CSE 544
Principles of Database Management Systems

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Fall 2015

Lecture 7 - Query optimization

Announcements

- HW1 due tonight at 11:45pm
- HW2 will be due in two weeks
  – You get to implement your own DBMS!
- We will meet with each project teams next week
  – Will send out doodle

References

- **Access path selection in a relational database management system.**

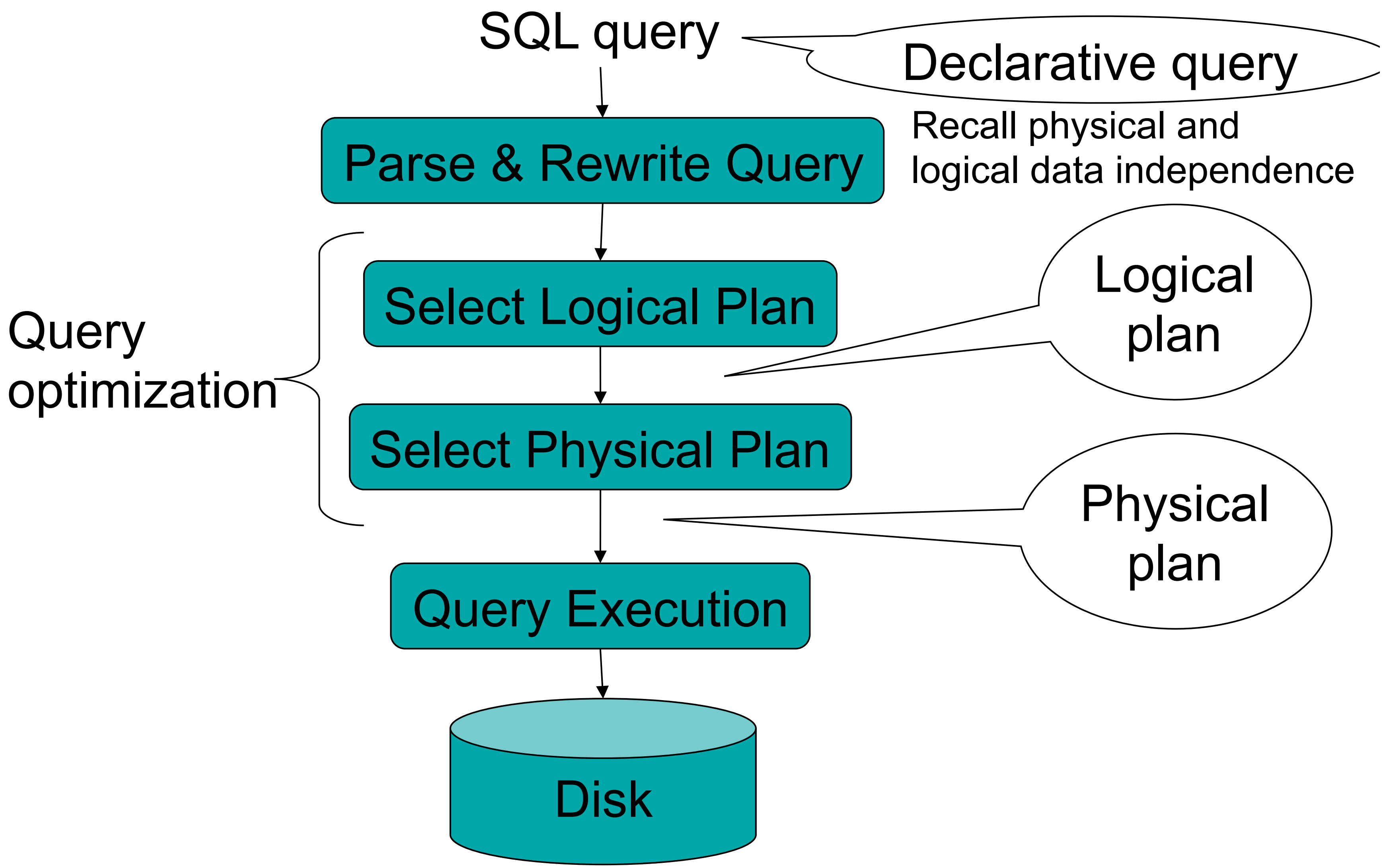
  Selinger. et. al. SIGMOD 1979

- **Database management systems.**

  Ramakrishnan and Gehrke.

  Third Ed. **Chapter 15.**

Query Optimization Motivation



What We Already Know…

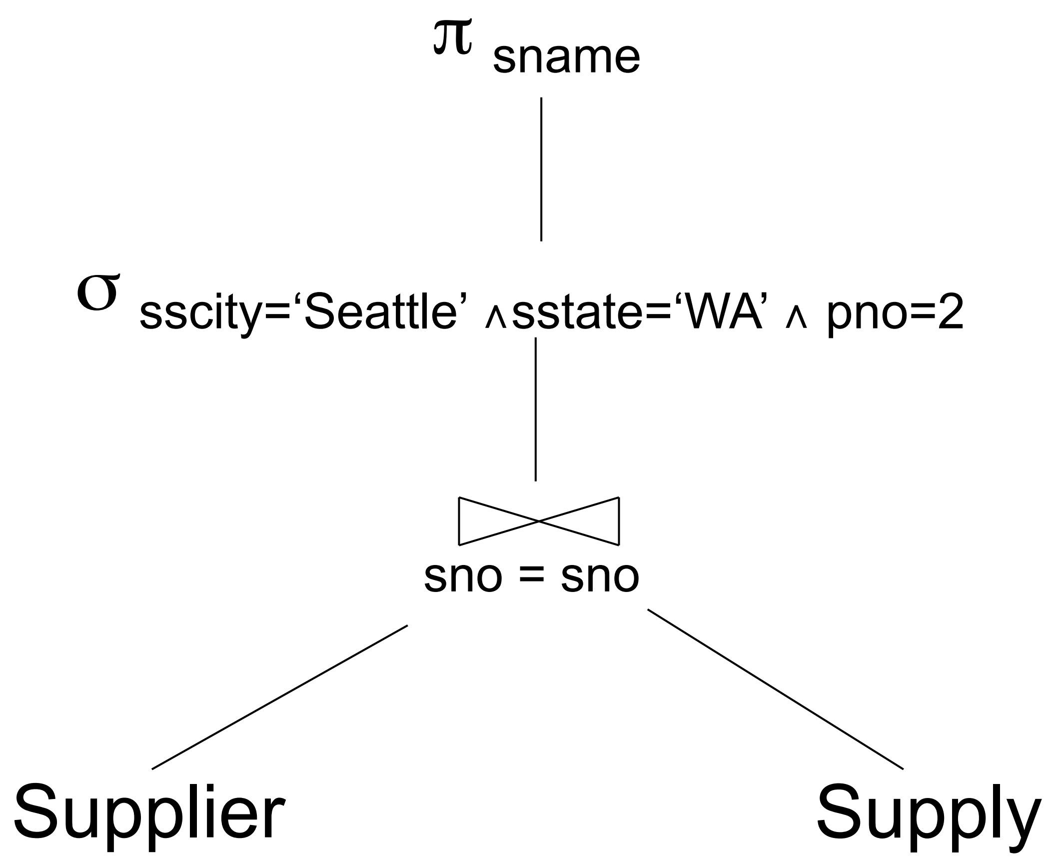
```
Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)
```

For each SQL query….

