Principles of Distributed Database Systems

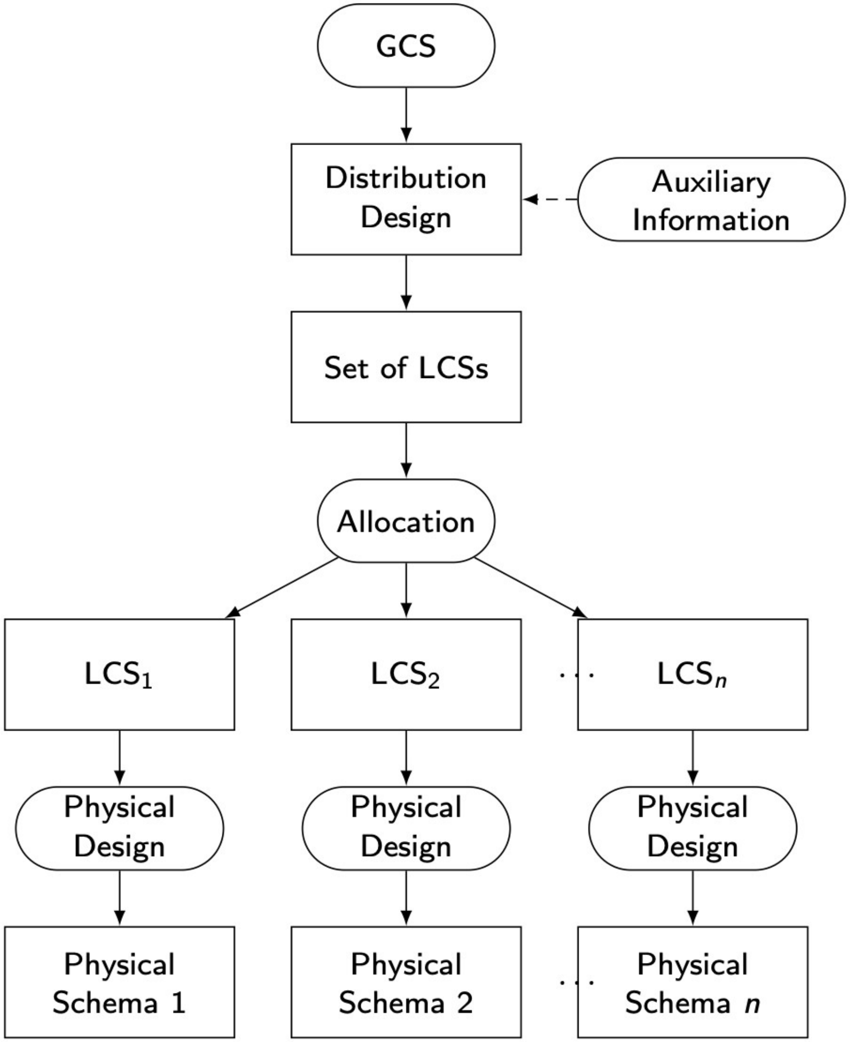
M. Tamer Özsu

Patrick Valduriez

Outline

- Introduction
- Distributed and Parallel Database Design
- Distributed Data Control
- Distributed Query Processing
- Distributed Transaction Processing
- Data Replication
- Database Integration – Multidatabase Systems
- Parallel Database Systems
- Peer-to-Peer Data Management
- Big Data Processing
- NoSQL, NewSQL and Polystores
- Web Data Management

Distribution Design



Outline

- Distributed and Parallel Database Design
  - Fragmentation
  - Data distribution
  - Combined approaches

Fragmentation

- Can't we just distribute relations?
- What is a reasonable unit of distribution?
  - relation
    - views are subsets of relations ⇒ locality
    - extra communication
  - fragments of relations (sub-relations)
    - concurrent execution of a number of transactions that access different portions of a relation
    - views that cannot be defined on a single fragment will require extra processing
    - semantic data control (especially integrity enforcement) more difficult

Example Database

EMP

ENO	ENAME	TITLE
E1	J. Doe	Elect. Eng.
E2	M. Smith	Syst. Anal.
E3	A. Lee	Mech. Eng.
E4	J. Miller	Programmer
E5	B. Casey	Syst. Anal.
E6	L. Chu	Elect. Eng.
E7	R. Davis	Mech. Eng.
E8	J. Jones	Syst. Anal.

