
Distributed DB design

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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) *
 - Fragmentation
 - Data distribution (allocation)
- Distributed Query Processing (Ch. 6-8) *
- Distributed Transaction Management (Ch. 10-12) *

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

Outline (today)

- Distributed DB design (Ch. 3) *
 - Introduction
 - Top-down (vs. bottom-up) design
 - Distribution design issues
 - ◆ Fragmentation
 - ◆ Allocation
 - Fragmentation
 - ◆ Horizontal Fragmentation (HF)
 - ✓ Primary Horizontal Fragmentation (PHF)
 - ✓ Derived Horizontal Fragmentation (DHF)
 - ◆ Vertical Fragmentation (VF)
 - ◆ Hybrid Fragmentation (HyF)
 - Allocation
 - Data directory

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

Design Problem

- In the general setting:

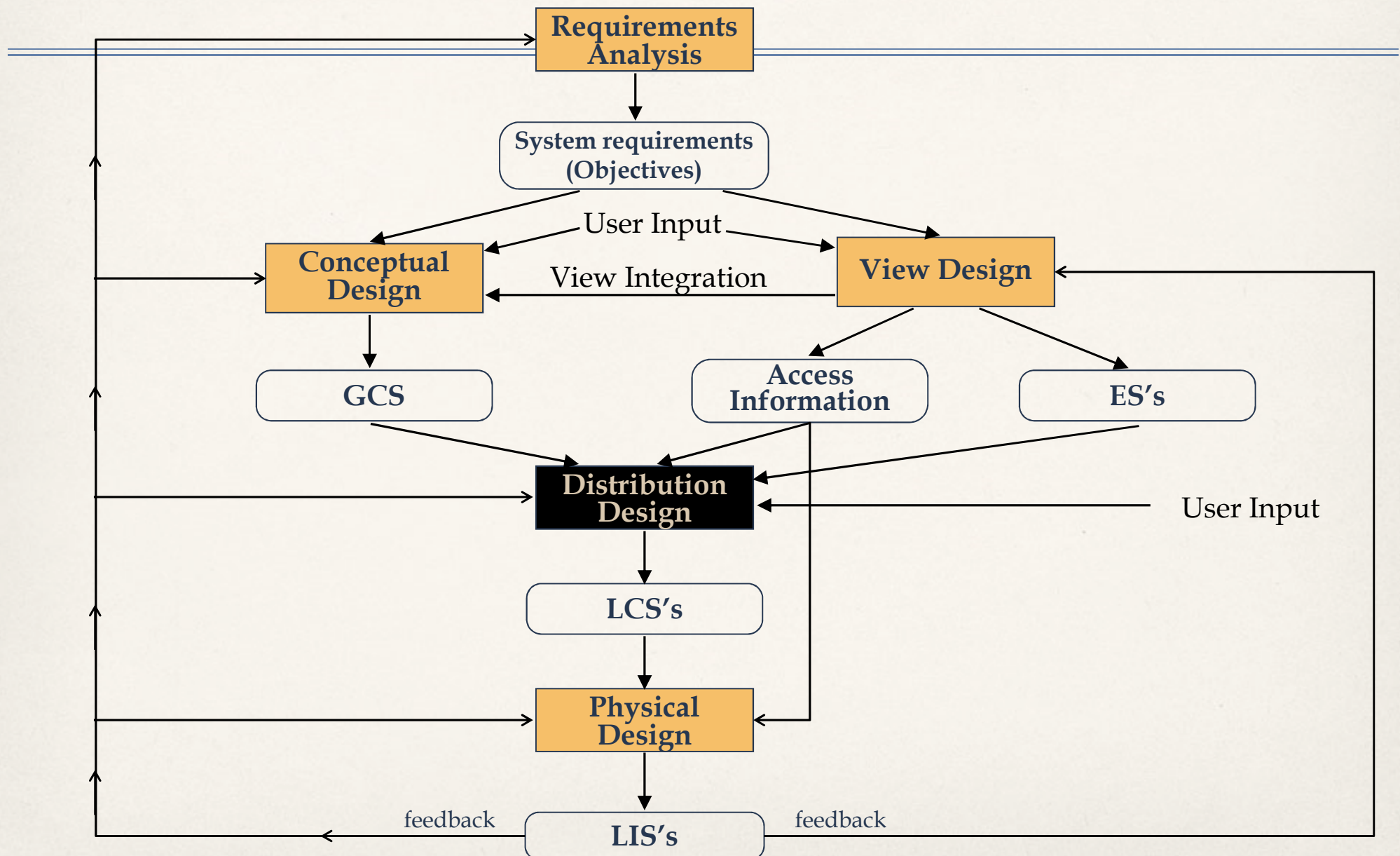
Making decisions about the placement of **data** and **programs (control)** across the sites of a computer network as well as possibly designing the network itself

- In Distributed DBMS, the placement of applications entails
 - placement of the distributed DBMS software; and
 - placement of the applications that run on the database

Distribution Design

- Top-down
 - mostly in designing systems from scratch
 - mostly in homogeneous systems
 - applies to fully distributed DBMS (a logical view of the whole DB exists)
- Bottom-up
 - when the databases already exist at a number of sites
 - applies to MDBS (we will not treat them)

