie_{c=d} T \equiv R \bowtie_{a=b \wedge c=d} (S \text{ X } T)$

- $\sigma_{a=b} (R \text{ X } S) \equiv R \bowtie_{a=b} S$?
  - Only useful if a is from R and S from b (vice-versa)

Why Cross-Products are bad

- We discussed efficient join algorithms
  - Merge-join O(n) resp. O(n log(n))
  - Vs. Nested-loop $O(n^2)$
- R X S
  - Result size is $O(n^2)$
    - Cannot be better than $O(n^2)$
  - Surprise, surprise: merge-join doesn't work
    no need to sort, but degrades to nested loop

Agenda

- 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**

Join Graph

- Assumptions
  - Only equi-joins (a = b)
    - a and b are either constants or attributes
  - Only conjunctive join conditions (AND)

Join Graph

- Nodes: Relations $R_1, \ldots, R_n$ of query
- Edges: Join conditions
  - Add edge between R_i and R_j labeled with C
    - if there is a join condition C
    - That equates an attribute from R_i with an attribute from R_j
  - Add a self-edge to R_i for each simple predicate

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’
```

Department

EmpDep

Employee

Join Graph Example

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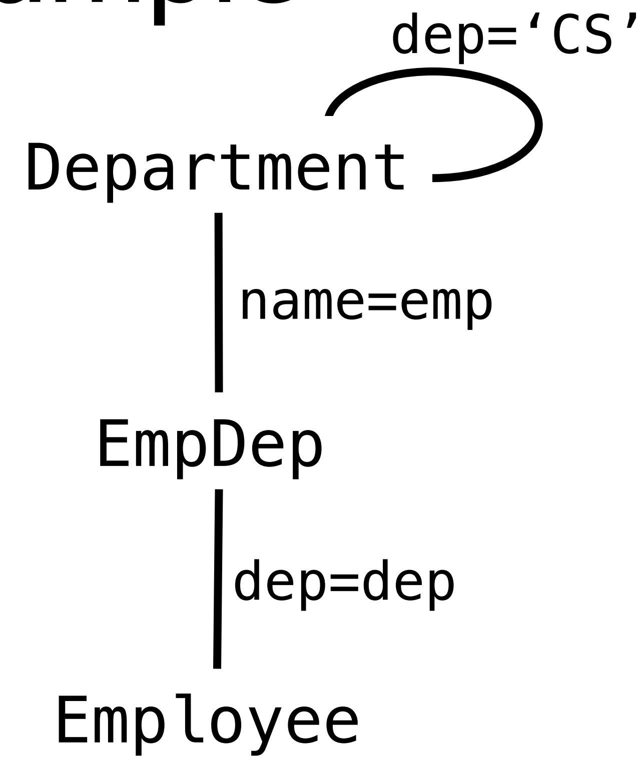
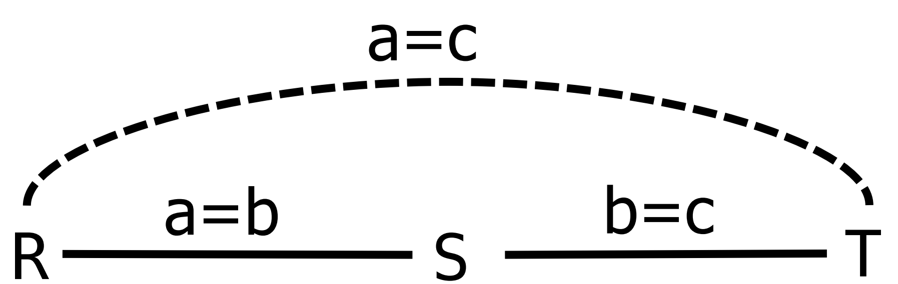
      AND d.dep = 'CS'
```

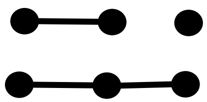


Notes on Join Graph

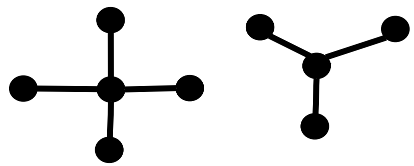
- Join Graph tells us in which ways we can join without using cross products
- However, …
  - Only if transitivity is considered



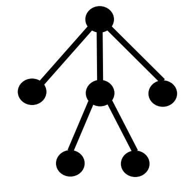
Join Graph Shapes



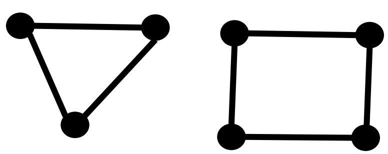
Chain queries



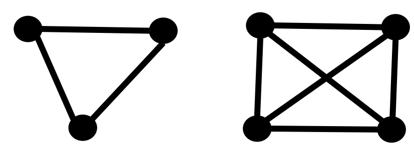
Star queries



Tree queries



Cycle queries



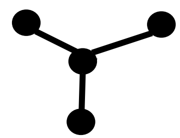
Clique queries

Join Graph Shapes

Chain queries

```
SELECT *
FROM R,S,T
WHERE R.a = S.b
      AND S.c = T.d
```

Join Graph Shapes

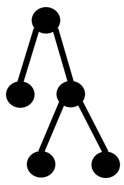


Star queries

```
SELECT *
FROM R,S,T,U
WHERE R.a = S.a
      AND R.b = T.b
      AND R.c = U.c
```

Join Graph Shapes

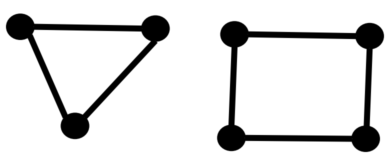
```
SELECT *
FROM R,S,T,U,V
WHERE R.a = S.a
      AND R.b = T.b
      AND T.c = U.c
      AND T.d = V.d
```



Tree queries

Join Graph Shapes

```
SELECT *
FROM R,S,T
WHERE R.a = S.a
      AND S.b = T.b
      AND T.c = R.c
```



