Distributed query optimization

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These slides are a modified version of the slides provided with the book

Özsu and Valduriez, *Principles of Distributed Database Systems* (3rd Ed.), 2011

The original version of the slides is available at: extras.springer.com

Outline (distributed DB)

- Introduction (Ch. 1) ⋆

- Distributed Database Design (Ch. 3) ⋆

- Distributed Query Processing (Ch. 6-8) ⋆
  - ➡ Overview (Ch. 6) ⋆
  - ➡ Query decomposition and data localization (Ch. 7) ⋆
  - ➡ **Distributed query optimization (Ch. 8)** ⋆

- Distributed Transaction Management (Ch. 10-12) ⋆

⋆ Özsu and Valduriez, *Principles of Distributed Database Systems* (3rd Ed.), 2011

Outline (today)

- Distributed query optimization (Ch. 8) ★
  - ➡ Overview
  - ➡ Join Ordering in Localized Queries
  - ➡ Semijoin-based Algorithm
  - ➡ Distributed query optimization strategies
  - ➡ Hybrid approaches

★ Özsu and Valduriez, *Principles of Distributed Database Systems* (3rd Ed.), 2011

Distributed Query Optimization

- In previous chapter (Ch. 7) [★] -- 1st optimization phase:
  - A distributed query is mapped into a query over fragments (decomposition and data localization)
  - Reduction ("optimization") independent from relation (fragment) statistics (e.g., cardinality)
- In this chapter (Ch. 8) [★]:-- 2nd optimization phase:
  - Optimization based on DB statistics (order of operations and operands, algorithm to perform simple operations) to produce a query execution plan (QEP)
    - In the distributed case a QEP is further extended with communication operations to support execution of queries over fragment sites
  - Statement of the problem
    - Input: Fragment query
    - Output: the *"best"* global strategy
  - Once again: the problem is NP-hard, so not looking for the optimal solution
  - Additional problems specific to the distributed setting
    - Where to execute (partial) queries? Which relation to ship where?
    - Choose between data transfer methods : ship-whole vs. fetch-as-needed
      - ✓ Decide on the use of semijoins (semijoins save on communication at the expense of more local processing)

[★] Özsu and Valduriez, *Principles of Distributed Database Systems* (3rd Ed.), 2011

Elements of the Optimizer

- The element of the optimization process are similar in distributed and centralized cases
  - Search space (aka solution space)
    - The set of equivalent QEP: algebra expressions enriched with implementation details and **communication choices**
  - Cost model
    - Cost function (in terms of time)
      - ✓ I/O cost + CPU cost + **communication cost**
      - ✓ In early approach only communication costs were considered; due to fast communication technology, communication and I/O costs become comparable
      - ✓ These might have different weights in different distributed environments (LAN vs WAN)
  - Search algorithm (aka search strategy)
    - How do we move inside the solution space?
      - ✓ Exhaustive search, heuristic algorithms
    - Goal is searching the solution space to find a good strategy according to the cost model
- Difference between centralized and distributed settings: search space and cost model (*search strategy* remains basically the same)

Search Space

- Search space is large
  - *N* relations ➡ ((2(N-1))!)/((N-1)!) equivalent join trees (by join commutativity and associativity)
  - **Larger search space** due to more options
- QEP are decorated with more information (on **data exchange**)
- Focus on join and **semijoin** order
- Different candidate solution in the search space
  - A good heuristics for centralized context: left-deep trees
  - In distributed context: non left-deep trees allow for **parallelization**

Cost model

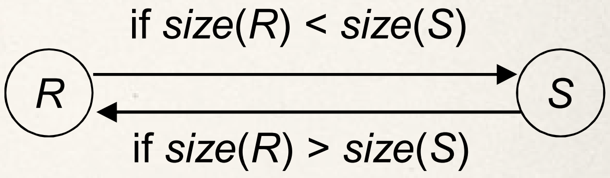
- The focus is on communication costs (local CPU costs and I/O costs are less significant)
- Locally, every D-DBMS acts a centralized optimizer to devise best execution plan of part of the queries that are assigned at that site
  - → This is the 3rd optimization phase: exactly like in the centralized case, cost model focuses on I/O costs

Join Ordering in the Distributed Context

- Join ordering is important in centralized query optimization
- It is even more in distributed query optimization (affect communication costs)
- Use of semijoins to reduce relation sizes (and thus communication costs) before performing join operations

