Part II

Distributed Database Systems

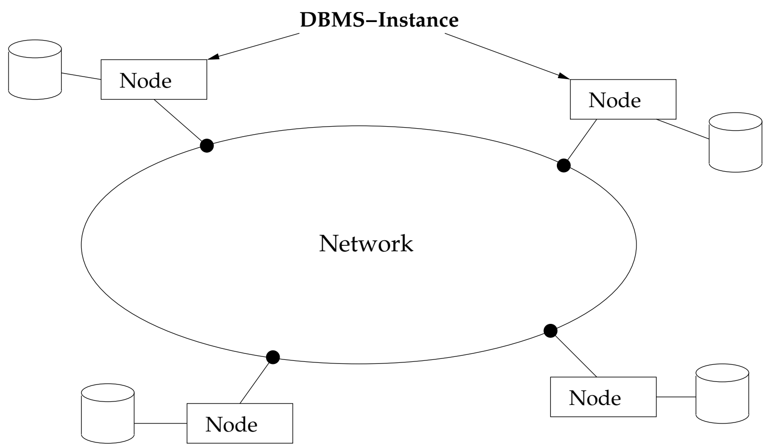
4 Distributed DBS Architecture

Overview

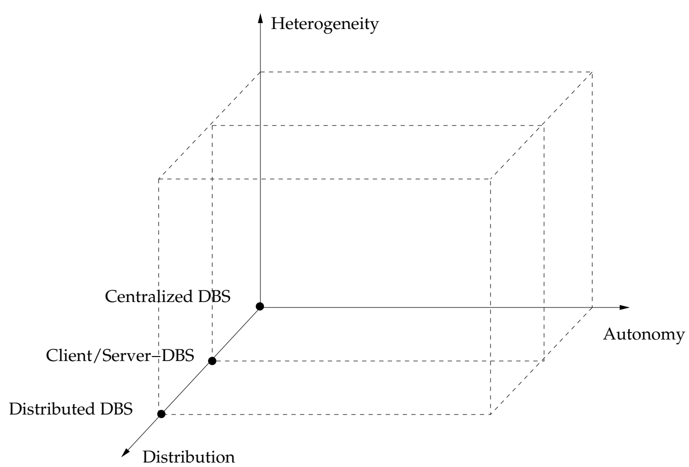
Contents

4.1 Foundations of DDBS

Architecture & Data Distribution



Dimensions



12 Rules for DDBMS by Date

1. Local Autonomy
   - Component system have maximal control over own data, local access does not require access to other components
2. No reliance on central site
   - Local components can perform independently of central component
3. Continuous operation/high availability
   - Overall system performs despite local interrupt
4. Location transparency
   - User of overall system should not be aware of physical storage location

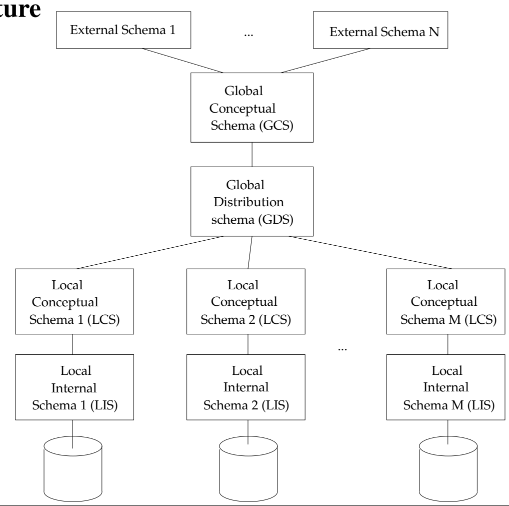
12 Rules for DDBMS by Date /2

5. Fragmentation transparency
   - If data of one relation is fragmented, user should not be aware of this
6. Replication transparency
   - User should not be aware of redundant copies of data
   - Management and redundancy is controlled by DBMS
7. Distributed query processing
   - Efficient access to data stored on different sites within one DB operation