Cycle queries

Join Graph Shapes

```
SELECT *
FROM R,S,T
WHERE R.a = S.a
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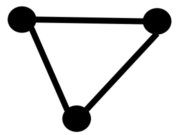
      AND T.c = R.c
```



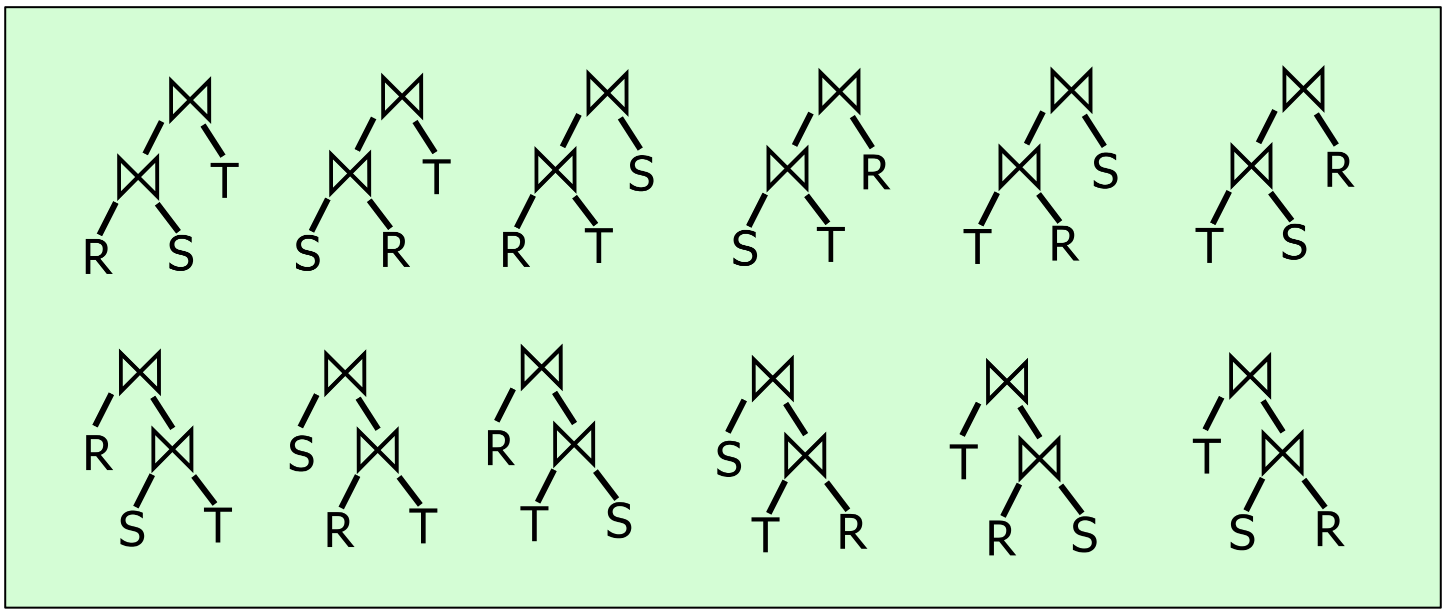
Clique queries

How many join orders?

- Assumption
  - Use cross products (can freely reorder)
  - Joins are binary operations
    - Two inputs
    - Each input either join result or relation access

How many join orders?

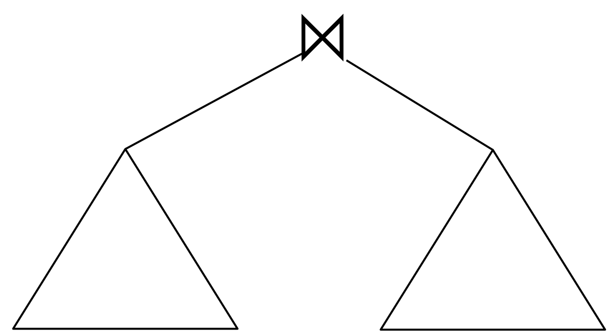
- Example 3 relations R,S,T
  - 12 orders



How many join orders?

- A join over **n+1** relations requires **n** binary joins
- The root of the join tree joins **k** with **n – k – 1** join operators (0 <= k <= n-1)

k joins



n – k - 1 joins

How many join orders?

- This are the **Catalan numbers**

$$\mathbf{C_n = \sum_{k=0}^{n-1} C_k \times C_{n-k-1} = (2n)! / (n+1)!n!}$$

$$\mathbf{C_0 = 1}$$

How many join orders?

- This are the **Catalan numbers**
- For each such tree we can permute the input relations **(n+1)!** Permutations

$$\mathbf{(2n)! / (n+1)!n! * (n+1)! = (2n)!/n!}$$

How many join orders?

#relations	#join trees
2	2
3	12
4	120
5	1,680
6	30,240
7	665,280
8	17,297,280
9	17,643,225,600
10	670,442,572,800
11	28,158,588,057,600

How many join orders?

- If for each join we consider **k** join algorithms then for **n** relations we have
  - Multiply with a factor $\mathbf{k^{n-1}}$
- 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?

- Even if costing is cheap
  - Unrealistic assumption 1 CPU cycle
  - Realistic are thousands or millions of instructions
- Cost all join options for 11 relations
  - 3GHz CPU, 8 cores
  - 69,280,686 sec > 2 years

How to deal with excessive number of combinations?

- Prune parts based on optimality
  - Dynamic programming
  - A*-search
- Only consider certain types of join trees
  - Left-deep, Right-deep, zig-zag, bushy
- Heuristic and random algorithms

Dynamic Programming

- Assumption: **Principle of Optimality**
  - To compute the **global** optimal plan it is only necessary to consider the optimal solutions for its **sub-queries**
- Does this assumption hold?
  - Depends on cost-function

What is dynamic programming?