Top-Down Design



Distribution Design Issues

Distribution design activity boils down to *fragmentation* and *allocation*

- ① Why fragment at all? [reasons for fragmentation]
- ② How to fragment? [fragmentation alternatives]
- ③ How much to fragment? [degree of fragmentation]
- ④ How to test correctness? [correctness rules of fragmentation]
- ⑤ How to allocate? [allocation alternatives]
- ⑥ Information requirements? [for both fragmentation and allocation]

1. Reasons for Fragmentation

- Can't we just distribute relations (no intrinsic reason to fragment)?
 - distributed file systems are not fragmented (i.e., distr. unit is the file)
- What is a reasonable unit of distribution?
 - advantages of fragmentation (why isn't relation the best choice?)
 - ◆ application views are subsets of relations → **locality** allows for finer accesses (applications only access to relevant subsets of relations)
 - ✓ 2 applications accessing different portion of a relation: **without fragmentation**, either unnecessary data replication or loss of locality (extra communication)
 - ◆ **without fragmentation**, no **intra-query parallelism**
 - disadvantages of fragmentation
 - ◆ might cause queries to be executed on more than one fragment (performance degradation, especially when fragments are not disjoint)
 - ◆ semantic data control (especially integrity enforcement) more difficult and costly

2. Fragmentation Alternatives

PROJ

PNO	PNAME	BUDGET	LOC
P1	Instrumentation	150000	Montreal
P2	Database Develop.	135000	New York
P3	CAD/CAM	250000	New York
P4	Maintenance	310000	Paris

Horizontal fragmentation

- PROJ₁: projects with budget < \$200,000
- PROJ₂: projects with budget ≥ \$200,000

PROJ₁

PNO	PNAME	BUDGET	LOC
P1	Instrumentation	150000	Montreal
P2	Database Develop.	135000	New York

PROJ₂

PNO	PNAME	BUDGET	LOC
P3	CAD/CAM	250000	New York
P4	Maintenance	310000	Paris

Vertical fragmentation

- PROJ₁: information about project budgets
- PROJ₂: information about project names and locations

PROJ₁

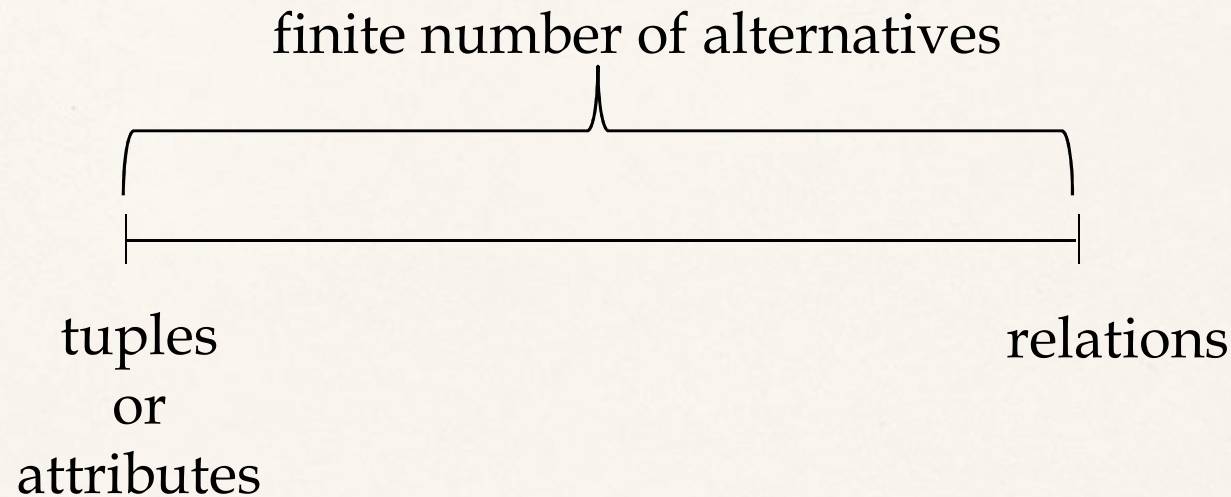
PNO	BUDGET
P1	150000
P2	135000
P3	250000
P4	310000

PROJ₂

PNO	PNAME	LOC
P1	Instrumentation	Montreal
P2	Database Develop.	New York
P3	CAD/CAM	New York
P4	Maintenance	Paris

Hybrid fragmentation: obtained by nesting horizontal and vertical fragmentation

3. Degree of Fragmentation



- Finding the suitable level of partitioning within this range
- It depends especially on the applications that will use the DB
- This is the real difficulty of fragmentation

4. Correctness of Fragmentation

- Completeness

- Decomposition of relation R into fragments R_1, R_2, \dots, R_n is complete if and only if each data item in R can also be found in some R_i

- Reconstruction

- If relation R is decomposed into fragments R_1, R_2, \dots, R_n , then there should exist some relational operator ∇ such that

$$R = \nabla_{1 \leq i \leq n} R_i$$

- Disjointness

- If relation R is decomposed into fragments R_1, R_2, \dots, R_n , and data item d_i is in R_j , then d_i should not be in any other fragment R_k ($k \neq j$).