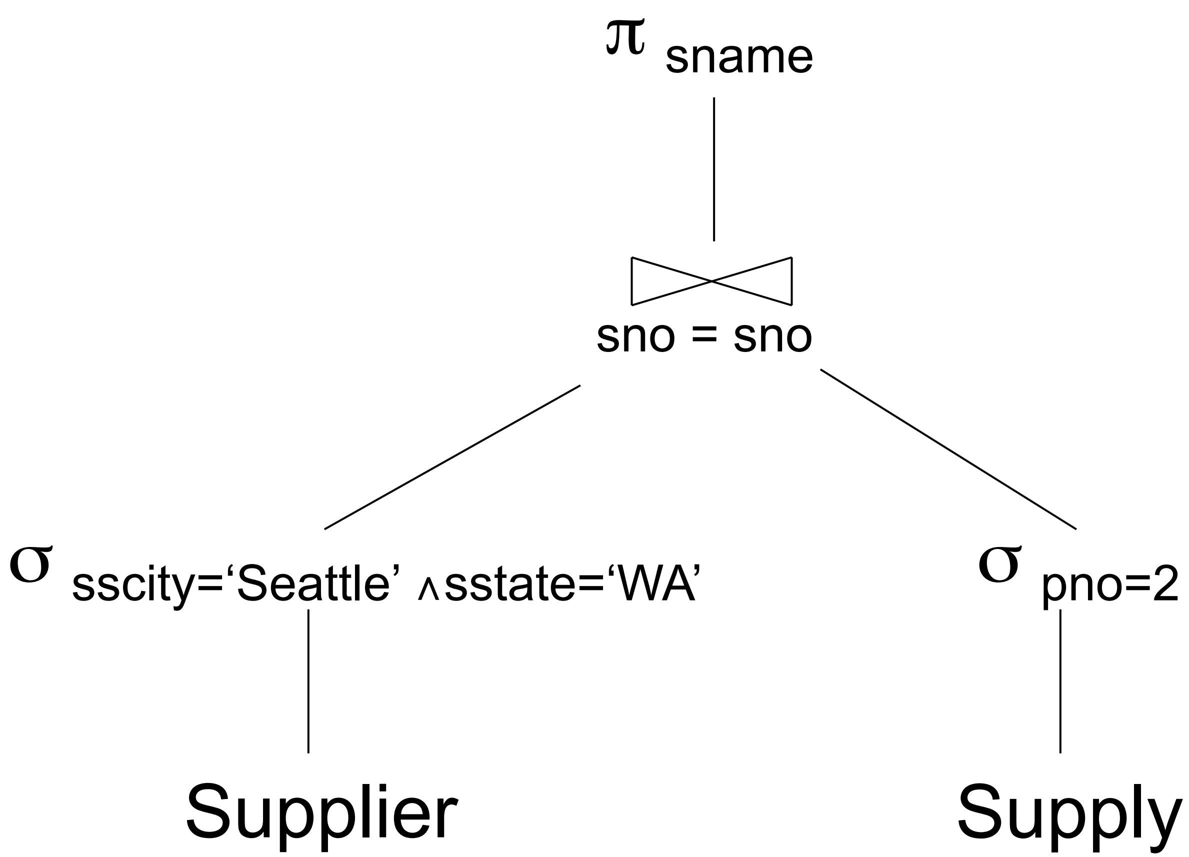
```
SELECT S.sname
FROM Supplier S, Supply U
WHERE S.scity='Seattle' AND S.sstate='WA'
AND S.sno = U.sno
AND U.pno = 2
```