ASG

ENO	PNO	RESP	DUR
E1	P1	Manager	12
E2	P1	Analyst	24
E2	P2	Analyst	6
E3	P3	Consultant	10
E3	P4	Engineer	48
E4	P2	Programmer	18
E5	P2	Manager	24
E6	P4	Manager	48
E7	P3	Engineer	36
E8	P3	Manager	40

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

PAY

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

Fragmentation Alternatives – Horizontal

$PROJ_1$: projects with budgets less than $200,000

$PROJ_2$: projects with budgets greater than or equal to $200,000

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
P2	Database Develop.	135000	New York

$PROJ_2$

PNO	PNAME	BUDGET	LOC
P3	CAD/CAM	255000	New York
P4	Maintenance	310000	Paris

Fragmentation Alternatives – Vertical

$PROJ_1$: information about project budgets

$PROJ_2$: information about project names and locations

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	BUDGET
P1	150000
P2	135000
P3	250000
P4	310000

$PROJ_2$

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

Correctness of Fragmentation

- Completeness
  - Decomposition of relation R into fragments $R_1, R_2, ..., R_n$ 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 $R_1, R_2, ..., R_n$, then there should exist some relational operator ∇ such that $R = \nabla_{1 \le i \le n} R_i$
- Disjointness
  - If relation R is decomposed into fragments $R_1, R_2, ..., R_n$, and data item d_i is in R_j, then d_i should not be in any other fragment R_k $(k \neq j)$.

Allocation Alternatives

- Non-replicated
  - partitioned : each fragment resides at only one site
- Replicated
  - fully replicated : each fragment at each site
  - partially replicated : each fragment at some of the sites
- Rule of thumb:
  - (update queries) / (read-only queries) << 1
  - replication is advantageous, otherwise not

Comparison of Replication Alternatives

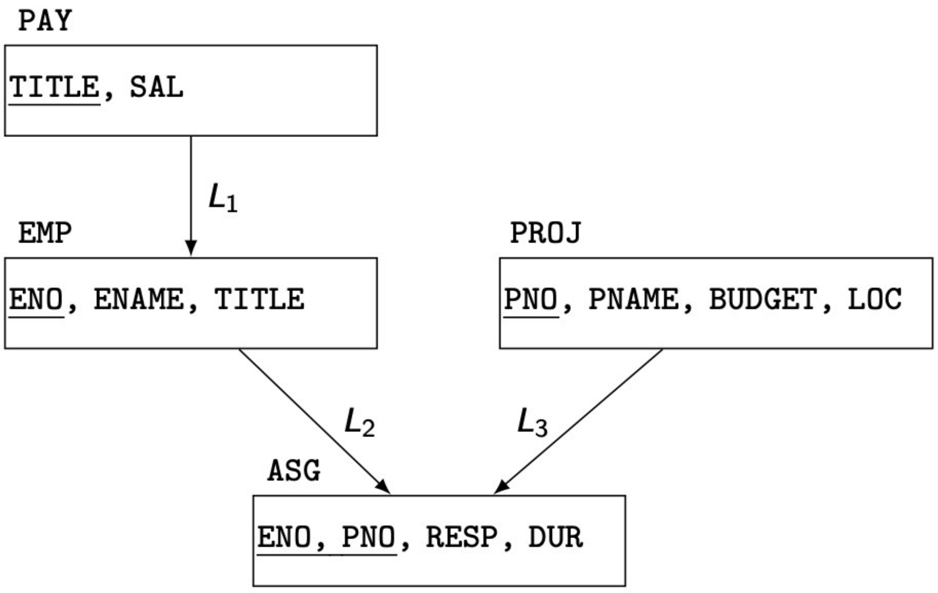
	Full replication	Partial replication	Partitioning
QUERY PROCESSING	Easy	Same difficulty	
DIRECTORY MANAGEMENT	Easy or nonexistent	Same difficulty	
CONCURRENCY CONTROL	Moderate	Difficult	Easy
RELIABILITY	Very high	High	Low
REALITY	Possible application	Realistic	Possible application