5. Allocation Alternatives

- Assigning fragments to sites and deciding **whether or not to replicate a fragment**
 - *partitioned* (aka *non-replicated*): each fragment resides at only one site
 - *fully replicated*: each fragment at each site
 - *partially replicated*: each fragment at some of the sites
- Rule of thumb:
 - If $\frac{\text{read-only queries}}{\text{update queries}} \gg 1$, replication is advantageous,
otherwise replication may cause problems
- In case of partially replicated DDBS, the number of copies of replicated fragments can either be an input to the allocation algorithm or a decision variable to be computed by the algorithm

6. Information Requirements

- The difficulty of the distributed DB design problem is that too many factors affect the choices towards an optimal design
 - Logical organization of the DB
 - Location of DBMS applications
 - Characteristics of user applications (how they access the DB)
 - Properties of (computers at) network nodes
 - ...
 - Those can be grouped into four categories:
 - Database information
 - Application information
 - Communication network information
 - Computer system information
- } quantitative information, mostly used for allocation, we will not treat them

Fragmentation

- Horizontal Fragmentation (HF)
 - Primary Horizontal Fragmentation (PHF)
 - Derived Horizontal Fragmentation (DHF)
- Vertical Fragmentation (VF)
- Hybrid Fragmentation (HyF)

PHF – Information Requirements

- application information needed for horizontal fragmentation

→ Predicates used in queries

- ♦ 80/20 rule: the most active 20% of user applications account for 80% of accesses
- ♦ **simple predicates**: Given $R[A_1, A_2, \dots, A_n]$, a **simple predicate** p_j over R is

$$A_i \ \theta \ Value$$

where $\theta \in \{=, <, \leq, >, \geq, \neq\}$, $Value \in D_i$ and D_i is the domain of A_i .

Example:

PNAME = "Maintenance"

BUDGET \leq 200 000

- ♦ **minterms**: Given a set $Pr = \{p_1, p_2, \dots, p_m\}$ of simple predicates over a relation R , a **minterm** (induced by Pr) is a conjunction

$$\bigwedge_{p_j \in Pr} p_j^*$$

where $p_j^* \in \{p_j, \neg p_j\}$, for all $p_j \in Pr$

We let $M_{Pr} = \{m_1, m_2, \dots, m_r\}$ be the set of all minterms induced by a set of simple predicates Pr

PHF – Information Requirements Example

Example

$$Pr = \{ \text{PNAME} = \text{"Maintenance"} , \text{BUDGET} < 200000 \}$$

$$M_{Pr} = \{ m_1 , m_2 , m_3 , m_4 \}$$

Where

- m_1 : $\text{PNAME} = \text{"Maintenance"} \wedge \text{BUDGET} < 200000$
- m_2 : $\neg(\text{PNAME} = \text{"Maintenance"}) \wedge \text{BUDGET} < 200000$
- m_3 : $\text{PNAME} = \text{"Maintenance"} \wedge \neg(\text{BUDGET} < 200000)$
- m_4 : $\neg(\text{PNAME} = \text{"Maintenance"}) \wedge \neg(\text{BUDGET} < 200000)$

PHF – Extra Information Requirements

- Application Information
 - access frequency of queries *(quantitative)*

Primary Horizontal Fragmentation

- Primary horizontal fragmentation (**PHF**) is induced by a set of minterms.
- **Definition:** A set $M = \{ m_1, m_2, \dots, m_n \}$ of minterm induces the fragmentation

$$F = \{ R_i \mid R_i = \sigma_{m_i}(R), m_i \in M, \text{ and } R_i \neq \emptyset \}$$

- Therefore, a horizontal fragment R_i of relation R consists of all the tuples of R which satisfy a minterm predicate m_i



Given a set of minterm predicates M , there are as many horizontal fragments of relation R as there are minterm predicates (some fragments might be empty)

PHF – Example (1)

- Assume there is only 1 application **Q: find projects with budget less than 200 000 €**
 $\sigma_{budget < 200\,000} (PROJ)$
- Then, it makes sense to consider the set of simple predicates $S = \{ BUDGET < 200000 \}$
 which induces the set of minterms $M_S = \{ BUDGET < 200000, \neg(BUDGET < 200000) \}$
 which, in turn, induces fragmentation $F = \{ PROJ_1, PROJ_2 \}$
- $PROJ_1$ and $PROJ_2$ are the **fragments induced by S**

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PROJ₁

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PROJ₂

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PHF – Example (2)

- Consider now another application **Q': find projects at a given location** $\sigma_{loc=x}(PROJ)$
Then, it makes sense to consider the set of simple predicates

$$S' = \{ \text{LOC} = \text{"Montreal"}, \text{LOC} = \text{"New York"}, \text{LOC} = \text{"Paris"} \}$$

which induces the set of minterms (use abbreviations L_M : LOC = "Montreal", L_N : LOC = "New York", L_P : LOC = "Paris")

$$M_{S'} = \{ \begin{array}{llll} L_M \wedge L_N \wedge L_P, & L_M \wedge L_N \wedge \neg L_P, & L_M \wedge \neg L_N \wedge L_P, & L_M \wedge \neg L_N \wedge \neg L_P, \\ \neg L_M \wedge L_N \wedge L_P, & \neg L_M \wedge L_N \wedge \neg L_P, & \neg L_M \wedge \neg L_N \wedge L_P, & \neg L_M \wedge \neg L_N \wedge \neg L_P \end{array} \}$$

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which reduces to

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which reduces to

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$$\{ L_M, L_N, L_P \}$$

or, even more succinctly,

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which reduces to

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or, even more succinctly,

which, in turn, induces fragmentation

$$F' = \{ PROJ'_1, PROJ'_2, PROJ'_3 \}$$

PROJ

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Completeness of the Set of Simple Predicates

- Sets of simple predicates (and thus sets of minterms) should be **complete** and minimal
- Intuitively, *complete* means that all applications (queries) are taken into account
- **Definition:** a set of simple predicates P_r is said to be **complete** if and only if any two tuples in a fragment induced by P_r have the same probability of being accessed by any application

Informal definition (completeness): in other words, we have that every application Q access either **all** or **none** of the tuples of a fragment F
(for every fragment F induced by P_r)

Completeness – Examples

Informal definition (completeness): Q and Q' access either **all** or **none** of the tuples in each fragment

- Only 2 applications Q and Q'
- Q : find projects with budget less than 200 000 €
- Q' : find projects based in New York
- Is $S' = \{ \text{LOC} = \text{"New York"} \}$ complete wrt. appl. Q and Q' ?