Join Ordering – 2 relations

- We assume query to be already localized (i.e., on fragments)
  - Fragments are relations entirely stored at a single site
    - We often use "fragments" and "relations" indistinguishably (no technical reason to distinguish them)
- We first focus on ordering issues without using semijoins
  - Consider 2-relation join: $R \bowtie S$ (where R and S are stored at different sites)
    - Move the smaller relation to the site of the larger one
    - Moving outer relation R has benefits:
      - ✓ No need for storing R in *nested-loop* or *block nested-loop* join algorithms
      - ✓ *indexed nested-loop* join algorithm remains available as index on inner relation S is preserved (index is lost when transfering S)
    - Therefore, a good choice is to use the smaller relation as outer relation and move it to the site of the larger relation

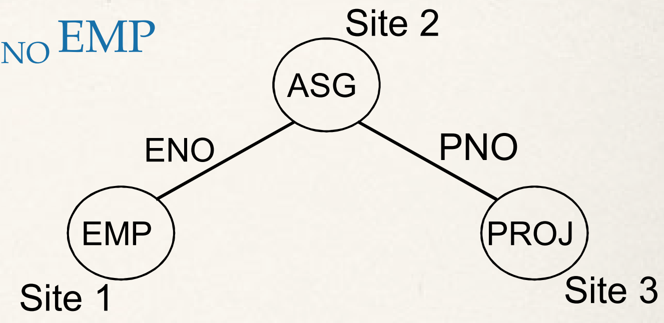


Join Ordering – Multiple Relations

- Multiple relations case: more difficult because too many alternatives
- Goal is still transmit small operands (relations)
  - ➡ Compute the cost of all alternatives and select the best one
    - ✦ Necessary to compute the size of intermediate relations which is difficult
      - ✓ In distributed context it is even more because information may be not available on site

Join Ordering – Example

Consider PROJ $\bowtie_{PNO}$ ASG $\bowtie_{ENO}$ EMP



Join graph of distributed query

Execution alternatives:

1. EMP→ Site 2
   Site 2 computes EMP'=EMP ⋈ ASG
   EMP'→ Site 3
   Site 3 computes EMP' ⋈ PROJ
2. ASG → Site 1
   Site 1 computes EMP'=EMP⋈ ASG
   EMP' → Site 3
   Site 3 computes EMP' ⋈ PROJ
3. ASG → Site 3
   Site 3 computes ASG'=ASG ⋈ PROJ
   ASG' → Site 1
   Site 1 computes ASG' ⋈EMP
4. PROJ → Site 2
   Site 2 computes PROJ'=PROJ ⋈ ASG
   PROJ' → Site 1
   Site 1 computes PROJ' ⋈ EMP
5. EMP → Site 2
   PROJ → Site 2
   Site 2 computes EMP ⋈ PROJ ⋈ ASG

Semijoin Algorithms

- Semijoins can be used to reduce the sizes of operands to transfer (similar to what selections do)
    - → Reduced communication costs
- Consider the join of two relations:
    - → R (at site 1)
    - → S (at site 2)
- Alternatives:
    1. Do the join $R \bowtie_A S$
    2. Perform one of the semijoin-based equivalent options

$$\begin{aligned} R \bowtie_A S \quad &\Leftrightarrow \quad (R \ltimes_A S) \bowtie_A S \\ &\Leftrightarrow \quad R \bowtie_A (S \ltimes_A R) \\ &\Leftrightarrow \quad (R \ltimes_A S) \bowtie_A (S \ltimes_A R) \end{aligned}$$

Tradeoff between

a) cost to compute and send semijoin to other site (and then perform the join there)

b) Cost to send the whole relation to other site (and then perform the join there)

Semijoin Algorithms – Example

- Perform the join
  - ➙ Send R to Site 2
  - ➙ Site 2 computes $R \bowtie_A S$
- Consider semijoin $(R \ltimes_A S) \bowtie_A S$
  - ➙ $S' = \Pi_A(S)$
  - ➙ $S' \rightarrow$ Site 1
  - ➙ Site 1 computes $R' = R \ltimes_A S'$
  - ➙ $R' \rightarrow$ Site 2
  - ➙ Site 2 computes $R' \bowtie_A S$
- Semijoin is better if

$$size(\Pi_A(S)) + size(R \ltimes_A S)) < size(R)$$

  - ➙ Only communication costs (time to transfer relations)