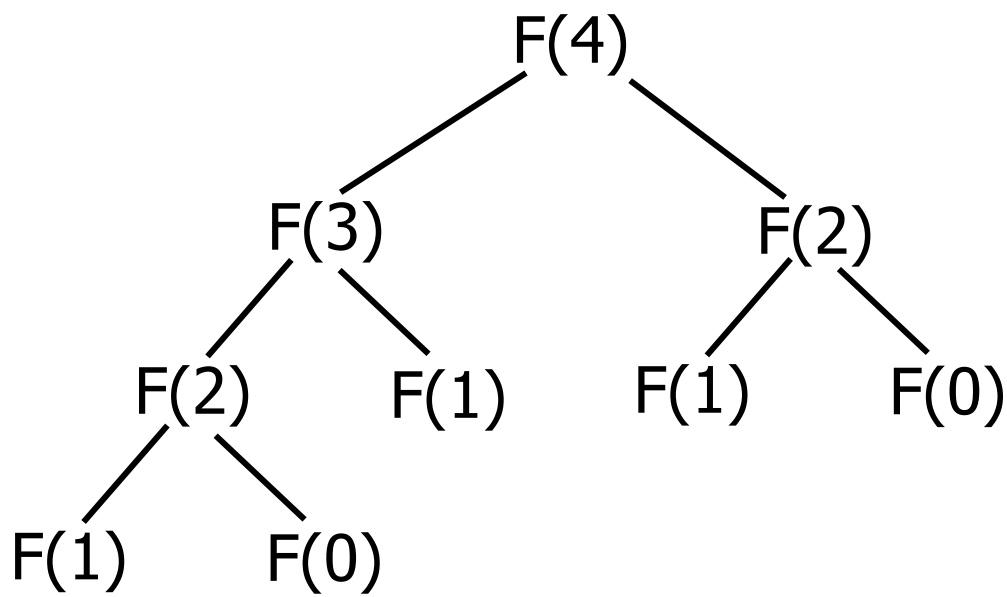
- Recall data structures and algorithms 101!
- Consider a **Divide-and-Conquer** problem
  - Solutions for a problem of size **n** can be build from solutions for sub-problems of smaller size (e.g., **n/2** or **n-1**)
- **Memoize**
  - Store solutions for sub-problems
  - -> Each solution has to be only computed once
  - -> Needs extra memory

Example Fibonacci Numbers

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

```
Fib(n)
{
      if (n = 0) return 0
      else if (n = 1) return 1
      else return Fib(n–1) + Fib(n–2)
}
```

Example Fibonacci Numbers



Complexity

- Number of calls
  - $C(n) = C(n-1) + C(n-2) + 1 = Fib(n+2)$
  - $O(2^n)$

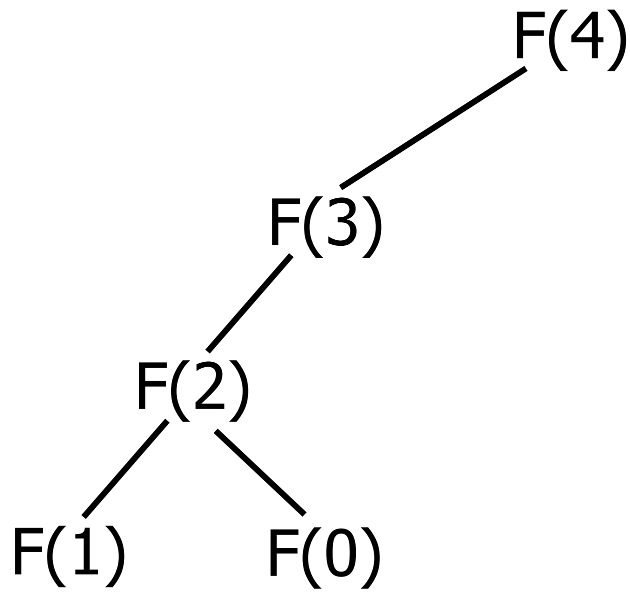
Using dynamic programming

```
Fib(n)
{
     int[] fib;
     fib[0] = 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

- Find cheapest plan for n-relation join in n passes
- For each **i** in **1** … **n**
  - Construct solutions of size **i** from best solutions of size **< i**

DP Join Enumeration

```
optPlan ← Map({R},{plan})