There exist many logical query plan…

Example Query: Logical Plan 1



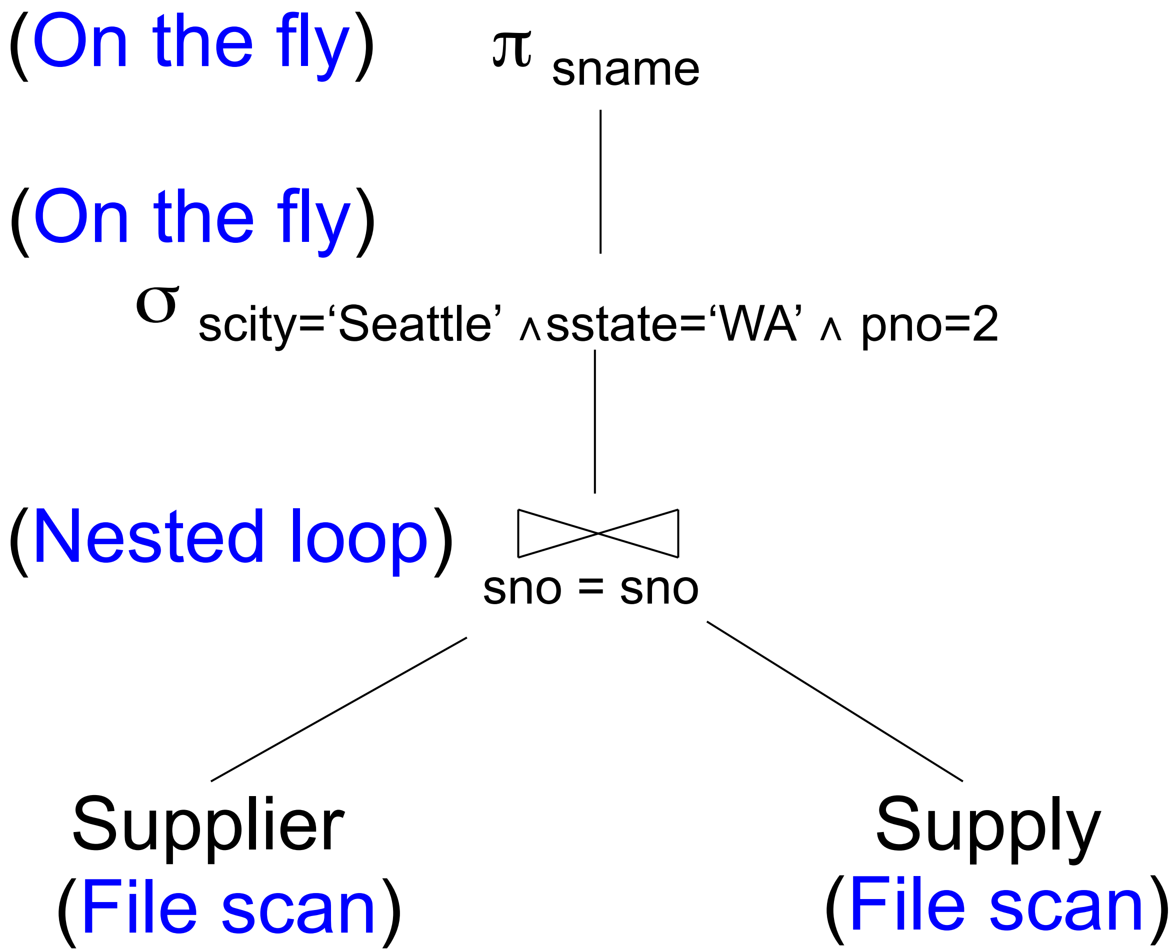
Example Query: Logical Plan 2



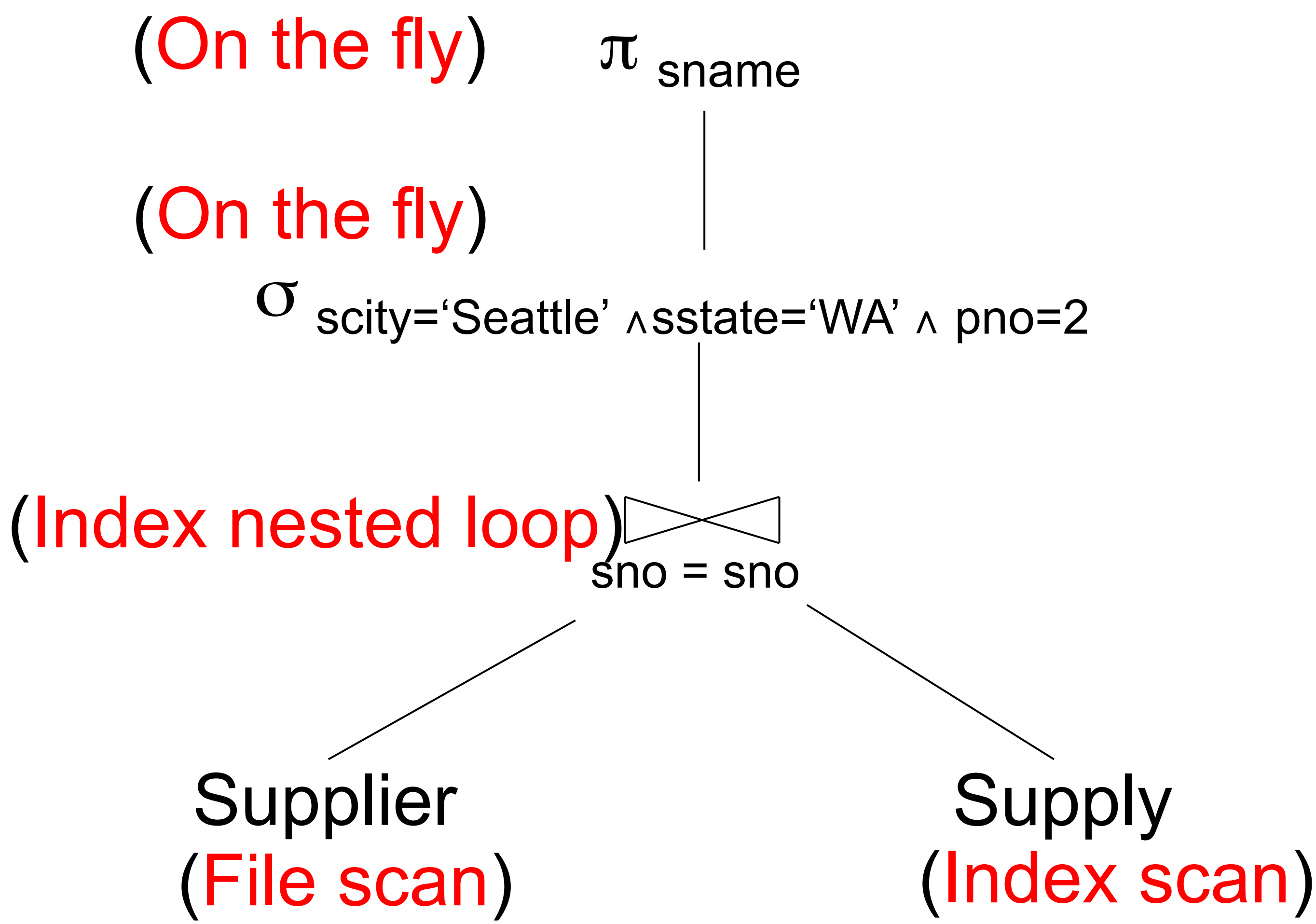
What We Also Know

- For each logical plan…
- There exist many physical plans

Example Query: Physical Plan 1



Example Query: Physical Plan 2



Query Optimization Algorithm

- For a query
  - There exists many physical query plans
  - Query optimizer needs to pick a good one

- Basic query optimization algorithm
  - Enumerate alternative plans
  - Compute estimated cost of each plan
    - Compute number of I/Os
    - Optionally take into account other resources
  - Choose plan with lowest cost
  - This is called cost-based optimization

Query Optimization

Three major components:

1. Cardinality and cost estimation

2. Search space

3. Plan enumeration algorithms

Estimating Cost of a Query Plan

- We already know how to
  - Compute the cost of different operations in terms of number IOs

- We still need to
  - Compute cost of retrieving tuples from disk with different access paths (for more sophisticated predicates than equality)
  - Compute cost of a complete plan

Access Path

- **Access path**: a way to retrieve tuples from a table
  - A file scan
  - An index *plus* a matching selection condition

- Index matches selection condition if it can be used to retrieve just tuples that satisfy the condition
  - Example: Supplier(sid,sname,scity,sstate)
  - B+-tree index on (scity,sstate)
    - matches scity='Seattle'
    - does not match sid=3, does not match sstate='WA'

Access Path Selection

- Supplier(sid,sname,scity,sstate)
- Selection condition: sid > 300 ∧ scity='Seattle'
- Indexes: B+-tree on sid and B+-tree on scity
- Which access path should we use?
- We should pick the **most selective** access path

Access Path Selectivity

- **Access path selectivity is the number of pages retrieved if we use this access path**
  - Most selective retrieves fewest pages
- As we saw earlier, **for equality predicates**
  - Selection on equality: $\sigma_{a=v}(R)$
  - V(R, a) = # of distinct values of attribute a
  - 1/V(R,a) is thus the reduction factor
  - Clustered index on a: cost B(R)/V(R,a)
  - Unclustered index on a: cost T(R)/V(R,a)
  - (we are ignoring I/O cost of index pages for simplicity)