12 Rules for DDBMS by Date /3

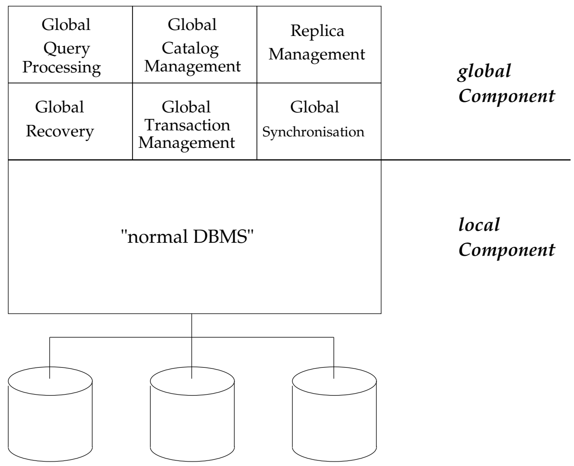
8. Distributed Transaction Management
   - ACID properties must persist for distributed operations
9. Hardware independence
   - Component DB processing on different hardware platforms
10. Operating system independence
    - Component DB processing on different OS
11. Network independence
    - DB processing using different network protocols
12. DBMS independence (ideal)
    - Usage of different DBMS possible

Schema Architecture



- Global conzeptual schema (GCS)
  - Logical structure of overall DB
  - Supported by all nodes
  - Ensures *transparency*
- Global distribution schema (GDS)
  - Describes fragmentation, replication, allocation

System Architecture



4.2 Catalog Management

Catalog Management

- Catalog: collection of metadata (schema, statistics, access rights, etc.)
  - Local catalog
    - * Identical to catalog of a centralized DBS
    - * consistes of LIS and LCS
  - Global ctalaog
    - * Also contains GCS and GDS
    - * System-wide management of users and access rights
- Storage
  - Local catalog: on each node
  - Global catalog: centralized, replicated, or partitioned

Global Catalog /1

- Centralized: one instance of global catalog managed by central node
  - Advantages: only one update operation required, litte space consumption
  - Disadvantages: request for each query, potential bottleneck, critical ressource
- Replicated: full copy of global catalog stored on each node
  - Advantage: low communication overhead during queries, availabilty
  - Disadvantage: high overhead for updates
- Mix- form: cluster-catalog with centralized catalog for certain clusters of nodes

Global Catalog /2

- Partitioned: (relevant) part of the catalog is stored on each node
  - No explicit GCS $\rightsquigarrow$ union of LCS
  - Partitioned GDS by extend object (relations, etc.) names (see System R*)

Coherency Control

- Idea: buffer for non-local parts of the catalog
  - Avoids frequent remote accesses for often used parts of the catalog
- Problem: invalidation of buffered copies after updates

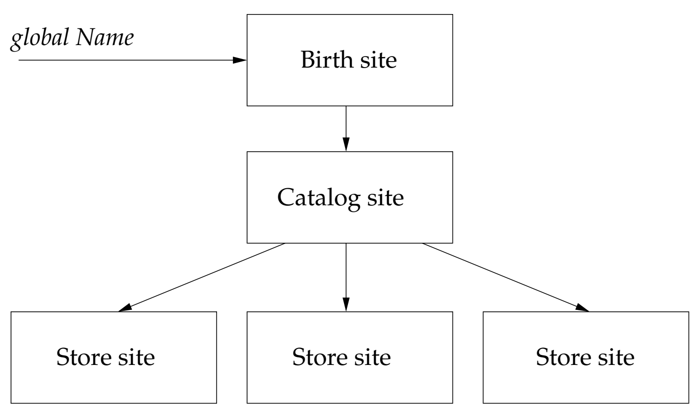
Coherency Control /2

- Approaches
  - Explicit invalidation:
    * Owner of catalog data keeps list of copy sites
    * After an update these nodes are informed of invalidation
  - Implicit invalidation:
    * Identification of invalid catalog data during processing time using version numbers or timestamps (see System R*)

DB Object Name Management

- Task: identification of relations, views, procedures, etc.
- Typical schema object names in RDBMS: [<*username*>.]<*objectname*>
- Requirement global uniqueness in DDBS
  - Name Server approach: management of names in centralized catalog
  - Hierarchic Naming: enrich object name with *node name* [[<*nodename*>.]<*username*>.]<*objectname*>
    * Node name: birth site (or simplification via alias)