Fragmentation

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

PHF – Information Requirements

- Database Information
  - relationship



  - cardinality of each relation: *card*(*R*)

PHF - Information Requirements

- Application Information
  - **simple predicates** : Given $R[A_1, A_2, \ldots, A_n]$, a simple predicate p_j is

    $$p_j : A_i \,\theta\, Value$$

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

    For relation R we define $Pr = \{p_1, p_2, \ldots, p_m\}$

    Example :

    PNAME = "Maintenance"
    BUDGET ≤ 200000
  - **minterm predicates** : Given R and $Pr = \{p_1, p_2, \ldots, p_m\}$

    define $M = \{m_1, m_2, \ldots, m_r\}$ as

    $$M = \{ m_i \mid m_i = \wedge_{p_j \in Pr} \; p_j^* \},\ 1 \leq j \leq m,\ 1 \leq i \leq z$$

    where $p_j^* = p_j$ or $p_j^* = \neg(p_j)$.

PHF – Information Requirements

Example

m_1: PNAME="Maintenance" $\wedge$ BUDGET≤200000

m_2: **NOT**(PNAME="Maintenance") $\wedge$ BUDGET≤200000

m_3: PNAME= "Maintenance" $\wedge$ **NOT**(BUDGET≤200000)

m_4: **NOT**(PNAME="Maintenance") $\wedge$ **NOT**(BUDGET≤200000)

PHF – Information Requirements

- Application Information
  - **minterm selectivities**: $sel(m_i)$
    - The number of tuples of the relation that would be accessed by a user query which is specified according to a given minterm predicate m_i.
  - **access frequencies**: $acc(q_i)$
    - The frequency with which a user application *qi* accesses data.
    - Access frequency for a minterm predicate can also be defined.

Primary Horizontal Fragmentation

Definition :

$R_j = \sigma_{F_j}(R),\ \ 1 \leq j \leq w$

where F_j is a selection formula, which is (preferably) a minterm predicate.

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.

Set of horizontal fragments also referred to as minterm fragments*.*

PHF – Algorithm

Given: A relation *R,* the set of simple predicates *Pr*

Output: The set of fragments of $R = \{R_1, R_2, \ldots, R_w\}$ which obey the fragmentation rules.

Preliminaries :

- *Pr* should be *complete*
- *Pr* should be *minimal*

Completeness of Simple Predicates

- A set of simple predicates *Pr* is said to be *complete* if and only if the accesses to the tuples of the minterm fragments defined on *Pr* requires that two tuples of the same minterm fragment have the same probability of being accessed by any application.

- Example :
  - Assume PROJ[PNO,PNAME,BUDGET,LOC] has two applications defined on it.
  - Find the budgets of projects at each location. (1)
  - Find projects with budgets less than $200000. (2)

Completeness of Simple Predicates

According to (1),

Pr={LOC="Montreal",LOC="New York",LOC="Paris"}

which is not complete with respect to (2).

Modify

Pr ={LOC="Montreal",LOC="New York",LOC="Paris",
BUDGET≤200000,BUDGET>200000}

which is complete.

Minimality of Simple Predicates

- If a predicate influences how fragmentation is performed, (i.e., causes a fragment f to be further fragmented into, say, f_i and f_j) then there should be at least one application that accesses f_i and f_j differently.
- In other words, the simple predicate should be *relevant* in determining a fragmentation.
- If all the predicates of a set *Pr* are relevant, then *Pr* is *minimal*.