find_join_dp(q(R1,…,Rn))
{
  for i=1 to n
    optPlan[{Ri}] ← access_paths(Ri)
  for i=2 to n
    foreach S ⊆ {R1,…,Rn} with |S|=i
      optPlan[S] ← ∅
      foreach O ⊂ S with O ≠ ∅
        optPlan[S] ← optPlan[S] ∪
              possible_joins(optPlan(O), optPlan(S\O))
      prune_plans(optPlan[S])
  return optPlan[{R1,…,Rn}]
}
```

Dynamic Programming for Join Enumeration

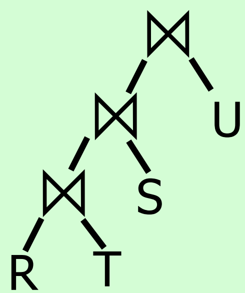
- `access_paths (R)`
  - Find cheapest access path for relation R
- `possible_joins(plan, plan)`
  - Enumerate all joins (merge, NL, …) variants between the input plans
- `prune_plans({plan})`
  - Only keep cheapest plan from input set

DP-JE Complexity

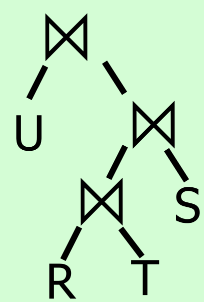
- Time: $O(3^n)$
- Space: $O(2^n)$
- Still to much for large number of joins (10-20)

Types of join trees

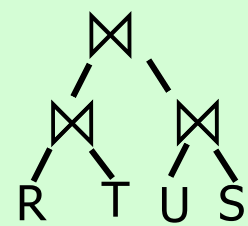
Left-deep



zig-zag

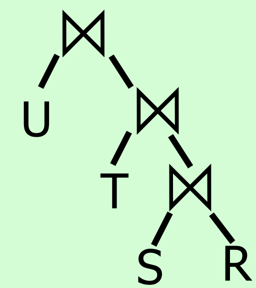


bushy



+left
+ zig-zag
+right

Right-deep



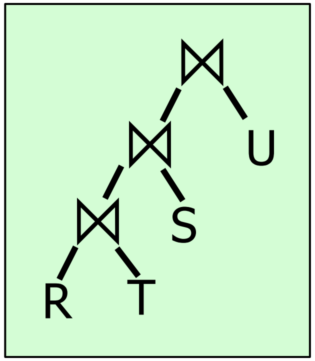
Number of Join-Trees

- Number of join trees for **n** relations
- Left-deep: **n!**
- Right-deep: **n!**
- Zig-zag: $\mathbf{2^{n-2} n!}$

How many join orders?

#relations	#bushy join trees	#left-deep join trees
2	2	2
3	12	6
4	120	24
5	1,680	120
6	30,240	720
7	665,280	5040
8	17,297,280	40,230
9	17,643,225,600	362,880
10	670,442,572,800	3,628,800
11	28,158,588,057,600	39,916,800

DP with Left-deep trees only



- Reduced search-space
- Each join is with input relation
  - ->can use index joins
  - ->easy to pipe-line
- DP with left-deep plans was introduced by system R, the first relational database developed by IBM Research

Revisiting the assumption

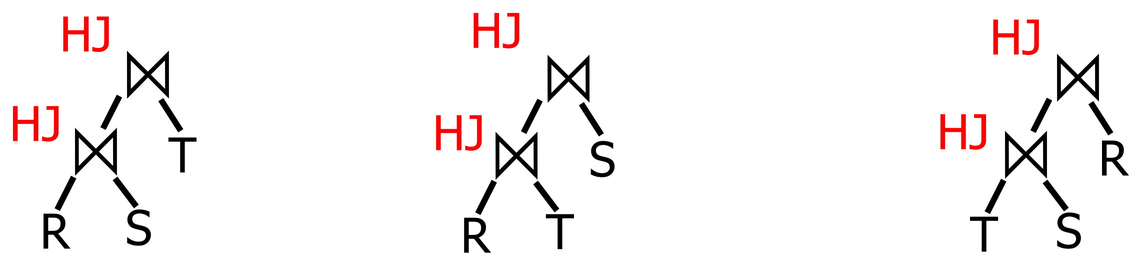
- Is it really sufficient to only look at the best plan for every sub-query?
- Cost of merge join depends whether the input is already sorted
  - -> A sub-optimal plan may produce results ordered in a way that reduces cost of joining above
  - Keep track of **interesting orders**

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

Example Interesting Orders

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

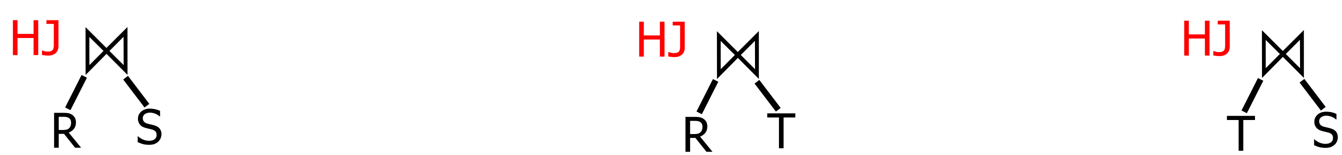


Left-deep best plans: 2-way

{R,S}

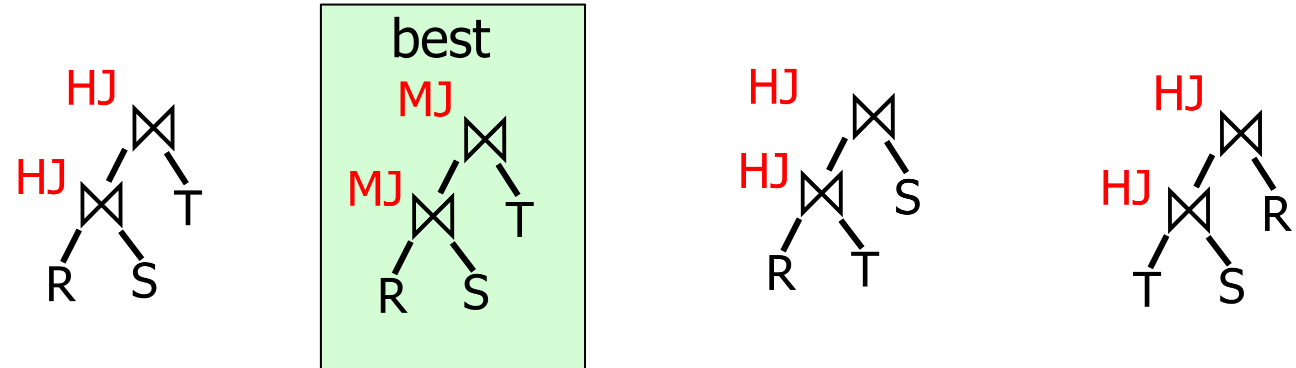
{R,T}

{S,T}

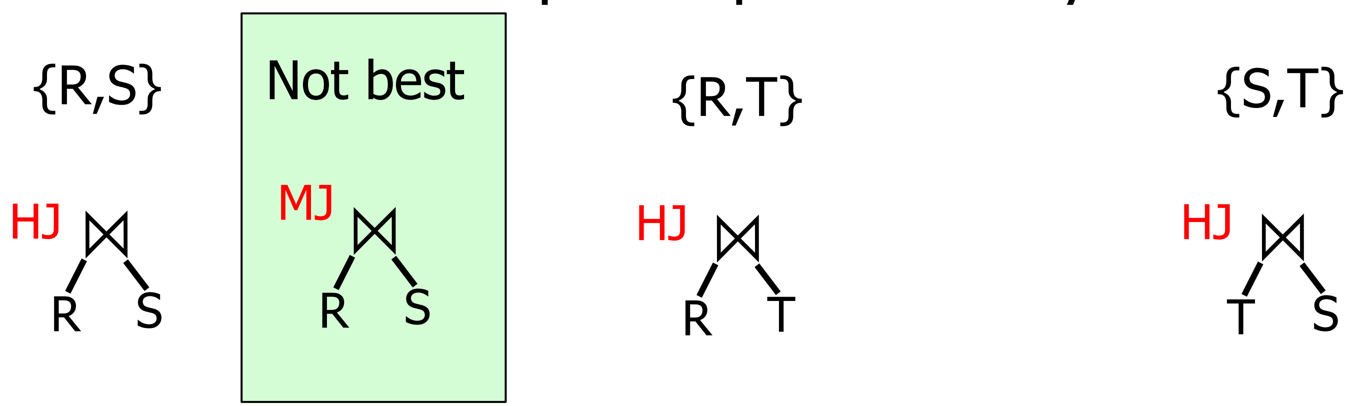


Example Interesting Orders

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



Left-deep best plans: 2-way



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

Greedy Join Enumeration