PROJ

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 - it produces $F = \{ \text{PROJ}_1, \text{PROJ}_2 \}$
 - Q only accesses project P2 in fragment PROJ_1

PROJ₁

PNO	PNAME	BUDGET	LOC
P2	Database Develop.	135000	New York
P3	CAD/CAM	250000	New York

PROJ₂

PNO	PNAME	BUDGET	LOC
P1	Instrumentation	150000	Montreal
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PROJ

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PROJ_1

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PROJ_2

PNO	PNAME	BUDGET	LOC
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PROJ

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- $S'' = \{ \text{BUDGET} < 200000, \text{LOC} = \text{"New York"} \}$ is **complete** wrt. appl. Q and Q'
 - it produces the minterm set (L_N stands for $\text{LOC} = \text{"New York"}$)

$$M_{S''} = \left\{ \begin{array}{ll} \text{BUDGET} < 200000 \wedge \neg L_N, & \text{BUDGET} \geq 200000 \wedge \neg L_N, \\ \text{BUDGET} < 200000 \wedge L_N, & \text{BUDGET} \geq 200000 \wedge L_N, \end{array} \right\}$$

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 - relevant wrt. to applications (there is at least one application that benefits from the predicate)

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 - relevant wrt. to applications (there is at least one application that benefits from the predicate)
 - **Definition:** a set of simple predicates Pr is said to be **minimal** if and only if every predicates $p \in Pr$ creates a new fragment (i.e., p divides fragment F into F_1 and F_2) and F_1 and F_2 are accessed differently by at least one application
- In other words:** we look for a set of simple predicates Pr that is **complete** and such that every subset of Pr is not complete (**minimality**)

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 - We have 3 applications Q , Q' , and Q''
 - Q : find projects with budget less than 200 000 €
 - Q' : find projects based in New York
 - Q'' : find “Database Develop.” projects
- L_N stands for LOC = “New York”
 $PNAME_{DBdevel}$ stands for PNAME = “Database Develop.”
- Is $S'' = \{ BUDGET < 200000, L_N, PNAME_{DBdevel} \}$ minimal wrt. applications Q, Q', Q'' ?

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	P4	Maintenance	310000	Paris

Minimality

- Intuitively, *minimal* means that all predicates should be relevant in the set wrt.:
 - final fragmentation (every predicate produces some fragments *not produced by other predicates*)
 - applications (there is at least one application that benefit from the predicate)
 - We have 3 applications Q , Q' , and Q''
 - Q : find projects with budget less than 200 000 €
 - Q' : find projects based in New York
 - Q'' : find “Database Develop.” projects
- L_N stands for LOC = “New York”
 $PNAME_{DBdevelop}$ stands for PNAME = “Database Develop.”
- Is $S'' = \{ BUDGET < 200000, L_N, PNAME_{DBdevelop} \}$ minimal wrt. applications Q, Q', Q'' ?
 - NO!
 - $PNAME_{DBdevelop}$ is not relevant wrt. final fragmentation
 - $S'' = \{ BUDGET < 200000, L_N \}$ produces the same fragmentation

PROJ	PNO	PNAME	BUDGET	LOC
	P1	Instrumentation	150000	Montreal
	P2	Database Develop.	135000	New York
	P3	CAD/CAM	250000	New York
	P4	Maintenance	310000	Paris

PROJ' ₁	PNO	PNAME	BUDGET	LOC
	P1	Instrumentation	150000	Montreal

PROJ'' ₂	PNO	PNAME	BUDGET	LOC
	P2	Database Develop.	135000	New York

PROJ''' ₂	PNO	PNAME	BUDGET	LOC
	P3	CAD/CAM	250000	New York

PROJ' ₃	PNO	PNAME	BUDGET	LOC
	P4	Maintenance	310000	Paris

PHF – Algorithm (Intuition)

Input: a relation R and a set of simple predicates Pr over attributes of R

Output: a *complete* and *minimal* set of simple predicates Pr' over R

Minimality rule (relevant predicates): a predicate $p \in Pr$ is **relevant in Pr** if and only if