Selectivity for Range Predicates

Selection on range: $\sigma_{a>v}(R)$

- How to compute the selectivity?
- Assume values are uniformly distributed
- Reduction factor X
- X = (Max(R,a) - v) / (Max(R,a) - Min(R,a))

- Clustered index on a: cost B(R)*X
- Unclustered index on a: cost T(R)*X

Back to Our Example

- Selection condition: **sid > 300 ∧ scity='Seattle'**
  - Index I1: B+-tree on sid clustered
  - Index I2: B+-tree on scity unclustered

- Let's assume
  - V(Supplier,scity) = 20
  - Max(Supplier, sid) = 1000, Min(Supplier,sid)=1
  - B(Supplier) = 100, T(Supplier) = 1000

- **Cost I1: B(R) * (Max-v)/(Max-Min) = 100*700/999 ≈ 70**
- **Cost I2: T(R) * 1/V(Supplier,scity) = 1000/20 = 50**

Selectivity with Multiple Conditions

What if we have an index on multiple attributes?

- Example selection $\sigma_{a=v1 \wedge b=v2}(R)$ and index on <a,b>

How to compute the selectivity?

- Assume attributes are independent
- X = 1 / (V(R,a) * V(R,b))

- Clustered index on <a,b>: cost B(R)*X
- Unclustered index on <a,b>: cost T(R)*X

Back to Estimating Cost of a Query Plan

- We already know how to
  - Compute the cost of different operations
  - Compute cost of retrieving tuples from disk with different access paths

- We still need to
  - Compute cost of a complete plan

Computing the Cost of a Plan

- Collect statistical summaries of stored data
- Compute cost in a bottom-up fashion
- For each operator compute
  - Estimate cost of executing the operation
  - Estimate statistical summary of the output data

Statistics on Base Data

- Collected information for each relation
  - Number of tuples (cardinality)
  - Indexes, number of keys in the index
  - Number of physical pages, clustering info
  - Statistical information on attributes
    - Min value, max value, number distinct values
    - Histograms
  - Correlations between columns (hard)

- Collection approach: periodic, using sampling

Computing Cost of an Operator

- The cost of executing an operator depends
  - On the operator implementation
  - On the input data
- We learned how to compute this in the previous lecture

Statistics on the Output Data

- Most important piece of information
  - **Size of operator result**
  - I.e., the number of output tuples

- Projection: output size same as input size
- Selection: multiply input size by reduction factor
  - Similar to what we did for estimating access path selectivity
  - Assume independence between conditions in the predicate
  - (use product of the reduction factors for the terms)

Estimating Result Sizes

- For joins R $\bowtie$ S
  - Take product of cardinalities of relations R and S
  - Apply reduction factors for each term in join condition
  - Terms are of the form: column1 = column2
  - Reduction: 1/ (MAX(V(R,column1), V(S,column2))
  - **Assumes each value in smaller set has a matching value in the larger set**

Assumptions

- *Containment of values*: if V(R,A) <= V(S,B), then the set of A values of R is included in the set of B values of S
  - Note: this indeed holds when A is a foreign key in R, and B is a key in S

- *Preservation of values*: for any other attribute C, $V(R \bowtie_{A=B} S, C) = V(R, C)$ (or $V(S, C)$)

Selectivity of $R \bowtie_{A=B} S$

Assume $V(R,A) <= V(S,B)$

- Each tuple t in R joins with $T(S)/V(S,B)$ tuple(s) in S

- Hence $T(R \bowtie_{A=B} S) = T(R)\ T(S)\ /\ V(S,B)$

In general: $T(R \bowtie_{A=B} S) = T(R)\ T(S)\ /\ \max(V(R,A),V(S,B))$

Complete Example

Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

```
SELECT sname
FROM Supplier x, Supply y
WHERE x.sid = y.sid
   and  y.pno = 2
   and x.scity = 'Seattle'
   and x.sstate = 'WA'
```

- Some statistics
  - T(Supplier) = 1000 records
  - T(Supply) = 10,000 records
  - B(Supplier) = 100 pages
  - B(Supply) = 100 pages
  - V(Supplier,scity) = 20, V(Suppliers,state) = 10
  - V(Supply,pno) = 2,500
  - Both relations are clustered
- M = 11

Computing the Cost of a Plan

- Estimate cardinality in a bottom-up fashion
  - Cardinality is the size of a relation (nb of tuples)
  - Compute size of *all* intermediate relations in plan