```
plans ← list({plan})

find_join_dp(q(R_1,…,R_n))
{
  for i=1 to n
    plans ← plans ∪ access_paths(R_i)
  for i=n to 2
    cheapest = argmin_{j,k∈{1,…,n}} (cost(P_j ⋈ P_k))
    plans ← plans \ {P_j,P_k} ∪ {P_j ⋈ P_k}
  return plans // single plan left
}
```

Greedy Join Enumeration

- Time: $O(n^3)$
  - Loop iterations: $O(n)$
  - In each iterations looking of pairs of plans in of max size n: $O(n^2)$
- Space: $O(n^2)$
  - Needed to store the current list of plans

Randomized Join-Algorithms

- Iterative improvement
- Simulated annealing
- Tabu-search
- Genetic algorithms

Transformative Approach

- Start from (random) complete solutions
- Apply transformations to generate new solutions
  - Direct application of equivalences
    - Commutativity
    - Associativity
  - Combined equivalences
    - E.g., $(R \bowtie S) \bowtie T \equiv T \bowtie (S \bowtie R)$

Concern about Transformative Approach

- Need to be able to generate random plans fast
- Need to be able to apply transformations fast
  - Trade-off: space covered by transformations vs. number and complexity of transformation rules

Iterative Improvement

```
improve(q(R1,…,Rn))
{
  best ← random_plan(q)
  while (not reached time limit)
    curplan ← random_plan(q)
    do
      prevplan ← curplan
      curplan ← apply_random_trans (prevplan)
    while (cost(curplan) < cost(prevplan))
    if (cost(prevplan) < cost(best)
      best ← prevplan
  return best
}
```

Iterative Improvement

- Easy to get stuck in local minimum
- **Idea:** Allow transformations that result in more expensive plans with the hope to move out of local minima
  - ->Simulated Annealing

Simulated Annealing

```
SA(q(R₁,…,Rₙ))
{
  best ← random_plan(q)
  curplan ← best
  t ← t_init // “temperature”
  while (t > 0)
    newplan ← apply_random_trans(curplan)
    if cost(newplan) < cost(curplan)
      curplan ← newplan
    else if random() < e^(-(cost(newplan)-cost(curplan))/t)
      curplan ← newplan
    if (cost(curplan) < cost(best)
      best ← curplan
   reduce(t)
  return best
}
```

Simulated Annealing