- produces some fragments which is not produced by any other predicate in Pr
- there is at least one application that benefit from p

repeat

 select a relevant predicate $p \in Pr$

$Pr := Pr \setminus \{ p \}$

$P' := P' \cup \{ p \}$

$P' := P' \setminus \{ p \in P' \mid p \text{ is not relevant in } P' \}$

until P' is complete (equivalently, there is no other relevant predicate)

compute set M of minterms induced by Pr

eliminate contradictory minterms from M

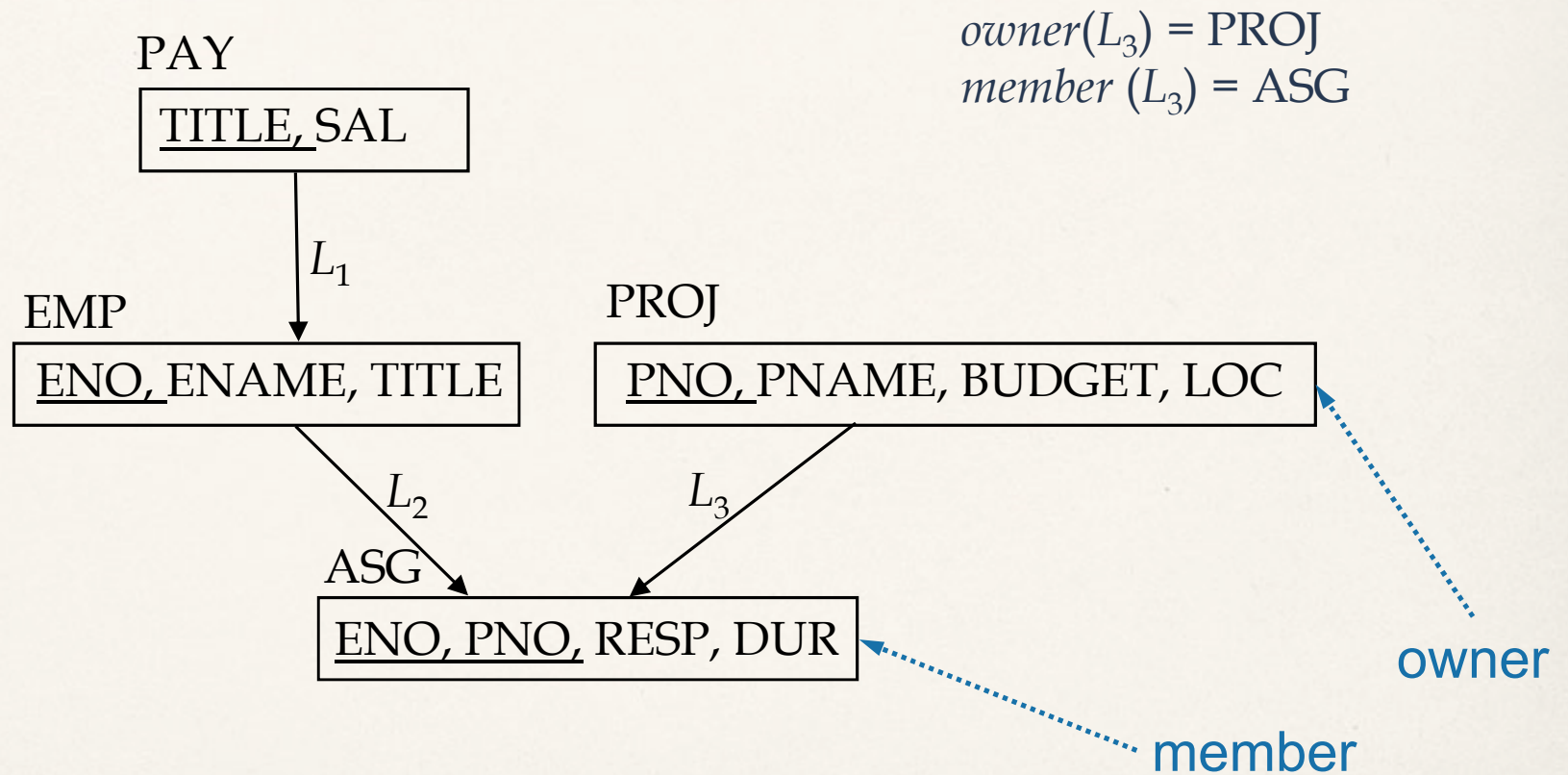
// i.e., minterms that

// produce empty fragments

return fragmentation $F = \{ R_m = \sigma_m(R) \mid m \in M \}$

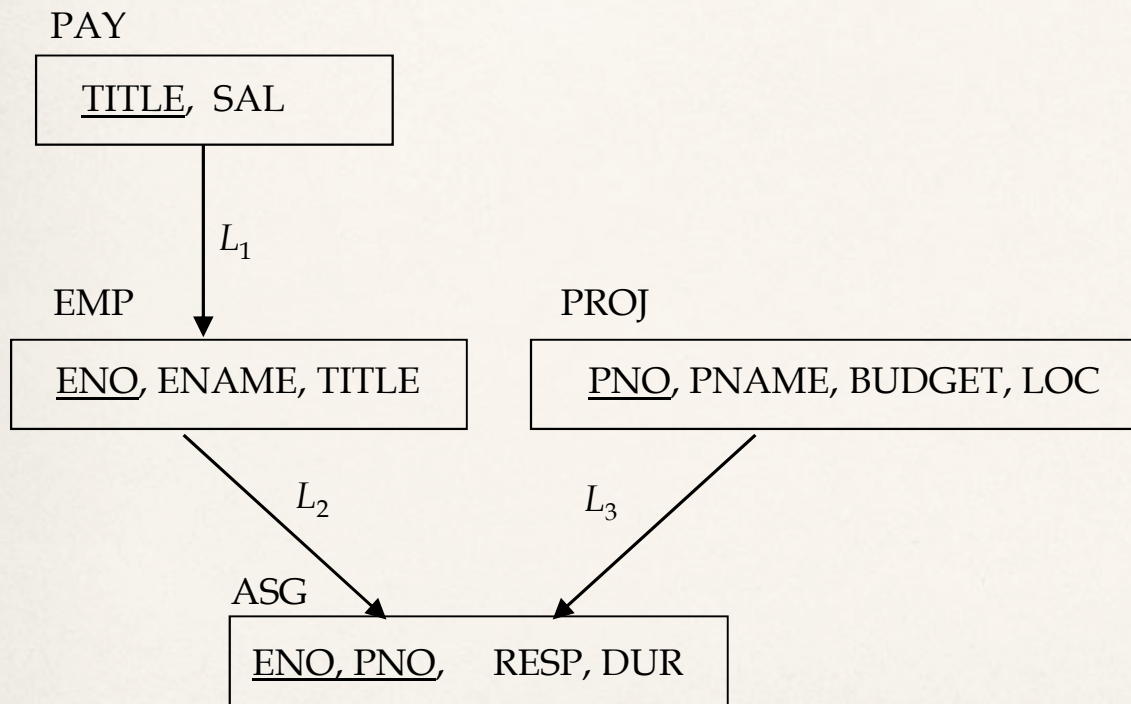
DHF – Information Requirements

- qualitative Database Information
 - relationship



Derived Horizontal Fragmentation

- Derived Horizontal Fragmentation (**DHF**) is defined on a member relation of a link according to a selection operation specified on its owner (propagated from owner to member)