Name Management: Node Types



Catalog Management in System R*

- Birth site
  - Prefix of the relation name
  - Knows about storage sites
- Query processing
  - Executing node gets catalog entry of relevant relation
  - Catalog entry is buffered for later accesses

Catalog Management in System R* /2

- Query processing (continued)
  - Partial query plans include time stamp of catalog entry
  - Node processing partial query checks whether catalog time stamp is still current
- In case of failure: buffer invalidation, re-set query and new query translation according to current schema
- Summary:
  - Advantage: high degree of autinomy, user-controlled invalidation of buffered catalog data, good performance
  - Disadvantage: no uniform realization of global views

4.3 DDBS Design: Fragmentation

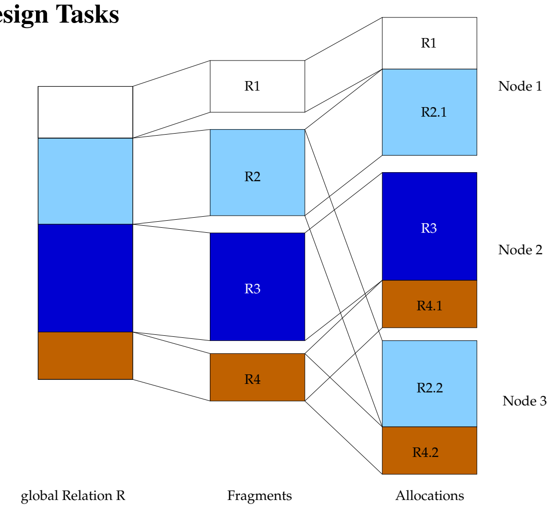
Database Distribution

- In Shared-Nothing-Systems (DDBS): definition of physical distribution of data
- Impact:
  - Communication efforts ⇝ overall performance
  - Load balancing
  - Availability

Bottom Up vs. Top Down

- Bottom Up
  - Subsumption of local conceptual schemata (LCS) into global conceptual schema (GCS)
  - Integration of existing DB ⇝ schema integration (Federated DBS)
- Top Down
  - GCS of local DB designed first
  - Distribution of schema to different nodes
  - *Distribution Design*

Distribution Design Tasks



Fragmentation

- Granularity of distribution: relation
  - Operations on one relation can always be performed on one node
  - Simplifies integrity control
- Granularity of distribution: fragments of relations
  - Grants locality of access
  - Load balancing
  - Reduced processing costs for operations performed only on part of the data
  - Parallel processing

Fragmentation /2

- Approach:
  - Column- or tuple-wise decomposition (vertical/horizontal)
  - Described using relational algebra expressions (queries)
  - Important rules/requirements
    * Completeness
    * Reconstructability
    * Disjointness

Example Database

MEMBER

MNo	MName	Position
M1	Ian Curtis	SW Developer
M2	Levon Helm	Analyst
M3	Tom Verlaine	SW Developer
M4	Moe Tucker	Manager
M5	David Berman	HW-Developer

PROJECT

PNr	PName	Budget	Loc
P1	DB Development	200.000	MD
P2	Hardware Dev.	150.000	M
P3	Web-Design	100.000	MD
P4	Customizing	250.000	B

ASSIGNMENT

MNr	PNr	Capacity
M1	P1	5
M2	P4	4
M2	P1	6
M3	P4	3
M4	P1	4
M4	P3	5
M5	P2	7

SALARY

Position	YSalary
SW Developer	60.000
HW-Developer	55.000
Analyst	65.000
Manager	90.000

Primary Horizontal Fragmentation

- "'Tupel-wise"' decomposition of a global relation R into n fragments R_i
- Defined by n selection predicates P_i on attributes from R

$$R_i := \sigma_{P_i}(R) \quad (1 \leq i \leq n)$$

- P_i: *fragmentation predicates*
- Completeness: each tuple from R must be assigned to a fragment
- Disjointness: decomposition into disjoint fragments $R_i \cap R_j = \emptyset \quad (1 \leq i, j \leq n, i \neq j)$,
- Reconstructability: $R = \bigcup_{1 \leq i \leq n} R_i$