```
SA(q(R1,…,Rn))
{
  best ← random_plan(q)
  curplan ← best
  t ← tinit // “temperature”
  while (t > 0)
    newplan ← apply_random_trans(curplan)
    if cost(newplan) < cost(curplan)
      curplan ← newplan
    else if random() < e^(−(cost(newplan)−cost(curplan))/t)
      curplan ← newplan
    if (cost(curplan) < cost(best)
      best ← curplan
   reduce(t)
  return best
}
```

Until “cooled down”

Reduce Chance To “jump”

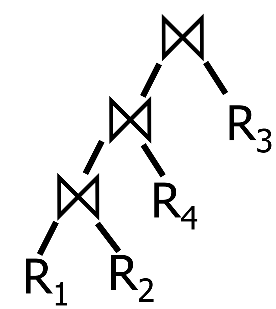
Probability to Take “bad” plan Based on temp.

Genetic Algorithms

- Represent solutions as sequences (strings) = genome
- Start with random population of solutions
- Iterations = Generations
  - Mutation = random changes to genomes
  - Cross-over = Mixing two genomes

Genetic Join Enumeration for Left-deep Plans

- A left-deep plan can be represented as a permutation of the relations
  - Represent each relation by a number
  - E.g., encode this tree as "1243"



Mutation

- Switch random two random positions
- Is applied with a certain fixed probability
- E.g., "1342" -> "4312"

Cross-over

- Sub-set exchange
  - For two solutions find subsequence
    - equals length with the same set of relations
  - Exchange these subsequences
- Example
  - J_1 = "5632478" and J_2 = "5674328"
  - Generate J' = "5643278"

Survival of the fittest

- Probability of survival determined by rank within the current population
- Compute ranks based on costs of solutions
- Assign Probabilities based on rank
  - Higher rank -> higher probability to survive
- Roll a dice for each solution

Genetic Join Enumeration

- Create an initial population **P** random plans
- Apply crossover and mutation with a fixed rate
  - E.g., crossover 65%, mutation 5%
- Apply selection until size is again **P**
- Stop once no improvement for at least **X** iterations

Comparison Randomized Join Enumeration

- Iterative Improvement
  - Towards local minima (easy to get stuck)
- Simulated Annealing
  - Probability to “jump” out of local minima
- Genetic Algorithms
  - Random transformation
  - Mixing solutions (crossover)
  - Probabilistic chance to keep solution based on cost

Join Enumeration Recap

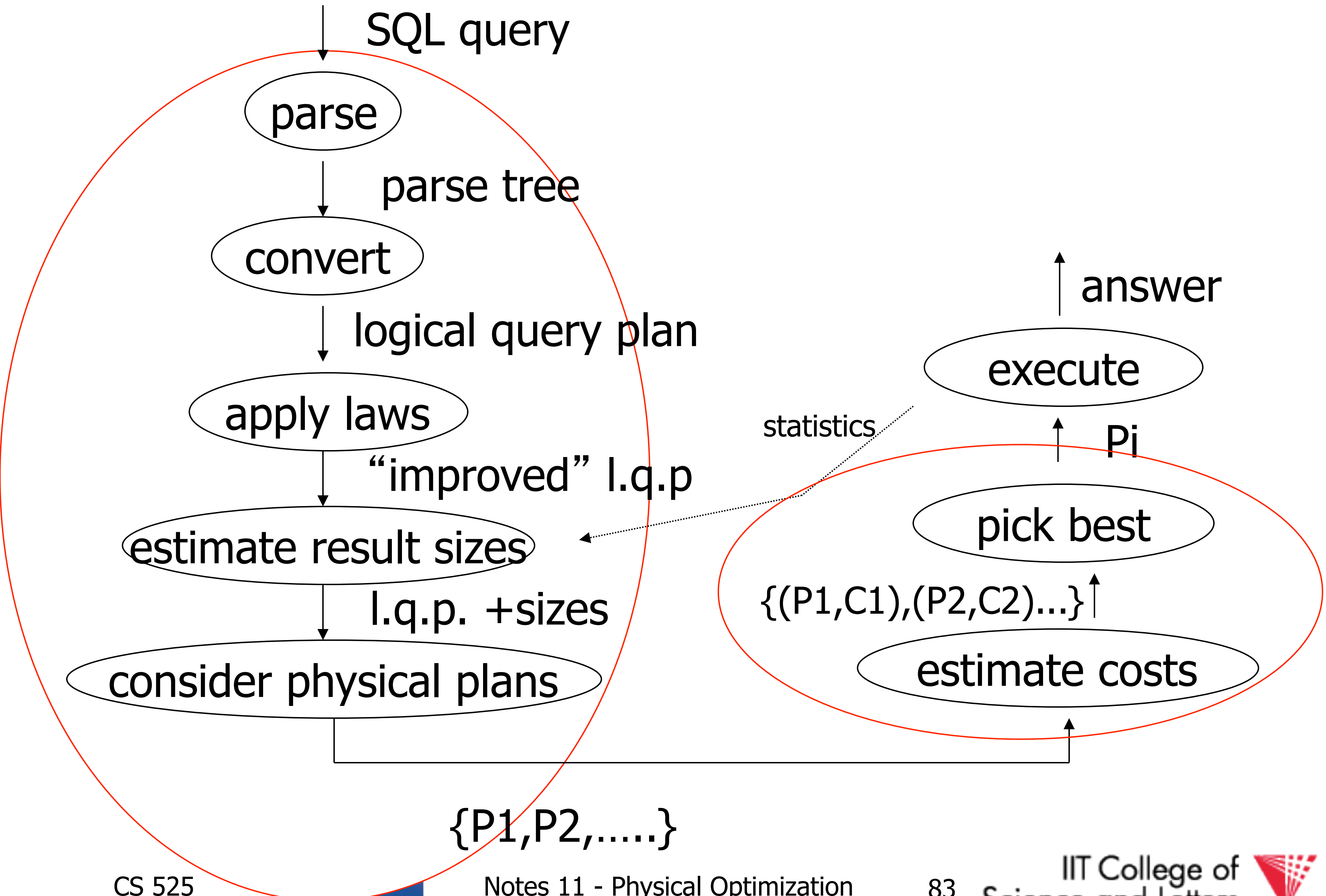
- Hard problem
  - Large problem size
    - Want to reduce search space
  - Large cost differences between solutions
    - Want to consider many solution to increase chance to find a good one.

Join Enumeration Recap

- Tip of the iceberg
  - More algorithms
  - Combinations of algorithms
  - Different representation subspaces of the problem
  - Cross-products / no cross-products
  - …

From Join-Enumeration to Plan Enumeration

- So far we only know how to reorder joins
- What about other operations?
- What if the query does consist of several SQL blocks?
- What if we have nested subqueries?


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,…..}
answer
execute
statistics
Pi
pick best
{(P1,C1),(P2,C2)...}
estimate costs

From Join-Enumeration to Plan Enumeration

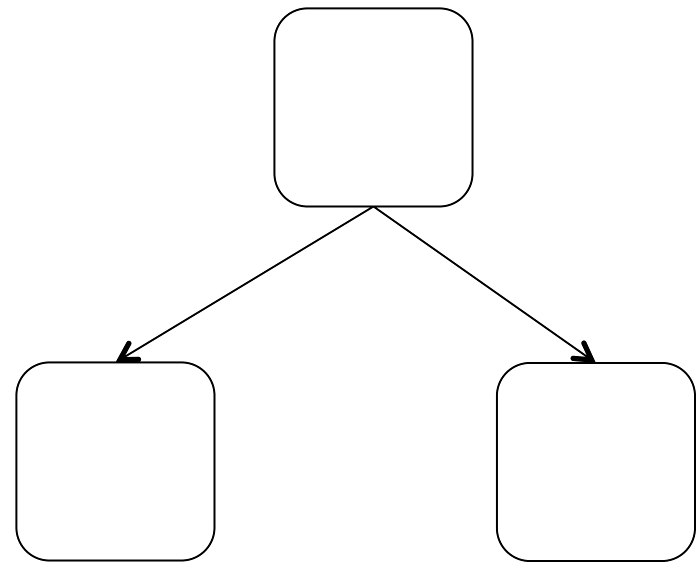
- Lets reconsider the input to plan enumeration!
  - We briefly touched on **Query graph models**
  - We discussed briefly why relational algebra is not sufficient

Query Graph Models

- Represents an SQL query as query blocks
  - A query block corresponds to the an SQL query block (SELECT FROM WHERE …)
  - Data type/operator/function information
    - Needed for execution and optimization decisions
  - Structured in a way suited for optimization

QGM example