Semijoin Algorithms – Sum up

- Using semijoin is convenient if $R \ltimes_A S$ is much smaller in size (MB) than $R \bowtie_A S$ (i.e., it has high selectivity (few tuples are selected) and/or size of tuples of R is large)
- It is bad otherwise, due to the additional transfer of $\Pi_A(S)$ and cost of local computation
- Cost of transferring $\Pi_A(S)$ can be reduced by using bit arrays
- A disadvantage of using semijoin is the loss of indices

Semijoin Algorithms – Sum up

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Bit arrays

- Let h be a hash function that distributes possible values for A into n buckets:

$$h : Dom(A) \longrightarrow \{ 0, \ldots, n\text{-}1 \}$$

- Bit array $BA[0 \,..\, n\text{-}1]$ over relation S is defined as:

$$BA[i] = 1 \qquad \text{iff} \qquad \exists \text{ value } v \text{ for attribute } A \text{ in } S \text{ s.t. } h(v) = i$$

- Transfer BA (n bits) rather than $\Pi_A(S)$
- A tuple of R with value v for attribute A belongs to R' iff $BA[h(v)] = 1$
- R' is an (over-)approximation of $R \ltimes_A S$

Bit Arrays for Seminoins

R

id$_R$	A
1	1
2	2
3	2
4	5
5	4
6	5
7	4
8	5

S

id$_S$	A
1	5
2	5
3	3
4	5
5	3

$R' \quad \supsetneq \quad R \ltimes_A S$

id$_R$	A
1	1
4	5
6	5
8	5

id$_S$	A
4	5
6	5
8	5

R' : $R \ltimes_A S$ computed with bit array

- Recall:
  - ○ $BA[i] = 1$ iff $\exists$ value v for attribute A in S s.t. $h(v) = i$
  - ○ a tuple of R with value v for A belongs to R' iff $BA[h(v)] = 1$
- $h(x) = x \bmod 4$
- $n = 4$ (4 buckets)
- $h(1) = h(5) = 1$
- $BA[0] = 0$ (no value v occurs in $S.A$ s.t. $h(v) = 0$)
- $BA[1] = 1$ (due to occurrence of 5 for attribute A in S)
- $BA[2] = 0$ (no value v occurs in $S.A$ s.t. $h(v) = 2$)
- $BA[3] = 1$ (due to occurrence of 3 for attribute A in S)

R′ contains tuple <1,1> that does not belong to $R \ltimes_A S$

However, R' is a good approximation because h has only one conflict ($h(1) = h(5)$) among values for attribute A in R and S

Semijoins for Joins among Multiple Relations

- Semijoins to optimize joins among more than 2 operands

$$\mathrm{EMP} \bowtie \mathrm{ASG} \bowtie \mathrm{PROJ} = \mathrm{EMP}' \bowtie \mathrm{ASG}' \bowtie \mathrm{PROJ}$$

where $\mathrm{EMP}' = \mathrm{EMP} \ltimes \mathrm{ASG}$
and $\mathrm{ASG}' = \mathrm{ASG} \ltimes \mathrm{PROJ}$

- Each operand can be further reduced using more than one semijoin in cascade

$$\mathrm{EMP}'' = \mathrm{EMP} \ltimes (\mathrm{ASG} \ltimes \mathrm{PROJ})$$

We have $\mathit{size}(\mathrm{ASG} \ltimes \mathrm{PROJ}) \quad <= \quad \mathit{size}(\mathrm{ASG})$
Therefore $\mathit{size}(\mathrm{EMP}'') \quad <= \quad \mathit{size}(\mathrm{EMP}')$

Semijoins for Joins among Multiple Relations

- Semijoins to optimize joins among more than 2 operands

$$EMP \bowtie ASG \bowtie PROJ = EMP' \bowtie ASG' \bowtie PROJ$$

where $EMP' = EMP \ltimes ASG$

and $ASG' = ASG \ltimes PROJ$

- Each operand can be further reduced using more than one semijoin in cascade

$$EMP'' = EMP \ltimes (ASG \ltimes PROJ)$$

Semijoin program

We have $size(ASG \ltimes PROJ) <= size(ASG)$

Therefore $size(EMP'') <= size(EMP')$

Semijoins for Joins among Multiple Relations

- Semijoins to optimize joins among more than 2 operands

$$EMP \bowtie ASG \bowtie PROJ = EMP' \bowtie ASG' \bowtie PROJ$$

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- Each operand can be further reduced using more than one semijoin in cascade

$$EMP'' = EMP \ltimes (ASG \ltimes PROJ)$$

Semijoin program

We have $size(ASG \ltimes PROJ) \quad <= \quad size(ASG)$

Therefore $size(EMP'') \quad <= \quad size(EMP')$

- Full reducer for a relation is the semijoin program that reduces the relation the most
- Finding full reducer for a relation with exhaustive brute force approach
  - For cyclic queries full reducer cannot be found
    - Solution: break the cycle
  - With other queries: inefficient (NP-hard)
    - Solution: only use semijoin when problem is simple
      - e.g., for chained queries, where relations are in sequence and each one joins with the next one