Primary Horizontal Fragmentation /2

- Example: fragmentation of PROJECT by predicate on location attribute "'Loc"'

$$\begin{aligned} \text{PROJECT}_1 &= \sigma_{\text{Loc='M'}}(\text{PROJECT}) \\ \text{PROJECT}_2 &= \sigma_{\text{Loc='B'}}(\text{PROJECT}) \\ \text{PROJECT}_3 &= \sigma_{\text{Loc='MD'}}(\text{PROJECT}) \end{aligned}$$

PROJECT_1

PNr	PName	Budget	Loc
P2	Hardware Dev.	150.000	M

PROJECT_2

PNr	PName	Budget	Loc
P4	Customizing	250.000	B

PROJECT_3

PNr	PName	Budget	Loc
P1	DB Development	200.000	MD
P3	Web-Design	100.000	MD

Derived Horizontal Fragmentation

- Fragmentation definition of relation S derived from existing horizontal fragmentation of relation R
- Using foreign key relationships
- Relation R with n fragments R_i
- Decomposition of depending relation S

$$S_i = S \ltimes R_i = S \ltimes \sigma_{P_i}(R) = \pi_{S.*}(S \bowtie \sigma_{P_i}(R))$$

- P_i defined only on R
- Reconstructability: see above
- Disjointness: implied by disjointness of R-fragments
- Completeness: granted for lossless semi-join (no null-values for foreign key in S)

Derived Horizontal Fragmentation /2

- Fragmentation of relation ASSIGNMENT derived from fragmentation of PROJECT relation

$$\begin{aligned} \text{ASSIGNMENT}_1 &= \text{ASSIGNMENT} \ltimes \text{PROJECT}_1 \\ \text{ASSIGNMENT}_2 &= \text{ASSIGNMENT} \ltimes \text{PROJECT}_2 \\ \text{ASSIGNMENT}_3 &= \text{ASSIGNMENT} \ltimes \text{PROJECT}_3 \end{aligned}$$

ASSIGNMENT$_1$

MNr	PNr	Capacity
M5	P2	7

ASSIGNMENT$_2$

MNr	PNr	Capacity
M2	P4	4
M3	P4	3

ASSIGNMENT$_3$

MNr	PNr	Capacity
M1	P1	5
M2	P1	6
M4	P1	4
M4	P3	5

Vertical Fragmentation

- Comlumn-wise decomposition of a relation using relational projection
- Completeness: each attribute must be in at least one fragment
- Reconstructability: through natural join $\rightsquigarrow$ primary key of global relation must be in each fragment

$$R_i := \pi_{K,A_i,\dots,A_j}(R)$$
$$R = R_1 \bowtie R_2 \bowtie \cdots \bowtie R_n$$

- Limited disjointness

Vertical Fragmentation /2

- Fragmentation of PROJECT-Relation regarding Budget and project name / location

$$\text{PROJECT}_1 = \pi_{\text{PNr, PName, Loc}}(\text{PROJECT})$$
$$\text{PROJECT}_2 = \pi_{\text{PNr, Budget}}(\text{PROJECT})$$

PROJECT_1

PNr	PName	Loc
P1	DB Development	MD
P2	Hardware Dev.	M
P3	Web-Design	MD
P4	Customizing	B

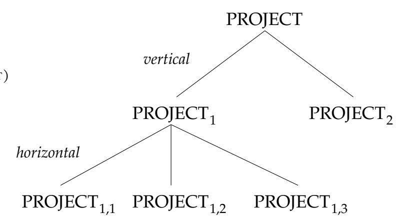
PROJECT_2

PNr	Budget
P1	200.000
P2	150.000
P3	100.000
P4	250.000

Hybrid Fragmentation

- Fragment of a relation → is relation itself
- Can be subject of further fragmentation
- Also possible: combination of horizontal and vertical fragmentation

$\text{PROJECT}_1 = \pi_{\text{PNr, PName, Loc}}(\text{PROJECT})$
$\text{PROJECT}_2 = \pi_{\text{PNr, Budget}}(\text{PROJECT})$
$\text{PROJECT}_{1,1} = \sigma_{\text{Loc='M'}}(\text{PROJECT}_1)$
$\text{PROJECT}_{1,2} = \sigma_{\text{Loc='B'}}(\text{PROJECT}_1)$
$\text{PROJECT}_{1,3} = \sigma_{\text{Loc='MD'}}(\text{PROJECT}_1)$