Minimality of Simple Predicates

Example :

Pr ={LOC=“Montreal”,LOC=“New York”, LOC=“Paris”, BUDGET≤200000,BUDGET>200000}

is minimal (in addition to being complete). However, if we add

PNAME = “Instrumentation”

then *Pr* is not minimal.

COM_MIN Algorithm

Given: a relation *R* and a set of simple predicates *Pr*

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

Rule 1: a relation or fragment is partitioned into at least two parts which are accessed differently by at least one application.

COM_MIN Algorithm

❶ Initialization :

- find a $p_i \in Pr$ such that p_i partitions R according to *Rule 1*
- set $Pr' = p_i$; $Pr \leftarrow Pr - \{p_i\}$; $F \leftarrow \{f_i\}$

❷ Iteratively add predicates to Pr' until it is complete

- find a $p_j \in Pr$ such that p_j partitions some f_k defined according to minterm predicate over Pr' according to *Rule 1*
- set $Pr' = Pr' \cup \{p_i\}$; $Pr \leftarrow Pr - \{p_i\}$; $F \leftarrow F \cup \{f_i\}$
- if $\exists p_k \in Pr'$ which is nonrelevant then

  $Pr' \leftarrow Pr' - \{p_i\}$

  $F \leftarrow F - \{f_i\}$

COM_MIN Algorithm

Algorithm 3.1: COM_MIN Algorithm

Input: R: relation; Pr: set of simple predicates
Output: Pr': set of simple predicates
Declare: F: set of minterm fragments
begin
    find $p_i \in Pr$ such that p_i partitions R according to *Rule* 1 ;
    $Pr' \leftarrow p_i$;
    $Pr \leftarrow Pr - p_i$;
    $F \leftarrow f_i$ $\{f_i$ is the minterm fragment according to $p_i\}$;
    repeat
        find a $p_j \in Pr$ such that p_j partitions some f_k of Pr' according to *Rule* 1 ;
        $Pr' \leftarrow Pr' \cup p_j$;
        $Pr \leftarrow Pr - p_j$;
        $F \leftarrow F \cup f_j$;
        if $\exists p_k \in Pr'$ *which is not relevant* **then**
            $Pr' \leftarrow Pr' - p_k$;
            $F \leftarrow F - f_k$;
    until Pr' *is complete* ;
end

PHORIZONTAL Algorithm

Makes use of COM_MIN to perform fragmentation.

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

Output: a set of minterm predicates M according to which relation R is to be fragmented

❶ $Pr' \leftarrow$ COM_MIN (R,Pr)

❷ determine the set M of minterm predicates

❸ determine the set I of implications among $p_i \in Pr'$

❹ eliminate the contradictory minterms from M

PHF – Example

- Two candidate relations : PAY and PROJ.
- Fragmentation of relation PAY
  - Application: Check the salary info and determine raise.
  - Employee records kept at two sites ⇒ application run at two sites
  - Simple predicates

p_1 : SAL ≤ 30000

p_2 : SAL > 30000

$Pr = \{p_1, p_2\}$ which is complete and minimal $Pr' = Pr$

  - Minterm predicates

m_1 : (SAL ≤ 30000)

m_2 : **NOT**(SAL ≤ 30000) = (SAL > 30000)

PHF – Example

$\mathtt{PAY}_1$

TITLE	SAL
Mech. Eng.	27000
Programmer	24000

$\mathtt{PAY}_2$

TITLE	SAL
Elect. Eng.	40000
Syst. Anal.	34000

PHF – Example

- Fragmentation of relation PROJ
  - Applications:
    - Find the name and budget of projects given their location
      - Issued at three sites
    - Access project information according to budget
      - one site accesses ≤200000 other accesses >200000
  - Simple predicates
  - For application (1)

p_1 : LOC = “Montreal”

p_2 : LOC = “New York”

p_3 : LOC = “Paris”