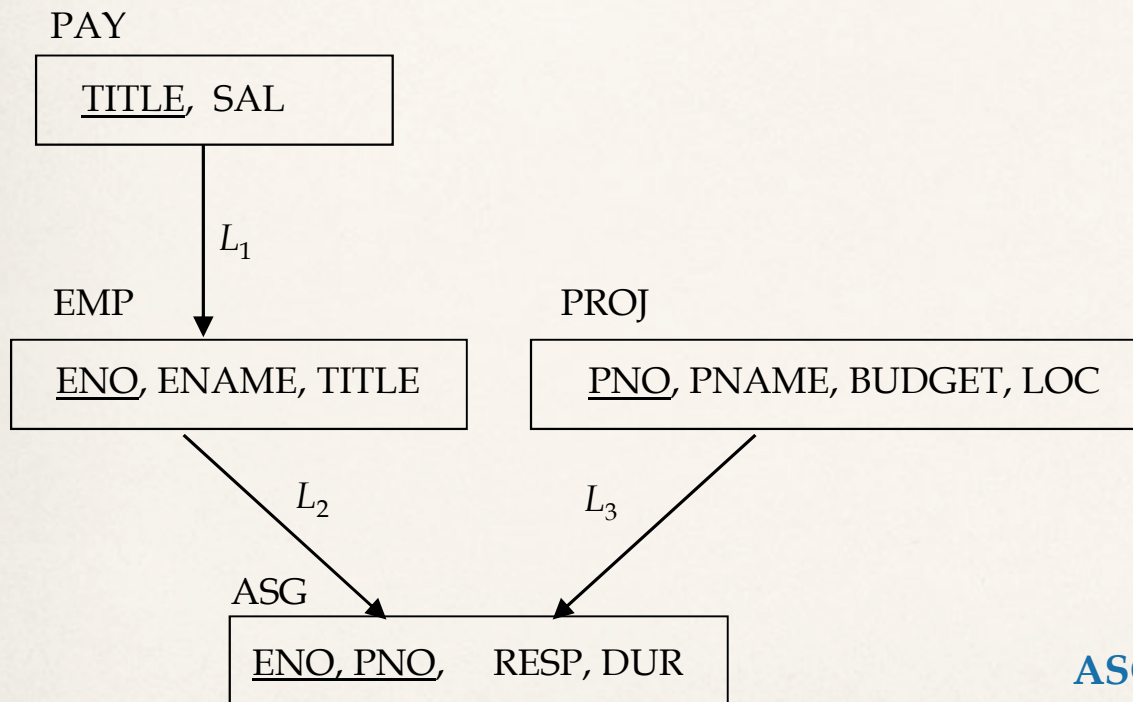
$owner(L_1) = \text{PAY}$
 $member(L_1) = \text{EMP}$

$owner(L_2) = \text{EMP}$
 $member(L_2) = \text{ASG}$

$owner(L_3) = \text{PROJ}$
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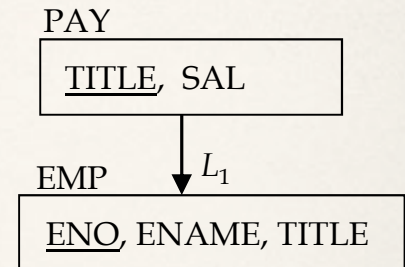
ASG could be fragmented by propagating either fragmentation on EMP or fragmentation on PROJ

DHF – Definition

Given

- a relation S fragmented into $F_S = \{ S_1, S_2, \dots, S_w \}$ and
- a link L where $owner(L)=S$ and $member(L)=R$,

the derived horizontal fragments of R are defined as $R_i = R \bowtie S_i (S_i \in F_S)$



PAY	TITLE	SAL
	Elect. Eng.	40000
	Syst. Anal.	34000
	Mech. Eng.	27000
	Programmer	24000

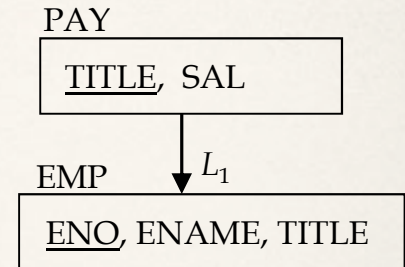
EMP	ENO	ENAME	TITLE
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	E2	M. Smith	Syst. Anal.
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	E4	J. Miller	Programmer
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$$PAY_1 = \sigma_{SAL \geq 30000}(PAY)$$