Fragmentation transparency

- Decomposition of a relation is for user/application not visble
- Only view on global relation
- Requires mapping of DB operations to fragments by DDBMS
- Example
  - Transparent: `select * from Project where PNr=P1`
  - Without transparency:

```
select * from Project1 where PNr=P1
if not-found then
   select * from Project2 where PNr=P1
if not-found then
   select * from Project3 where PNr=P1
```

Fragmentation transparency /2

- Example (continued)
  - Transparent: `update Project set Ort='B' where PNr=P3`
  - Without transparency:

```
select PNr, PName, Budget
   into :PNr, :PName, :Budget
   from Project3 where PNr=P3
insert into Project2
   values (:PNr, :PName, :Budget, 'B')
delete from Project3 where PNr=P3
```

Computation of an optimal Fragmentation

- In huge systems with many relations/nodes: intuitive decomposition often too complex/not possible
- In this case: systematic process based on access characteristics
  - Kind of access (read/write)
  - Frequency
  - Relations / attributes
  - Predicates in queries
  - Transfer volume and times

Optimal horizontal Fragmentation

- Based on [Özsu/Valduriez 99] and [Dadam 96]
- Given: relation $R(A_1, \ldots, A_n)$, operator $\theta \in \{<, \leq, >, \geq, =, \neq\}$, Domain $\mathrm{dom}(A_i)$
- Definition: **simple predicate** p_i of the form $A_j \theta\, \mathrm{const}$ with $\mathrm{const} \in \mathrm{dom}(A_j)$
  - Defines possible binary fragmentation of R
  - Example:

$$\text{PROJECT}_1 = \sigma_{\text{Budget}>150.000}(\text{PROJECT})$$
$$\text{PROJECT}_2 = \sigma_{\text{Budget}\leq 150.000}(\text{PROJECT})$$

- Definition: **Minterm** m is conjunction of simple predicates as $m = p_1^* \wedge p_2^* \wedge \cdots \wedge p_j^*$ with $p_i^* = p_i$ oder $p_i^* = \neg p_i$

Optimal horizontal Fragmentation /2

- Definition: Set $M_n(P)$ of all n-ary Minterms for the set P of simple predicates:

$$M_n(P) = \{m \mid m = \bigwedge_{i=1}^{n} p_i^*, p_i \in P\}$$

  - Defines *complete* fragmentation of R without redundancies
    * $R = \bigcup_{m \in M_n(P)} \sigma_m(R)$
    * $\sigma_{m_i} \cap \sigma_{m_j} = \emptyset, \forall m_i, m_j \in M_n(P), m_i \neq m_j$

Optimal horizontal Fragmentation /3

- Completeness and no redundancy not sufficient:
  - $P = \{$ Budget $<$ 100.000, Budget $>$ 200.000, Ort = 'MD', Ort = 'B' $\}$
  - Minterm $p_1 \land p_2 \land p_3 \land p_4$ not satisfiable; but $\neg p_1 \land \neg p_2 \land \neg p_3 \land \neg p_4$
- Identification of *practically relevant* Minterms $M(P)$
  1. $M(P) := M_n(P)$
  2. Remove irrelevant Minterms from $M(P)$

Elimination of irrelevant Minterms

1. Elimination of unsatisfiable Minterms If two terms p_i^* and p_j^* in one $m \in M(P)$ contradict, m is not satisfiable and can be removed from $M(P)$.
2. Elimination of dependent predicates If a p_i^* from $m \in M(P)$ implies another term p_j^* (e.g. functional dependency, overlapping domains), p_j^* can be removed from m.
3. Relevance of a fragmentation
   - Minterms m_i and m_j, m_i contains p_i, m_j contains $\neg p_i$
   - Access statistics: $\text{acc}(m)$ (e.g. derived from query log)
   - Fragment size: $\text{card}(f)$ (derived from data distribution statistics)
   - p_i is *relevant*, if $\frac{\text{acc}(m_i)}{\text{card}(f_i)} \neq \frac{\text{acc}(m_j)}{\text{card}(f_j)}$