  - For application (2)

p_4 : BUDGET ≤ 200000

p_5 : BUDGET > 200000

  - $Pr = Pr' = \{p_1,p_2,p_3,p_4,p_5\}$

PHF – Example

- Fragmentation of relation PROJ continued
  - Minterm fragments left after elimination

m_1 : (LOC = “Montreal”) ∧ (BUDGET ≤ 200000)
m_2 : (LOC = “Montreal”) ∧ (BUDGET > 200000)
m_3 : (LOC = “New York”) ∧ (BUDGET ≤ 200000)
m_4 : (LOC = “New York”) ∧ (BUDGET > 200000)
m_5 : (LOC = “Paris”) ∧ (BUDGET ≤ 200000)
m_6 : (LOC = “Paris”) ∧ (BUDGET > 200000)

PHF – Example

$PROJ_1$

PNO	PNAME	BUDGET	LOC
P1	Instrumentation	150000	Montreal

$PROJ_3$

PNO	PNAME	BUDGET	LOC
P2	Database Develop.	135000	New York

$PROJ_4$

PNO	PNAME	BUDGET	LOC
P3	CAD/CAM	255000	New York

$PROJ_6$

PNO	PNAME	BUDGET	LOC
P4	Maintenance	310000	Paris

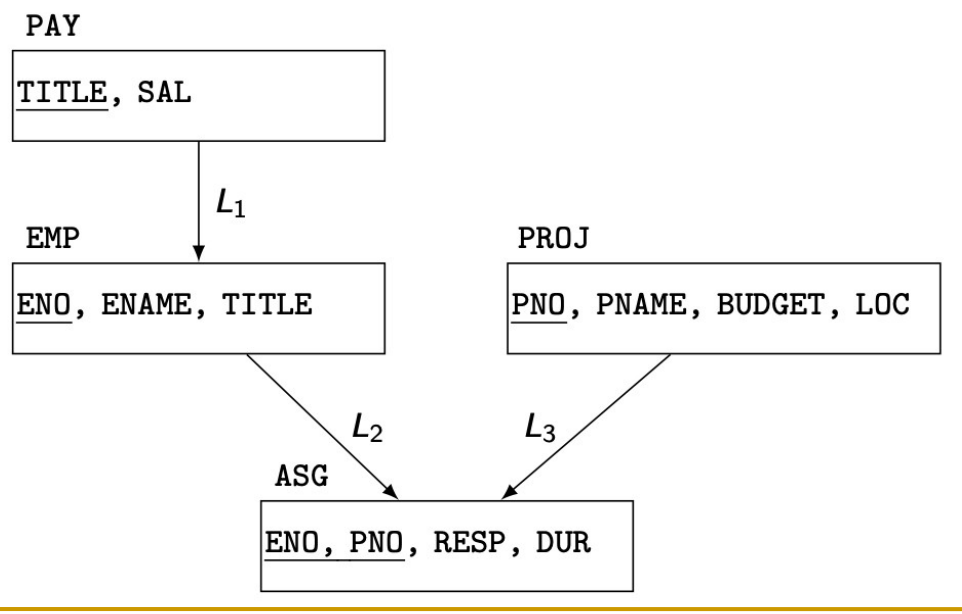
PHF – Correctness

- Completeness
  - Since *Pr*' is complete and minimal, the selection predicates are complete
- Reconstruction
  - If relation R is fragmented into $F_R = \{R_1, R_2, \ldots, R_r\}$

    $R = \bigcup_{\forall R_i \in F_R} R_i$
- Disjointness
  - Minterm predicates that form the basis of fragmentation should be mutually exclusive.

Derived Horizontal Fragmentation

- Defined on a member relation of a link according to a selection operation specified on its owner.
  - Each link is an equijoin.
  - Equijoin can be implemented by means of semijoins.