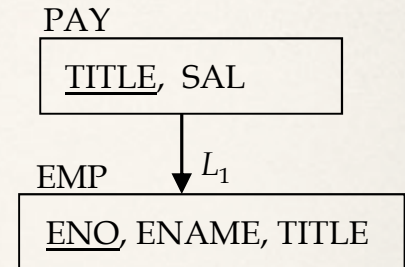
$$PAY_2 = \sigma_{SAL < 30000}(PAY)$$

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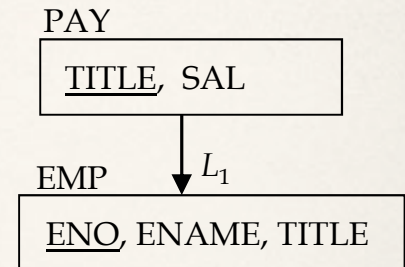
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- **Completeness and disjointness** for **derived** horizontal fragmentation
 - Both come from **integrity constraints** of foreign keys and from completeness/disjointness of PHF
 - ♦ fragmentation propagates from *owner* to *member* following one-to-many associations; thus, each tuple of *member* is associated with exactly 1 tuple of *owner* (a NOT NULL constraint must be defined on the foreign key in the *member* relation that refer to the *owner* relation); by disjointness and completeness of PHF, such tuple of owner appears in exactly 1 fragment of owner

Vertical Fragmentation

- Has been studied within the centralized context
 - design methodology
 - physical clustering
- Choose a partition $P = \{ P_1, P_2, \dots, P_n \}$ of the set of attribute of relation. Then,
$$F = \{ R_i \mid R_i = \Pi_{P_i \cup key}(R) \text{ and } P_i \in P \}$$
where *key* is the (set of) key attribute(s): they are replicated in each fragment
- The problem boils down to finding the best partition
 - Number of elements of the partition
 - Distribution of attributes among elements of the partition
- More difficult than horizontal, because more alternatives exist
 - Number of possible partitions of a set of size n is the Bell's number B_n (its growth rate is more than **exponential**)
- Two approaches :
 - Grouping (bottom-up) - from single attributes to fragments
 - Splitting (top-down) - from relation to fragments
 - ♦ preferable for 2 reasons
 - ✓ close to the design approach
 - ✓ optimal solution is more likely to be close to the full relation than to the fully fragmented situation

VF – The General Idea

- Partition is guided by a measure of affinity (“togetherness”)
- Affinity measures how much attributes that are accessed together by queries

VF – Information Requirements (Qualitative Application Info)

- The matrix $use(q, A)$ for attribute usage values
 - R relation over attributes A_1, A_2, \dots, A_n
 - $Q = \{q_1, q_2, \dots, q_q\}$: set of queries that will run on R
 - ♦ (the 80/20 rule can be used here, too: select the most active 20% of queries only)

$$use(q_i, A_j) = \begin{cases} 1 & \text{if attribute } A_j \text{ is referenced by query } q_i \\ 0 & \text{otherwise} \end{cases}$$

VF – Example of $use(q_i, A_j)$

Consider the following 4 queries for relation PROJ

q_1 : **SELECT** BUDGET
FROM PROJ
WHERE PNO=Value

q_2 : **SELECT** PNAME,BUDGET
FROM PROJ

q_3 : **SELECT** PNAME
FROM PROJ
WHERE LOC=Value

q_4 : **SELECT** SUM(BUDGET)
FROM PROJ
WHERE LOC=Value

$use(q, A)$	PNO	PNAME	BUDGET	LOC
q_1	1	0	1	0
q_2	0	1	1	0
q_3	0	1	0	1
q_4	0	0	1	1

VF – Information Requirements (Quantitative Application Info)

- matrix $acc_s(q)$ for the number of execution of q at s in a given period
- **attribute affinity measure** $aff(A_i, A_j)$ between any two attributes A_i and A_j of a relation R with respect to a set of applications Q

$$aff(A_i, A_j) = \sum_{\substack{\text{all sites } s \\ \text{and query } q}} use(q, A_i) * use(q, A_j) * acc_s(q)$$

we are considering frequencies only of queries q that access both A_i and A_j ,
i.e., $use(q, A_i) = use(q, A_j) = 1$

$use(q, A)$	PNO	PNAME	BUDGET	LOC
q_1	1	0	1	0
q_2	0	1	1	0
q_3	0	1	0	1
q_4	0	0	1	1

VF – Computation of $aff(A_i, A_j)$

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- Example: affinity between *PNO* and *BUDGET*
- q_1 is the only query that access both *PNO* and *BUDGET*

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- q_1 is the only query that access both *PNO* and *BUDGET*
- Also consider the access frequencies: $acc_s(q)$

$acc_s(q)$

	S_1	S_2	S_3
q_1	15	20	10
q_2	5	0	0
q_3	25	25	25
q_4	3	0	0

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$use(q, A)$

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$aff(A_i, A_j)$

	PNO	PNAME	BUDGET	LOC
PNO	45	0	45	0
PNAME	0	80	5	75
BUDGET	45	5	53	3
LOC	0	75	3	78

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- Also consider the access frequencies: $acc_s(q)$
- Then, $aff(PNO, BUDGET) = 15 + 20 + 10 = 45$
- $aff(., .)$ is stored in the **attribute affinity matrix AA**
- Any clustering algorithm based on the attribute affinity values
 - Bond energy algorithm
 - Neural network
 - Machine learning
 - **(some details later in the course)**