```
SELECT name, city
FROM
     (SELECT *
     FROM person) AS p,
     (SELECT *
     FROM address) AS a
WHERE p.addrId = a.id
```



Postgres Example

```
{QUERY
          :commandType 1
          :querySource 0
          :canSetTag true
          :utilityStmt <>
          :resultRelation 0
          :intoClause <>
          :hasAggs false
          :hasSubLinks false
          :rtable (
            {RTE
            :alias
              {ALIAS
              :aliasname p
              :colnames <>
              }
            :eref
              {ALIAS
              :aliasname p
              :colnames ("name" "addrid")
              }
            :rtekind 1
            :subquery
              {QUERY
              :commandType 1
              :querySource 0
              :canSetTag true
...
```

How to enumerate plans for a QGM query

- Recall the correspondence between SQL query blocks and algebra expressions!
- If block is (A)SPJ
  - Determine join order
  - Decide which aggregation to use (if any)
- If block is set operation
  - Determine order

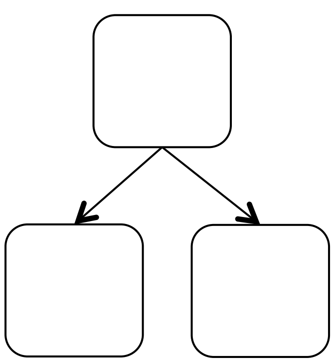
More than one query block

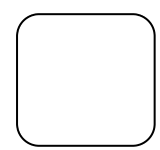
- Recursive create plans for subqueries
  - Start with leaf blocks
- Consider our example
  - Even if blocks are only SPJ we would not consider reordering of joins across blocks
  - -> try to "pull up" subqueries before optimization

Subquery Pull-up

```
SELECT name, city
FROM
      (SELECT *
      FROM person) AS p,
      (SELECT *
      FROM address) AS a
WHERE p.addrId = a.id
```

```
SELECT name, city
FROM
      person p,
      address a
WHERE p.addrId = a.id
```





Parameterized Queries

- Problem
  - Repeated executed of similar queries
- Example
  - Webshop
  - Typical operation: Retrieve product with all user comments for that product
  - Same query modulo product id

Parameterized Queries

- Naïve approach
  - Optimize each version individually
  - Execute each version individually
- Materialized View
  - Store common parts of the query
  - -> Optimizing a query with materialized views
  - -> Separate topic not covered here

Caching Query Plans

- Caching Query Plans
  - Optimize query once
  - Adapt plan for specific instances
  - **Assumption:** varying values do not effect optimization decisions
  - **Weaker Assumption**: Additional cost of "bad" plan less than cost of repeated planning

Parameterized Queries

- How to represent varying parts of a query
  - Parameters
  - Query planned with parameters assumed to be unknown
  - For execution replace parameters with concrete values

PREPARE statement

- In SQL
  - `PREPARE name (parameters) AS query`
  - **EXECUTE** name (parameters)

Nested Subqueries

```
SELECT name
FROM person p
WHERE EXISTS (SELECT newspaper
              FROM hasRead h
              WHERE h.name = p.name
                AND h.newspaper = 'Tribune')
```

How to evaluate nested subquery?

- If no correlations:
  - Execute once and cache results
- For correlations:
  - Create plan for query with parameters
- -> called nested iteration

Nested Iteration - Correlated

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  qt ← q'(t) // parameterize q' with values from t
  result' ← execute (qt)
  evaluate_nested_condition (t,result')
```

Nested Iteration - Uncorrelated

```
q ← outer query
q' ← inner query
result ← execute(q)
result' ← execute (q_t)
foreach tuple t in result
  evaluate_nested_condition (t,result')
```

Nested Iteration - Example

```
SELECT name
FROM person p
WHERE EXISTS (SELECT newspaper
                FROM hasRead h
                WHERE h.name = p.name
                      AND h.newspaper = 'Tribune')
```

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  qt ← q'(t)
  result' ← execute (qt)
  evaluate_nested_condition (t,result')
```

```
SELECT newspaper
FROM hasRead h
WHERE h.name = p.name
      AND h.newspaper
        = 'Tribune')
```

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  qt ← q'(t)
  result' ← execute (qt)
  evaluate_nested_condition (t,result')
```

```
SELECT newspaper
FROM hasRead h
WHERE h.name = 'Alice'
      AND h.newspaper
          = 'Tribune')
```

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  qt ← q'(t)
  result' ← execute (qt)
  evaluate_nested_condition (t,result')
```

```
SELECT newspaper
FROM hasRead h
WHERE h.name = p.name
      AND h.newspaper
         = 'Tribune')
```

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

result'

newspaper
Tribune

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  q_t ← q'(t)
  result' ← execute (q_t)
  evaluate_nested_condition (t,result')
```

EXISTS evaluates to true!