DHF – Definition

Given a link L where *owner*(L)=S and *member*(L)=R, the derived horizontal fragments of R are defined as

$$R_i = R \ltimes_F S_i,\ 1 \leq i \leq w$$

where w is the maximum number of fragments that will be defined on R and $S_i = \sigma_{F_i}(S)$

where F_i is the formula according to which the primary horizontal fragment S_i is defined.

DHF – Example

Given link L_1 where owner(L_1)=SKILL and member(L_1)=EMP

$EMP_1 = EMP \ltimes SKILL_1$

$EMP_2 = EMP \ltimes SKILL_2$

where

$SKILL_1 = \sigma_{SAL \leq 30000}(SKILL)$

$SKILL_2 = \sigma_{SAL > 30000}(SKILL)$

EMP_1

ENO	ENAME	TITLE
E3	A. Lee	Mech. Eng.
E4	J. Miller	Programmer
E7	R. Davis	Mech. Eng.

EMP_2

ENO	ENAME	TITLE
E1	J. Doe	Elect. Eng.
E2	M. Smith	Syst. Anal.
E5	B. Casey	Syst. Anal.
E6	L. Chu	Elect. Eng.
E8	J. Jones	Syst. Anal.

DHF – Correctness

- Completeness
  - Referential integrity
  - Let R be the member relation of a link whose owner is relation S which is fragmented as $F_S = \{S_1, S_2, ..., S_n\}$. Furthermore, let A be the join attribute between R and S. Then, for each tuple t of R, there should be a tuple t' of S such that
    $t[A] = t'[A]$
- Reconstruction
  - Same as primary horizontal fragmentation.
- Disjointness
  - Simple join graphs between the owner and the member fragments.

Vertical Fragmentation

- Has been studied within the centralized context
  - design methodology
  - physical clustering
- More difficult than horizontal, because more alternatives exist.

  Two approaches :
  - grouping
    - attributes to fragments
  - splitting
    - relation to fragments

Vertical Fragmentation

- Overlapping fragments
  - grouping
- Non-overlapping fragments
  - splitting

We do not consider the replicated key attributes to be overlapping.

Advantage:
Easier to enforce functional dependencies
(for integrity checking etc.)

VF – Information Requirements

- Application Information
  - Attribute affinities
    - a measure that indicates how closely related the attributes are
    - This is obtained from more primitive usage data
  - Attribute usage values
    - Given a set of queries $Q = \{q_1, q_2, \ldots, q_q\}$ that will run on the relation $R[A_1, A_2, \ldots, A_n]$,

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

$use(q_i, \bullet)$ can be defined accordingly

VF – Definition 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

$$
\begin{array}{c}
\\
q_1 \\ q_2 \\ q_3 \\ q_4
\end{array}
\begin{array}{c}
\begin{array}{cccc} A_1 & A_2 & A_3 & A_4 \end{array} \\
\begin{bmatrix}
1 & 0 & 1 & 0 \\
0 & 1 & 1 & 0 \\
0 & 1 & 0 & 1 \\
0 & 0 & 1 & 1
\end{bmatrix}
\end{array}
$$

A1=PNO
A2=PNAME
A3=BUDGET
A4=LOC)

VF – Affinity Measure $aff(A_i,A_j)$

The attribute affinity measure between two attributes A_i and A_j of a relation $R[A_1, A_2, \ldots, A_n]$ with respect to the set of applications $Q = (q_1, q_2, \ldots, q_q)$ is defined as follows :

$$aff(A_i, A_j) = \sum_{\text{all queries that access } A_i \text{ and } A_j} (\text{query access})$$

$$\text{query access} = \sum_{\text{all sites}} \text{access frequency of a query} * \frac{\text{access}}{\text{execution}}$$

VF – Calculation of $aff(A_i, A_j)$

Assume each query in the previous example accesses the attributes once during each execution.