$use(q, A)$

	PNO	PNAME	BUDGET	LOC
q_1	1	0	1	0
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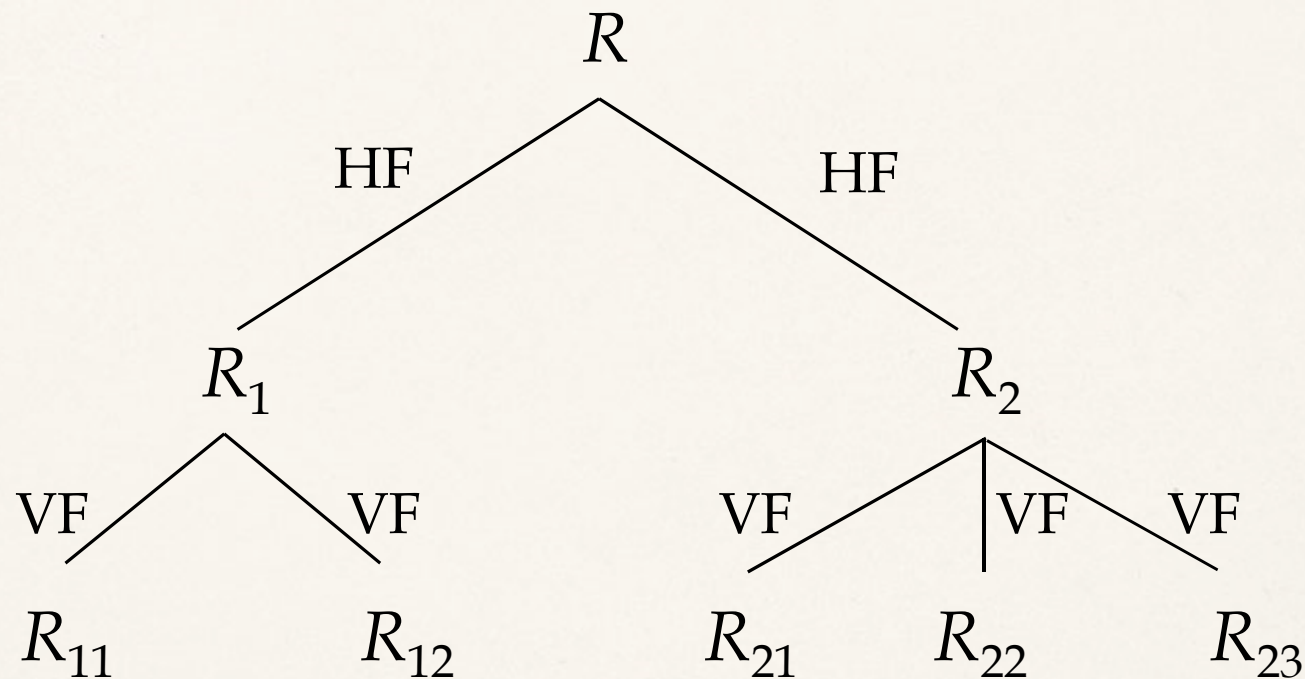
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- Reconstruction
 - Let $F_R = \{R_1, R_2, \dots, R_n\}$ be the vertical fragmentation obtained for R
 - R is recovered by joining the fragments

$$R = R_1 \bowtie R_2 \bowtie \dots \bowtie R_n$$

Hybrid Fragmentation

Hybrid fragmentation, aka *mixed* or *nested fragmentation*



To reconstruct R : start from the leaves and move upward applying fragmentation reconstruction methods depending on fragmentation types

Fragment Allocation

- Fragment allocation concerns distribution of resources across network nodes
 - Assignment (possibly with replications) of fragments to sites
- Problem formalization
 - Given
$$F = \{F_1, F_2, \dots, F_n\} \quad \text{fragments}$$
$$S = \{S_1, S_2, \dots, S_m\} \quad \text{network sites}$$
Qualitative and quantitative information about DB, applications, network, and computer system
Find the best (“optimal”) distribution of fragments in F among sites in S according to information
- Optimality factors
 - Minimal cost
 - ♦ Communication, Storage (of F_i at site s_j), Querying (F_i at site s_j , from site s_k), Updating (F_i at all sites where it is replicated, from site s_k)
 - Performance
 - ♦ Response time and/or total time
 - Can be formulated as an operations research problem
 - ♦ one of the above optimality factors is the cost function to minimize, the others are constraint to satisfy
$$\begin{array}{ll} \min & \text{(cost function)} & \text{e.g., response/total time} \\ \text{s.t.} & \text{constraints} & \text{e.g., storage/communication capacity} \end{array}$$
 - ♦ techniques and heuristics from the field of operations research apply (no optimal solution, NP-hard)

Data directory

- Data directory (aka. data dictionary or catalog)
- Both in classic (centralized) and distributed DB, it stores metadata about DB
 - Centralized context
 - ◆ Schema (relation metadata) definitions
 - ◆ Usage statistics
 - ◆ Memory usage
 - ◆ ...
 - Distributed context
 - ◆ Info to reconstruct global view of whole DB
 - ◆ What relation/fragment is stored at which site
 - ◆ ...
- It is itself part of the DB, so considerations about fragmentation and allocation issues apply