- Estimate cost by using the estimated cardinalities

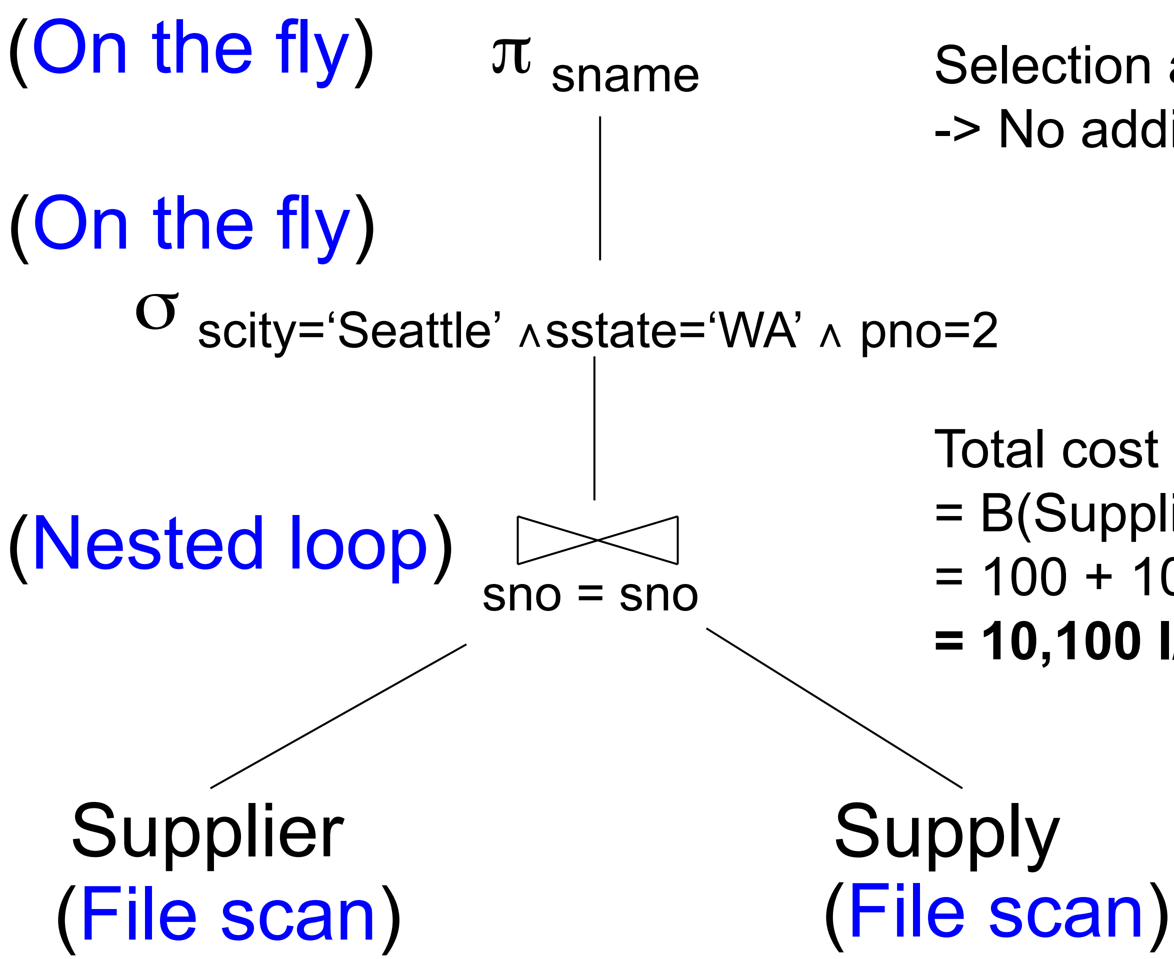
T(Supplier) = 1000
T(Supply) = 10,000

B(Supplier) = 100
B(Supply) = 100

V(Supplier,scity) = 20
V(Supplier,state) = 10
V(Supply,pno) = 2,500

M = 11

Physical Query Plan 1



Selection and project on-the-fly
-> No additional cost.

Total cost of plan is thus cost of join:
= B(Supplier)+B(Supplier)*B(Supplies)
= 100 + 100 * 100
= 10,100 I/Os

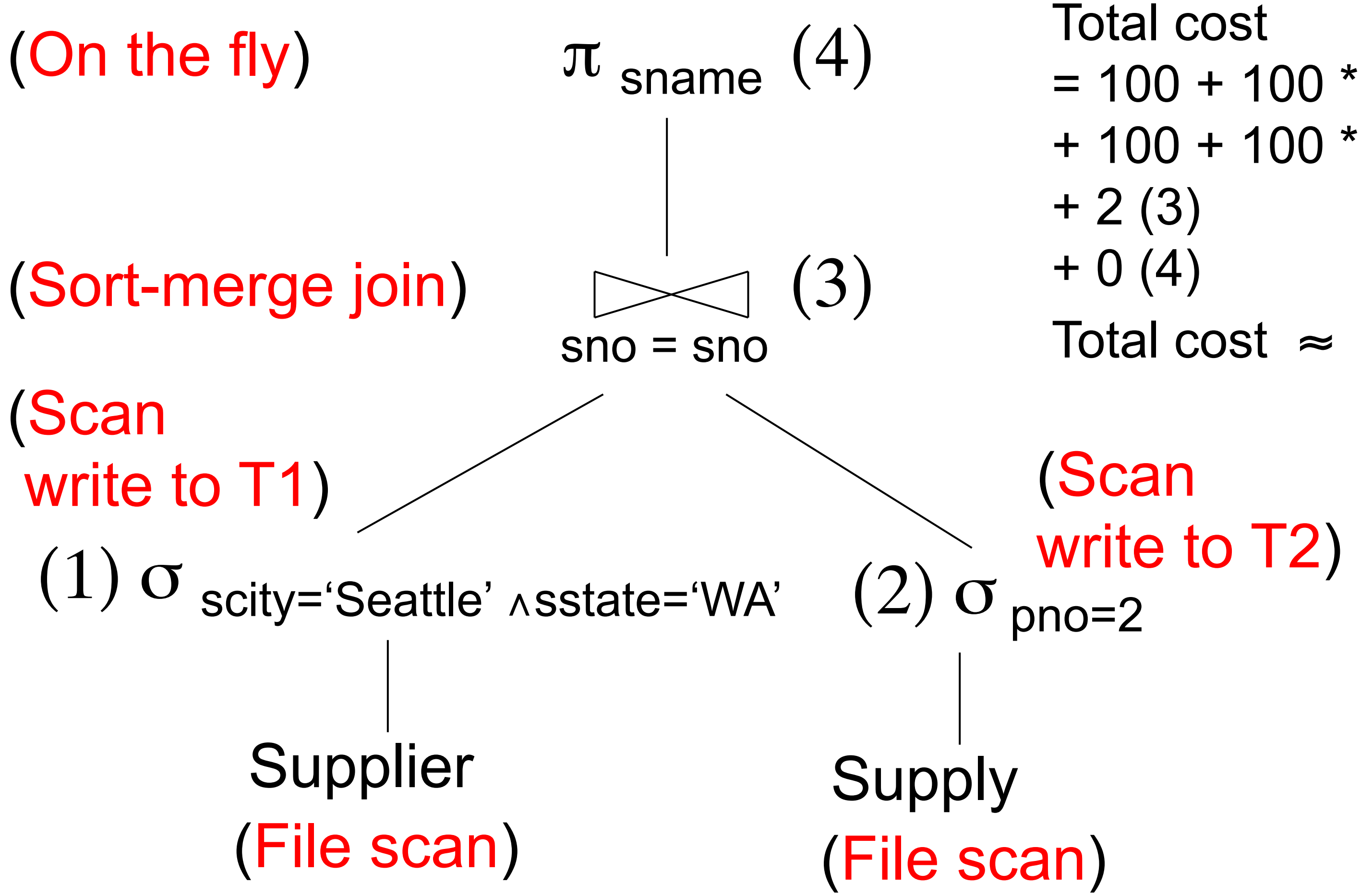
T(Supplier) = 1000
T(Supply) = 10,000

B(Supplier) = 100
B(Supply) = 100

V(Supplier,scity) = 20
V(Supplier,state) = 10
V(Supply,pno) = 2,500

M = 11

Physical Query Plan 2



Total cost
= 100 + 100 * 1/20 * 1/10 (1)
+ 100 + 100 * 1/2500 (2)
+ 2 (3)
+ 0 (4)

Total cost ≈ **204 I/Os**

Plan 2 with Different Numbers

What if we had:
10K pages of Suppliers
10K pages of Supplies

(4) π_{sname}

(3) $\bowtie_{sno = sno}$ (Sort-merge join)

(1) $\sigma_{scity=\text{'Seattle'} \wedge sstate=\text{'WA'}}$ (Scan write to T1)