Also assume the access frequencies

$$\begin{array}{c} \\ q_1 \\ q_2 \\ q_3 \\ q_4 \end{array} \begin{array}{c} \begin{array}{ccc} S_1 & S_2 & S_3 \end{array} \\ \begin{bmatrix} 15 & 20 & 10 \\ 5 & 0 & 0 \\ 25 & 25 & 25 \\ 3 & 0 & 0 \end{bmatrix} \end{array}$$

Then

$aff(A_1, A_3)$ = 15*1 + 20*1+10*1

= 45

and the attribute affinity matrix AA is

(Let A_1=PNO, A_2=PNAME, A_3=BUDGET, A_4=LOC)

$$\begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & A_2 & A_3 & A_4 \end{array} \\ \begin{bmatrix} 45 & 0 & 45 & 0 \\ 0 & 80 & 5 & 75 \\ 45 & 5 & 53 & 3 \\ 0 & 75 & 3 & 78 \end{bmatrix} \end{array}$$

VF – Clustering Algorithm

- Take the attribute affinity matrix *AA* and reorganize the attribute orders to form clusters where the attributes in each cluster demonstrate high affinity to one another.
- Bond Energy Algorithm (BEA) has been used for clustering of entities. BEA finds an ordering of entities (in our case attributes) such that the global affinity measure is maximized.

$$AM = \sum_i \sum_j (\text{affinity of } A_i \text{ and } A_j \text{ with their neighbors})$$

VF – Clustering Algorithm

$$AM = \sum_{i=1}^{n}\sum_{j=1}^{n} aff(A_i,A_j)[aff(A_i,A_{j-1}) + aff(A_i,A_{j+1})$$
$$+ aff(A_{i-1},A_j) + aff(A_{i+1},A_j)]$$

where

$$aff(A_0,A_j) = aff(A_i,A_0) = aff(A_{n+1},A_j) = aff(A_i,A_{n+1}) = 0$$

The AA matrix is symmetrical:

$$AM = \sum_{i=1}^{n}\sum_{j=1}^{n} aff(A_i,A_j)[aff(A_i,A_{j-1}) + aff(A_i,A_{j+1})]$$

Bond Energy Algorithm

Input: The *AA* matrix

Output: The clustered affinity matrix *CA* which is a perturbation of *AA*

1. *Initialization*: Place and fix one of the columns of *AA* in *CA*.
2. *Iteration*: Place the remaining *n-i* columns in the remaining *i*+1 positions in the *CA* matrix. For each column, choose the placement that makes the most contribution to the global affinity measure.
3. *Row order*: Order the rows according to the column ordering.

Bond Energy Algorithm

"Best" placement? Define contribution of a placement:

$$cont(A_i, A_k, A_j) = 2bond(A_i, A_k)+2bond(A_k, A_j) - 2bond(A_i, A_j)$$

where

$$bond(A_x,A_y) = \sum_{z=1}^{n} aff(A_z,A_x)aff(A_z,A_y)$$

BEA – Example

Consider the following *AA* matrix and the corresponding *CA* matrix where `PNO` (A_1) and `PNAME` (A_2) have been placed. Place `BUDGET`(A_3):

$$
AA = \begin{array}{c|cccc|}
 & A_1 & A_2 & A_3 & A_4 \\
\hline
A_1 & 45 & 0 & 45 & 0 \\
A_2 & 0 & 80 & 5 & 75 \\
A_3 & 45 & 5 & 53 & 3 \\
A_4 & 0 & 75 & 3 & 78
\end{array}
\qquad
CA = \begin{array}{c|cccc|}
 & A_1 & A_2 & & \\
\hline
 & 45 & 0 & & \\
 & 0 & 80 & & \\
 & 45 & 5 & & \\
 & 0 & 75 & &
\end{array}
$$

Ordering (0-3-1) :

$cont(A_0,A_3,A_1) = 2bond(A_0 , A_3)+2bond(A_3 , A_1)–2bond(A_0 , A_1)$

$= 2^* 0 + 2^* 4410 – 2^*0 = 8820$

Ordering (1-3-2) :