Distributed Query Optimization

- We focus on optimization of joins
- The algorithm for optimizing a join is adapted from the one for the centralized case
- In distributed context
  - ➞ There is a coordinator (master site) where query is initiated
  - ➞ Coordinator chooses
    1. execution site and
    2. transfer method
  - ➞ Apprentice sites (where fragments are stored and queries are executed)
    - ✦ Apprentices behave as in the case of centralized query optimization in optimizing partial localized queries (over fragments) assigned to them
      - ✓ Choose best join ordering, join algorithm, and access method for relations

Choices of the Master Site

1. Choice of the execution sites
   - E.g., $R \bowtie S$ can be executed:
     - at the site where R is stored
     - at the site where S is stored
     - at a third site (e.g., where a 3rd relation waits to be joined – allows for parallel transfer)
2. Transfer method
   - *ship-whole*: relation is transferred to the join execution site entirely
     - In some cases (e.g., for outer relations of in case of block nested-loop join) there is no need to store the relation: join as it arrives, in pipelined mode
   - *fetch-as-needed* (only needed tuples are transferred, i.e., tuples that join with at least one tuple):
     - do semijoin of one relation with the other one (to reduce size of the former) before doing the join
     - e.g., semi-join of inner relation wrt outer one (only needed tuples of inner relation are transferred)
       - ✓ tuples of the outer relation are sent (only the join attribute) to the site of the inner relation
       - ✓ matching tuples of the inner relation are sent to the site of the external relation to execute the join

Not all combinations are worth being considered (we consider 4 strategies)

Strategy 1 – *ship-whole/inner* site

1. *ship-whole*/site of *inner* relation: move outer relation (R) to the site of the inner relation (S)
   - (a) Retrieve all tuples of outer relation R
   - (b) Send them to the inner relation site
   - (c) Join them as they arrive

- $CT(x)$: communication time to transfer x bytes
- $LT(x)$: local processing time to perform op. x
- s: average number of tuples of S that match a single tuple of R

Total Cost = LT (retrieve $card(R)$ tuples from R)

\+ CT ($size(R)$)

\+ LT (retrieve s tuples from S) * $card(R)$

Join is done as *R* comes because *R* is the outer relation

Strategy 2 – *ship-whole/outer* site

2. *ship-whole*/site of *outer* relation: move inner relation (S) to the site of outer relation (R)

Cannot join as S arrives; it needs to be stored. And index over S is lost

Total cost = LT (retrieve $card$(S) tuples from S)

+ CT ($size(S)$)

+ LT (store $card(S)$ tuples in temporary relation T)

+ LT (retrieve $card(R)$ tuples from R)

+ LT (retrieve $card$(S) tuples from T) * $card(R)$ ***[no index over T]***

- $CT(x)$: communication time to transfer x bytes
- $LT(x)$: local processing time to perform op. x
- s: average number of tuples of S that match a single tuple of R

Strategy 3 – *fetch-as-needed/outer* site

3. *fetch-as-needed*/site of *outer* relation
   (a) Retrieve tuples at outer relation (R) site
   (b) For each tuple of R, send join attribute values to inner relation (S) site
   (c) Retrieve matching inner tuples at inner relation site
   (d) Send the matching inner tuples to outer relation site
   (e) Join as they arrive (use R as inner relation since it is already in memory)

$$\begin{aligned}\text{Total Cost} \quad = \quad & LT\,(\text{ retrieve } card(\,R\,) \text{ tuples from } R\,) \\ & +\; CT\,(\,length\,(\,A\,)\,)\,*\,card\,(\,R\,) \\ & +\; LT\,(\text{ retrieve } s \text{ tuples from } S\,)\,*\,card\,(\,R\,) \\ & +\; CT\,(\,s\,*\,length\,(\,S\,)\,)\,*\,card\,(\,R\,)\end{aligned}$$

- $CT(x)$: communication time to transfer x bytes
- $LT(x)$: local processing time to perform op. x
- s: average number of tuples of S that match a single tuple of R