(2) $\sigma_{pno=2}$ (Scan write to T2)

Supplier (File scan)

Supply (File scan)

Total cost
= 10000 + 50 (1)
+ 10000 + 4 (2)
+ 4*50 + 2*4 + 4 + 50 (3)
+ 0 (4)
Total cost ≈ 20,316 I/Os

Assuming naive two-pass sort algorithm

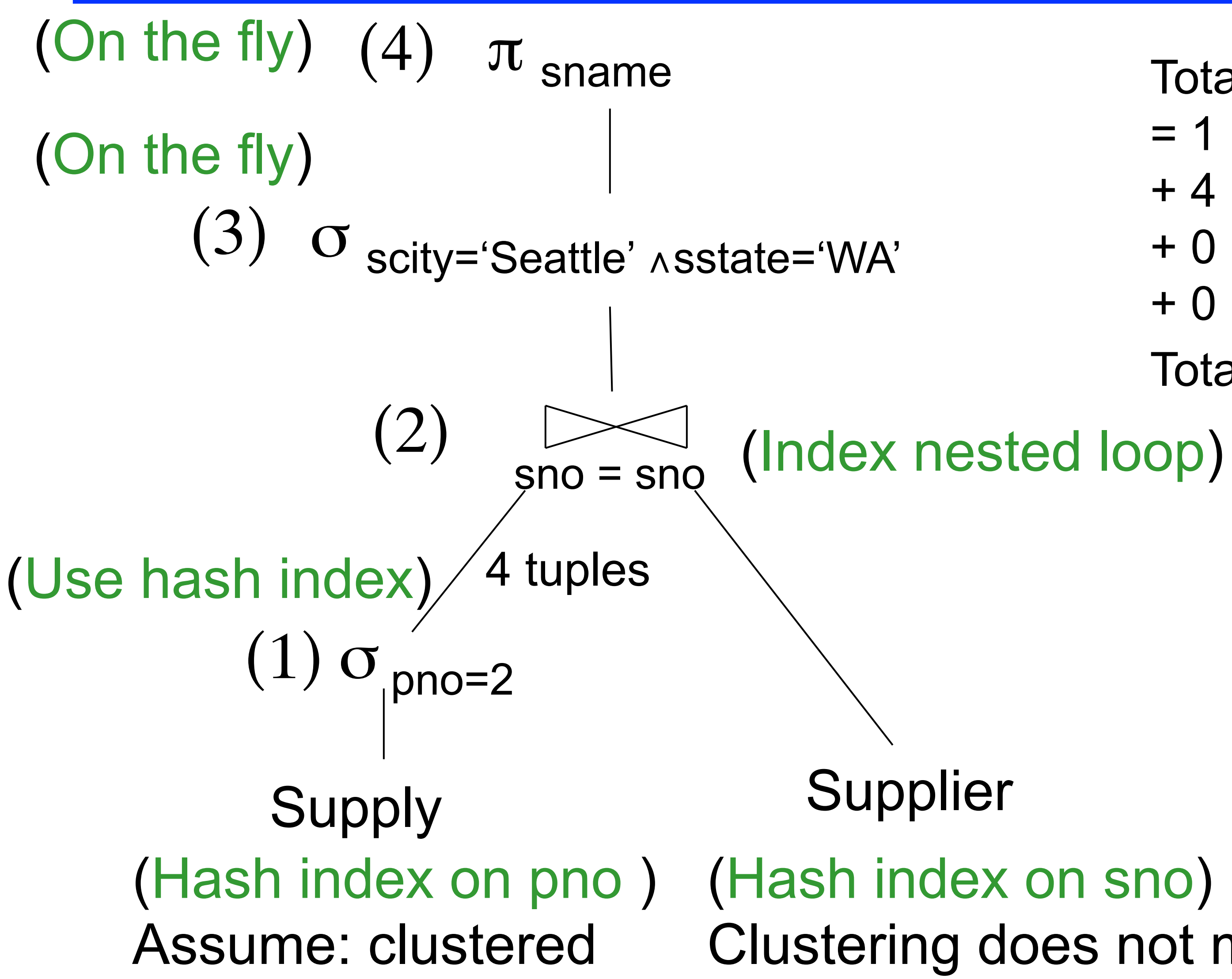
T(Supplier) = 1000
T(Supply) = 10,000

B(Supplier) = 100
B(Supply) = 100

V(Supplier,scity) = 20
V(Supplier,state) = 10
V(Supply,pno) = 2,500

M = 11

Physical Query Plan 3



Total cost
= 1 (1)
+ 4 (2)
+ 0 (3)
+ 0 (3)
Total cost ≈ **5 I/Os**

Simplifications

- In the previous examples, we assumed that all index pages were in memory
- When this is not the case, we need to add the cost of fetching index pages from disk

Different Cost Models

- In previous examples, we considered IO costs
- Typically, want IO+CPU
- For parallel/distributed queries, add network bandwidth
- If need to compare *logical* plans
  - Compute the cardinality of each *intermediate* relation
  - Sum up all the cardinalities

Summary

- What we know
  - Different types of physical query plans
  - How to compute the cost of a query plan
  - Although it is hard to compute the cost accurately

- We can now compare query plans

- Let's now consider how the query optimizer searches through the space of possible plans

Query Optimization

Three major components:

1. Cardinality and cost estimation

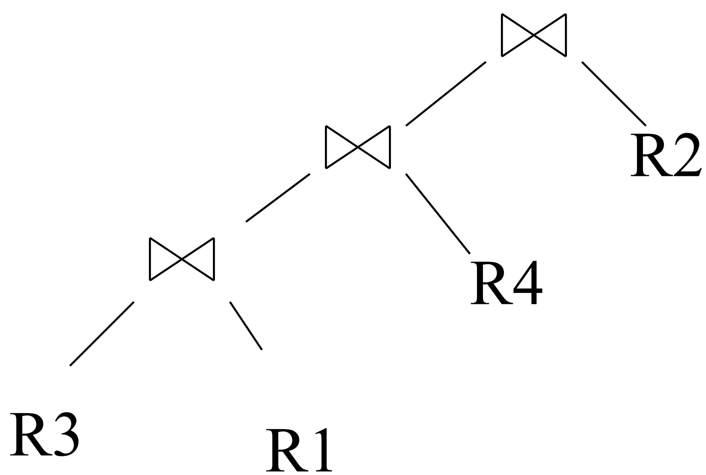
2. Search space

3. Plan enumeration algorithms

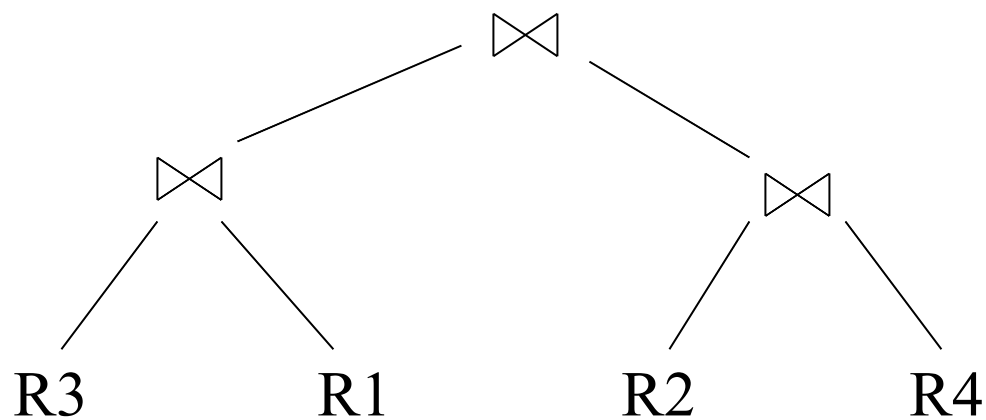
Relational Algebra Laws

- Selections
  - Commutative: $\sigma_{c1}(\sigma_{c2}(R))$ same as $\sigma_{c2}(\sigma_{c1}(R))$
  - Cascading: $\sigma_{c1 \wedge c2}(R)$ same as $\sigma_{c2}(\sigma_{c1}(R))$
- Projections
  - Cascading
- Joins
  - Commutative : $R \bowtie S$ same as $S \bowtie R$
  - Associative: $R \bowtie (S \bowtie T)$ same as $(R \bowtie S) \bowtie T$

Left-Deep Plans and Bushy Plans



Left-deep plan



Bushy plan

Relational Algebra Laws

- Selects, projects, and joins
  - We can commute and combine all three types of operators
  - We just have to be careful that the fields we need are available when we apply the operator
  - Relatively straightforward. See book 15.3.

- More info in optional paper (by Chaudhuri), Section 4.

Group-by and Join

R(A, B), S(C,D)

$$\gamma_{A,\ sum(D)}(R(A,B) \bowtie_{B=C} S(C,D)) = \qquad ?$$

Group-by and Join

R(A, B), S(C,D)

$$\gamma_{A,\ sum(D)}(R(A,B) \bowtie_{B=C} S(C,D)) =$$
$$\gamma_{A,\ sum(D)}(R(A,B) \bowtie_{B=C} (\gamma_{C,\ sum(D)} S(C,D)))$$

These are very powerful laws.
They were introduced only in the 90's.

Search Space Challenges

- Search space is huge!
  - Many possible equivalent trees (logical)
  - Many implementations for each operator (physical)
  - Many access paths for each relation (physical)

- Cannot consider ALL plans
- Want a search space that includes low-cost plans

Query Optimization

Three major components:

1. Cardinality and cost estimation
2. Search space
3. Plan enumeration algorithms

Two Types of Optimizers

- Heuristic-based optimizers:
  - Apply greedily rules that always improve plan
    - Typically: push selections down
  - Very limited: no longer used today

- Cost-based optimizers:
  - Use a cost model to estimate the cost of each plan
  - Select the “cheapest” plan
  - We focus on cost-based optimizers

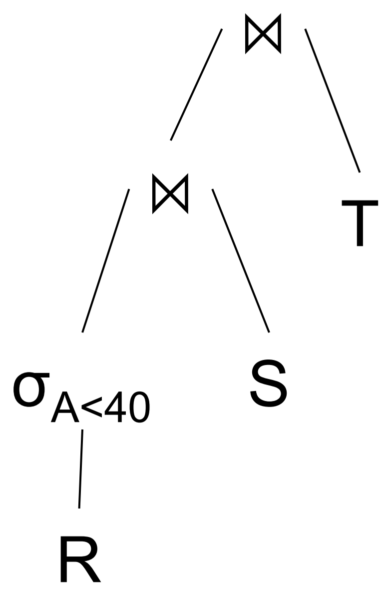
Three Approaches to Search Space Enumeration

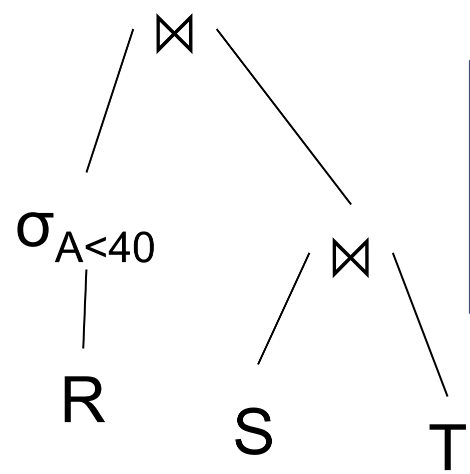
- Complete plans
- Bottom-up plans
- Top-down plans

Complete Plans

R(A,B)
S(B,C)
T(C,D)

```
SELECT *
FROM R, S, T
WHERE R.B=S.B and S.C=T.C and R.A<40
```





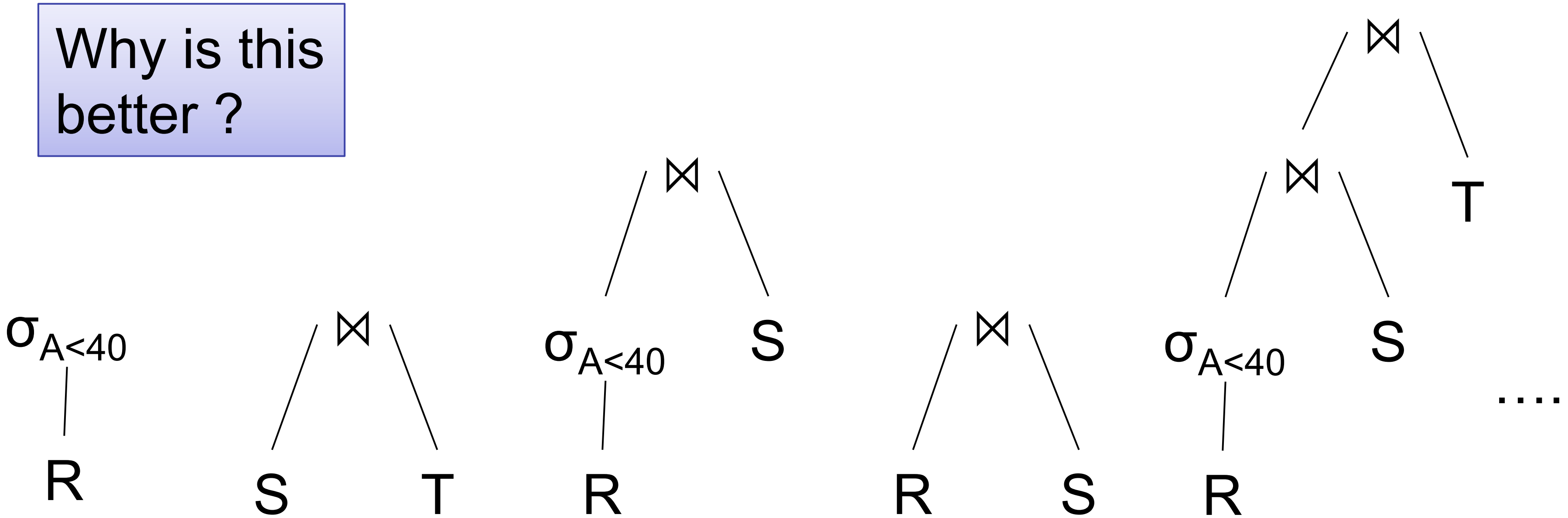
Why is this search space inefficient ?