Output(Alice)

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

result'

newspaper
Tribune

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  qt ← q'(t)
  result' ← execute (qt)
  evaluate_nested_condition (t,result')
```

Empty result set -> EXISTS evaluates to false

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

result'

newspaper

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  q_t ← q'(t)
  result' ← execute (q_t)
  evaluate_nested_condition (t,result')
```

Empty result set -> EXISTS evaluates to false

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

result'

newspaper

Nested Iteration - Discussion

- Repeated evaluation of nested subquery
  - If correlated
  - Improve:
    - Plan once and substitute parameters
    - EXISTS: stop processing after first result
    - IN/ANY: stop after first match
- No optimization across nesting boundaries

Unnesting and Decorrelation

- Apply equivalences to transform nested subqueries into joins
- **Unnesting:**
  - Turn a nested subquery into a join
- **Decorrelation:**
  - Turn correlations into join expressions

Equivalences

- Classify types of nesting
- Equivalence rules will have preconditions
- Can be applied heuristically before plan enumeration or using a transformative approach

N-type Nesting

- Properties
  - Expression ANY comparison (or IN)
  - No Correlations
  - Nested query does not use aggregation
- Example

```
SELECT name
FROM orders o
WHERE o.cust IN (SELECT cId
                 FROM customer
                 WHERE region = 'USA')
```

A-type Nesting

- Properties
  - Expression is ANY comparison (or scalar)
  - No Correlations
  - Nested query uses aggregation
  - No Group By
- Example

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i)
```

J-type Nesting

- Properties
  - Expression is ANY comparison (IN)
  - Nested query uses equality comparison with correlated attribute
  - No aggregation in nested query
- Example

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
                   FROM orders i
                   WHERE i.cust = o.cust
                         AND i.shop = 'New York')
```

JA-type Nesting

- Properties
  - Expression equality comparison
  - Nested query uses equality comparison with correlated attribute
  - Nested query uses aggregation and no GROUP BY
- Example

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

Unnesting A-type

- Move nested query to FROM clause
- Turn nested condition (op ANY, IN) into op with result attribute of nested query

Unnesting N/J-type

- Move nested query to FROM clause
- Add DISTINCT to SELECT clause of nested query
- Turn equality comparison with correlated attributes into join conditions
- Turn nested condition (op ANY, IN) into op with result attribute of nested query

Example

1. To FROM clause
2. Add DISTINCT
3. Correlation to join
4. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
              FROM orders i
              WHERE i.cust = o.cust
                    AND i.shop = 'New York')
```

```
SELECT name
FROM orders o,
     (SELECT amount
     FROM orders i
     WHERE i.cust = o.cust
           AND i.shop = 'New York') AS sub
```

Example

1. To FROM clause
2. Add DISTINCT
3. Correlation to join
4. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
              FROM orders i
              WHERE i.cust = o.cust
                    AND i.shop = 'New York')
```

```
SELECT name
FROM orders o,
     (SELECT DISTINCT amount
     FROM orders i
     WHERE i.cust = o.cust
           AND i.shop = 'New York') AS sub
```

Example

1. To FROM clause
2. Add DISTINCT
3. Correlation to join
4. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
              FROM orders i
              WHERE i.cust = o.cust
                    AND i.shop = 'New York')
```

```
SELECT name
FROM orders o,
     (SELECT DISTINCT amount, cust
     FROM orders i
     WHERE i.shop = 'New York') AS sub
WHERE sub.cust = o.cust
```

Example

1. To FROM clause
2. Add DISTINCT
3. Correlation to join
4. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
                   FROM orders i
                   WHERE i.cust = o.cust
                         AND i.shop = 'New York')
```

```
SELECT name
FROM orders o,
     (SELECT DISTINCT amount, cust
     FROM orders i
     WHERE i.shop = 'New York') AS sub
WHERE sub.cust = o.cust
      AND o.amount = sub.amount
```

Unnesting JA-type

- Move nested query to FROM clause
- Turn equality comparison with correlated attributes into
  - GROUP BY
  - Join conditions
- Turn nested condition (op ANY, IN) into op with result attribute of nested query

Example

1. To FROM clause
2. Introduce GROUP BY and join conditions
3. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

```
SELECT name
FROM orders o,
    (SELECT max(amount)
    FROM orders I
    WHERE i.cust = o.cust) sub
```

Example

1. To FROM clause
2. Introduce GROUP BY and join conditions
3. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

```
SELECT name
FROM orders o,
    (SELECT max(amount) AS ma, i.cust
    FROM orders i
    GROUP BY i.cust) sub
WHERE i.cust = sub.cust
```

Example

1. To FROM clause
2. Introduce GROUP BY and join conditions
3. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                FROM orders i
                WHERE i.cust = o.cust)
```

```
SELECT name
FROM orders o,
    (SELECT max(amount) AS ma, i.cust
    FROM orders i
    GROUP BY i.cust) sub
WHERE sub.cust = o.cust
      AND o.amount = sub.ma
```

Unnesting Benefits Example

- N(orders) = 1,000,000
- V(cust,orders) = 10,000
- S(orders) = 1/10 block

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

```
SELECT name
FROM orders o,
    (SELECT max(amount) AS ma, i.cust
    FROM orders i
    GROUP BY i.cust) sub
WHERE sub.cust = o.cust
      AND o.amount = sub.ma
```

- N(orders) = 1,000,000
- V(cust,orders) = 10,000
- S(orders) = 1/10 block
- M = 10,000

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

- Inner query:
  - One scan B(orders) = 100,000 I/Os
- Outer query:
  - One scan B(orders) = 100,000 I/Os
  - 1,000,000 tuples
- Total cost: 1,000,001 x 100,000=~ 10^{11} I/Os

- N(orders) = 1,000,000
- V(cust,orders) = 10,000
- S(orders) = 1/10 block
- M = 10,000

```
SELECT name
FROM orders o,
    (SELECT max(amount) AS ma, i.cust
    FROM orders i
    GROUP BY i.cust) sub
WHERE sub.cust = o.cust
      AND o.amount = sub.ma
```

- Inner queries:
  - One scan B(orders) = 100,000 I/Os
    - 1,000,000 result tuples
  - Aggregation: Sort (assume 1 pass) = 3 x 100,000 = 300,000 I/Os
    - 10,000 result tuples -> + 1,000 pages to write to disk
- The join: use merge – join during merge
  - 3 x (1,000 + 100,000) I/Os = 303,000 I/Os
- Total cost: 604,000 I/Os