Strategy 4 – Move Both Relation at Third Site

4. move both inner (*S*) and outer (*R*) relations to another site

Total cost = *LT* (retrieve *card* (*S*) tuples from *S*)

+ *CT* (*size* (*S*))

+ *LT* (store *card*(*S*) tuples in temporary relation *T*)

+ *LT* (retrieve *card* (*R*) tuples from *R*)

+ *CT* (*size*(*R*))

+ *LT* (retrieve *card*(*S*) tuples from *T*) * *card*(*R*) ***[no index over T]***

- *CT*(*x*): communication time to transfer *x* bytes
- *LT*(*x*): local processing time to perform op. *x*
- *s*: average number of tuples of *S* that match a single tuple of *R*

Moving inner relation *S* first is better so we can then join as outer relation *R* arrives

Strategy comparison

$$\text{PROJ} \bowtie_{\text{PNO}} \text{ASG}$$

- PROJ (outer rel.) and ASG (inner rel.) are stored at different sites
- Index on PNO for relation ASG

1. Ship whole PROJ at site of ASG	$CT(\mathit{size}(\text{PROJ}))$
2. Ship whole ASG at site of PROJ	$CT(\mathit{size}(\text{ASG}))$
3. Fetch tuples of ASG as needed at site of PROJ	$CT(\mathit{length}(PNO)) * \mathit{card}(\text{PROJ})$ $+ CT(s * \mathit{length}(\text{ASG})) * \mathit{card}(\text{PROJ})$
4. Move both ASG and PROJ to a third site	$CT(\mathit{size}(\text{ASG})) + CT(\mathit{size}(\text{PROJ}))$

- If there is no upper level operation then **4** is a bad choice
- If *size* (*PROJ*) >> *size* (*ASG*), then **2** is a good choice (if local processing time is not too bad compared with **1** and **3**, which can exploit index on ASG in their local processing)
- If *PROJ* is large/few tuples of *ASG* match, then **3** is better than **1**
- Otherwise, **1** is better than **3**