Bottom-up Partial Plans

R(A,B)
S(B,C)
T(C,D)

```
SELECT *
FROM R, S, T
WHERE R.B=S.B and S.C=T.C and R.A<40
```

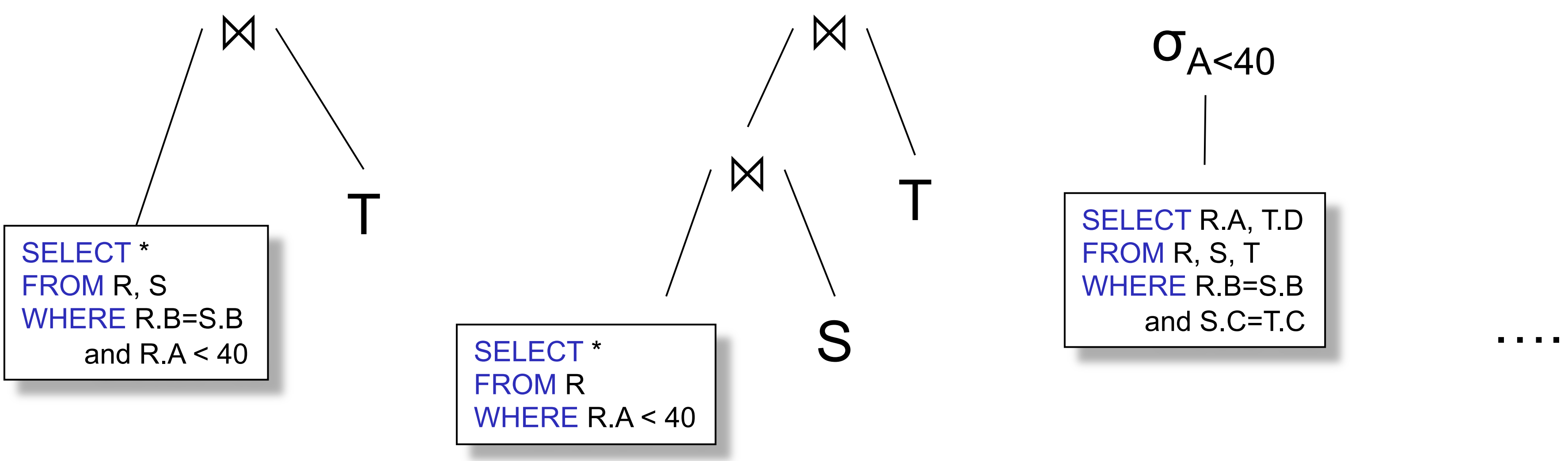
Why is this better ?



Top-down Partial Plans

R(A,B)
S(B,C)
T(C,D)

```
SELECT *
FROM R, S, T
WHERE R.B=S.B and S.C=T.C and R.A<40
```



Two Types of Plan Enumeration Algorithms

- Dynamic programming (in class)
  - Based on System R (aka Selinger) style optimizer[1979]
  - Limited to joins: *join reordering algorithm*
  - Bottom-up

- Rule-based algorithm (will not discuss)
  - Database of rules (=algebraic laws)
  - Usually: dynamic programming
  - Usually: top-down

System R Search Space

- Only left-deep plans
  - Enable dynamic programming for enumeration
  - Facilitate tuple pipelining from outer relation
- Consider plans with all "interesting orders"
- Perform cross-products after all other joins (heuristic)
- Only consider nested loop & sort-merge joins
- Consider both file scan and indexes
- Try to evaluate predicates early

Plan Enumeration Algorithm

- Idea: use dynamic programming
- For each subset of {R1, …, Rn}, compute the best plan for that subset
- In increasing order of set cardinality:
  - Step 1: for {R1}, {R2}, …, {Rn}
  - Step 2: for {R1,R2}, {R1,R3}, …, {Rn-1, Rn}
  - …
  - Step n: for {R1, …, Rn}
- It is a bottom-up strategy
- A subset of {R1, …, Rn} is also called a *subquery*

Dynamic Programming Algo.

- For each subquery Q ⊆{R1, …, Rn} compute the following:
  - Size(Q)
  - A best plan for Q: Plan(Q)
  - The cost of that plan: Cost(Q)

Dynamic Programming Algo.

- **Step 1**: Enumerate all single-relation plans
  - Consider selections on attributes of relation
  - Consider all possible access paths
  - Consider attributes that are not needed
  - Compute cost for each plan
  - Keep cheapest plan per "interesting" output order

Dynamic Programming Algo.

- **Step 2**: Generate all two-relation plans
  - For each each single-relation plan from step 1
  - Consider that plan as outer relation
  - Consider every other relation as inner relation
  - Compute cost for each plan
  - Keep cheapest plan per "interesting" output order

Dynamic Programming Algo.

- **Step 3**: Generate all three-relation plans
  - For each each two-relation plan from step 2
  - Consider that plan as outer relation
  - Consider every other relation as inner relation
  - Compute cost for each plan
  - Keep cheapest plan per "interesting" output order
- **Steps 4 through n**: repeat until plan contains all the relations in the query

Commercial Query Optimizers

DB2, Informix, Microsoft SQL Server, Oracle 8

- Inspired by System R
  - Left-deep plans and dynamic programming
  - Cost-based optimization (CPU and IO)
- Go beyond System R style of optimization
  - Also consider right-deep and bushy plans (e.g., Oracle and DB2)
  - Variety of additional strategies for generating plans (e.g., DB2 and SQL Server)

Other Query Optimizers

- Randomized plan generation
  - Genetic algorithm
  - PostgreSQL uses it for queries with many joins

- Rule-based
  - ***Extensible*** collection of rules
  - Rule = Algebraic law with a direction
  - Algorithm for firing these rules
    - Generate many alternative plans, in some order
    - Prune by cost
  - Startburst (later DB2) and Volcano (later SQL Server)