Algorithm HORIZFRAGMENT

- Identification of a complete, non-redundant and minimal horizontal fragmentation of a relation R for a given set of predicates P
- Input:
  - P: set of predicates over R
- (Intermediate) Results:
  - $M(P)$: set of relevant Minterms
  - $F(P)$: set of Minterm-fragments from R

$$R(m) := \sigma_m(R) \;\text{ with }\; m \in M(P)$$

Algorithm HORIZFRAGMENT

```
forall p ∈ P do
    Q' := Q ∪ {p}
    compute M(Q') and F(Q')
    compare F(Q') with F(Q)
    if F(Q') significant improvement over F(Q) then
        Q := Q'
        forall q ∈ Q \ {p} do /* unnecessary Fragmentation? */
            Q' := Q \ {q}
            compute M(Q') and F(Q')
            compare F(Q') with F(Q)
            if F(Q) no significant improvement over F(Q') then
                Q := Q' /* d.h., remove q from Q */
            end
        end
    end
```

4.4 Allocation and Replication

Allocation and Replication

- Allocation
  - Assignment of relations or fragments to physical storage location
  - *Non-redundant*: fragments are stored in only one place $\leadsto$ partitioned DB
  - *Redundant*: fragments can be stored more than once $\leadsto$ replicated DB
- Replication
  - Storage of redundant copies of fragments or relations
  - *Full*: Each global relation stored on every node (no distribution design, no distributed query processing, high costs for storage and updates)
  - *Partial*: Fragments are stored on selected nodes

Allocation and Replication /2

- Aspects of allocation
  - Efficiency:
    - Minimization of costs for remote accesses
    - Avoidance of bottlenecks
  - Data security:
    - Selection of nodes depending on their "‘reliability"’

Identification of an optimal Allocation

- Cost model for non-redundant allocation [Dadam 96]
- Goal: Minimize storage and transfer costs $\sum_{Storage} + \sum_{Transfer}$ for K fragments and L nodes
- Storage costs:

$$\sum\nolimits_{Storage} = \sum_{p,i} S_p D_{pi} SC_i$$

  - S_p: Size of fragment p in data units
  - SC_i: StorageCosts per data unit on node i
  - D_{pi}: Distribution of fragment with $D_{pi} = 1$ if p stored on node i, 0 otherwise

Identification of an optimal Allocation /2

- Transfer costs:

$$\sum\nolimits_{Transfer} = \sum_{i,t,p,j} F_{it} O_{tp} D_{pj} TC_{ij} + \sum_{i,t,p,j} F_{it} R_{tp} D_{pj} TC_{ji}$$

  - F_{it}: Frequency of operation of type t on node i
  - O_{tp}: Size of operation t for fragment p in data units (e.g. size of query string)
  - TC_{ij}: TransferCosts from node i to j in data units
  - R_{tp}: Size o the result of one operation of type t on fragment p

Identification of an optimal Allocation /3

- Additional constraints:

$$\sum_i D_{pi} = 1 \text{ for } p = 1, \ldots, K$$

$$\sum_p S_p D_{pi} \leq M_i \text{ for } p = i, \ldots, L$$

  where M_i is max. storage capacity on node i
- Integer optimization problem
- Often heuristic solution possible:
  - Identify relevant candidate distributions
  - Compute costs and compare candidates

Identification of an optimal Allocation /4

- Cost model for redundant replication
- Additional constraints slightly modified:

$$\sum_i D_{pi} \geq 1 \text{ for } p = 1, \ldots, K$$
$$\sum_p S_p D_{pi} \leq M_i \text{ ffr } p = i, \ldots, L$$

Identification of an optimal Allocation /5

- Transfer costs
  - Read operations on p send from node i to j with minimal TC_{ij} and $D_{pj} = 1$
  - Update operations on p send to all nodes j with $D_{pj} = 1$
  - Φ_t: of an operation $\sum$ (in case of update) or $\min$ (in case of read operation)

$$\sum\nolimits_T ransfer = \sum_{i,t,p} F_{it} \underset{j:D_{pj}=1}{\Phi_t} (O_{tp} TC_{ij} + R_{tp} TC_{ji})$$

Evaluation of Approaches

- Model considering broad spectrum of applications
- Exact computation possible
- *But*:
  - High computation efforts (optimization problem)
  - Exact input values are hard to obtain