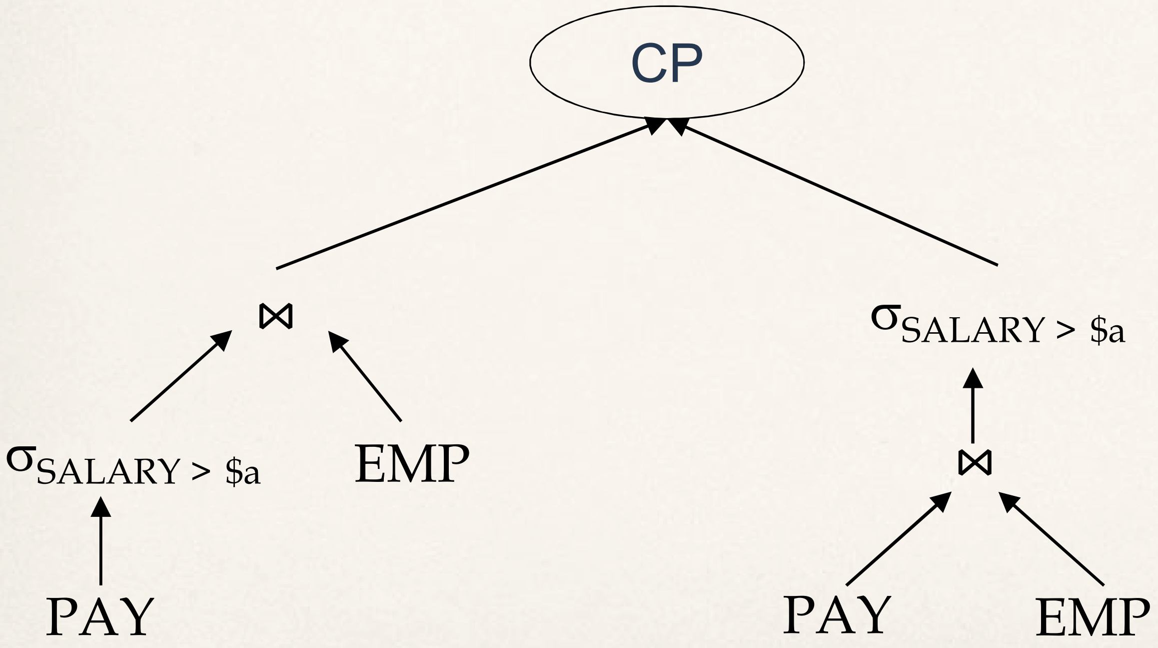
Hybrid approach

- Optimization can be *static* or *dynamic*
  - *static*: strategies (QEP) are evaluated and compared not at run-time (i.e., not when query is requested but, e.g., in low-workload periods of the system)
    - advantages: query optimization is done once and used for several query executions
    - disadvantages: cost evaluation is less accurate because statistic and estimations for computing the costs are not available or less accurate (e.g., some parameters of a query might be known only at runtime)
  - *dynamic*: strategies (QEP) are evaluated and compared at run-time (i.e., when query is requested)
    - advantages: cost evaluation is not that accurate
    - disadvantages: optimization is costly and doing it at runtime slow the running time of queries
      - less accurate exploration of the search space
- Problems of static query optimization are much more severe in the distributed context: more infomation variability at runtime
  - Sites may become unavailable or overloaded
  - Selection of site and fragment copy should be done at runtime to increase availability and load balancing
- hybrid solutions (some decisions are taken at runtime)
  - CP (choose-plan) operator, which is resolved at runtime, when an exact plan comparison can be done
  - 2-step optimization: operation order and algorithm are chosen statically, site where to execute operations and transfer method are chosen at runtime

The CP (choose-plan) Operator

SELECT *
FROM EMP, PAY
WHERE SALARY > $a

where $a is a variable whose value is specified by the user at runtime



CP

⋈

$\sigma_{SALARY > \$a}$

EMP

PAY

$\sigma_{SALARY > \$a}$

⋈

PAY

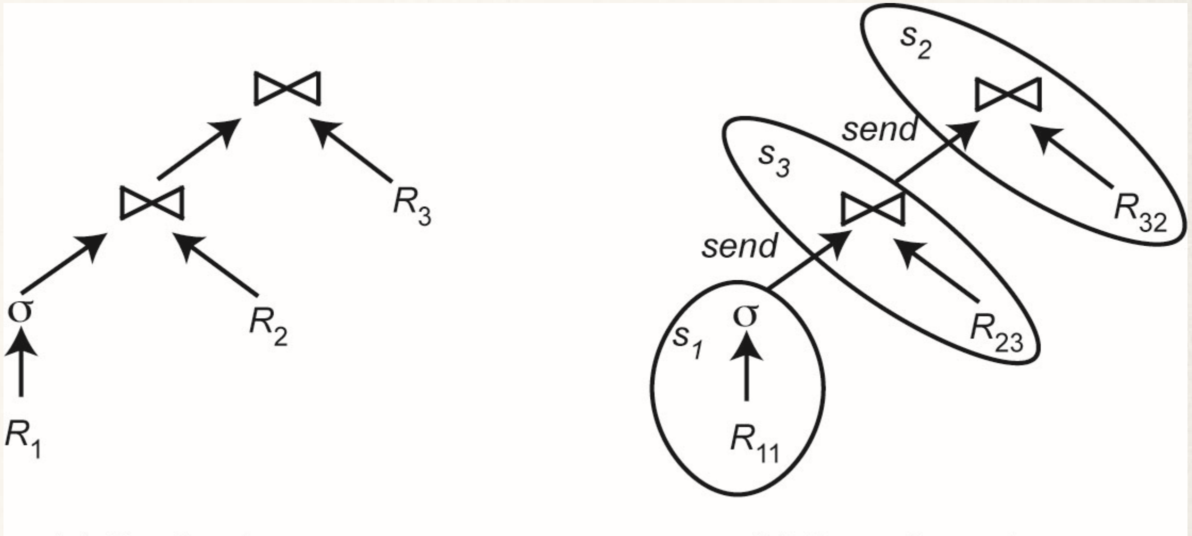
EMP

Normally, pushing σ inside ⋈ is a good heuristics, but it can be bad if selection rate of ⋈ is higher than the one of σ

2-Step Optimization

- 2-Step optimization: a simpler approach (more efficient, less exhaustive) than the one based on CP operator; it reduces workload at runtime (no CP operator)
  - ➞ At runtime labels are added about sites, fragment copies, and shipping methods only

1. At compile time, generate a static plan with operation ordering and access methods/algorithms only
2. At startup (running) time, select sites, fragment copies, and shipping methods, and allocate operations to sites



(a) Static plan (b) Run-time plan

- Site (and copy) selection is done in a greedy fashion
  - ➞ best load balancing,
  - ➞ best benefit (# of queries already executed at the site, possible saving of communication costs as the site might have already data available)