$cont(A_1,A_3,A_2) = 2bond(A_1 , A_3)+2bond(A_3 , A_2)–2bond(A_1,A_2)$

$= 2^* 4410 + 2^* 890 – 2^*225 = 10150$

Ordering (2-3-4) :

$cont (A_2,A_3,A_4) = 1780$

BEA – Example

- Therefore, the CA matrix has the form

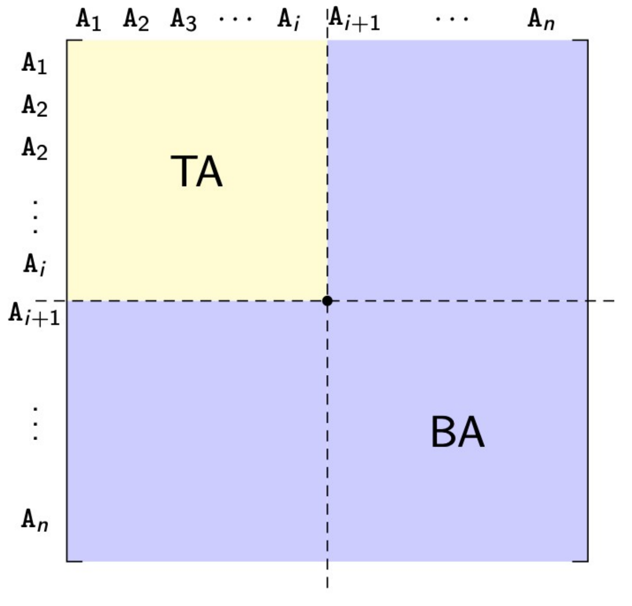
$$\begin{array}{ccc} A_1 & A_3 & A_2 \\ \end{array}$$
$$\begin{bmatrix} 45 & 45 & 0 \\ 0 & 5 & 80 \\ 45 & 53 & 5 \\ 0 & 3 & 75 \end{bmatrix}$$

- When LOC is placed, the final form of the *CA* matrix (after row organization) is

$$\begin{array}{cc} & \begin{array}{cccc} \mathtt{PNO} & \mathtt{BUDGET} & \mathtt{PNAME} & \mathtt{LOC} \end{array} \\ \begin{array}{r} \mathtt{PNO} \\ \mathtt{BUDGET} \\ \mathtt{PNAME} \\ \mathtt{LOC} \end{array} & \begin{bmatrix} 45 & 45 & 0 & 0 \\ 45 & 53 & 5 & 3 \\ 0 & 5 & 80 & 75 \\ 0 & 3 & 75 & 78 \end{bmatrix} \end{array}$$

VF – Algorithm

How can you divide a set of clustered attributes $\{A_1, A_2, \ldots, A_n\}$ into two (or more) sets $\{A_1, A_2, \ldots, A_i\}$ and $\{A_i, \ldots, A_n\}$ such that there are no (or minimal) applications that access both (or more than one) of the sets.



VF – ALgorithm

Define

TQ = set of applications that access only *TA*

BQ = set of applications that access only *BA*

OQ = set of applications that access both *TA* and *BA*

and

CTQ = total number of accesses to attributes by applications that access only *TA*

CBQ = total number of accesses to attributes by applications that access only *BA*

COQ = total number of accesses to attributes by applications that access both *TA* and *BA*

Then find the point along the diagonal that maximizes

$$CTQ \ast CBQ - COQ^2$$

VF – Algorithm

Two problems :

- Cluster forming in the middle of the *CA* matrix
  - Shift a row up and a column left and apply the algorithm to find the “best” partitioning point
  - Do this for all possible shifts
  - Cost $O(m^2)$
- More than two clusters
  - *m*-way partitioning
  - try 1, 2, …, *m*–1 split points along diagonal and try to find the best point for each of these
  - Cost $O(2^m)$

VF – Correctness

A relation R, defined over attribute set A and key K, generates the vertical partitioning $F_R = \{R_1, R_2, \ldots, R_r\}$.

- Completeness
  - The following should be true for A:

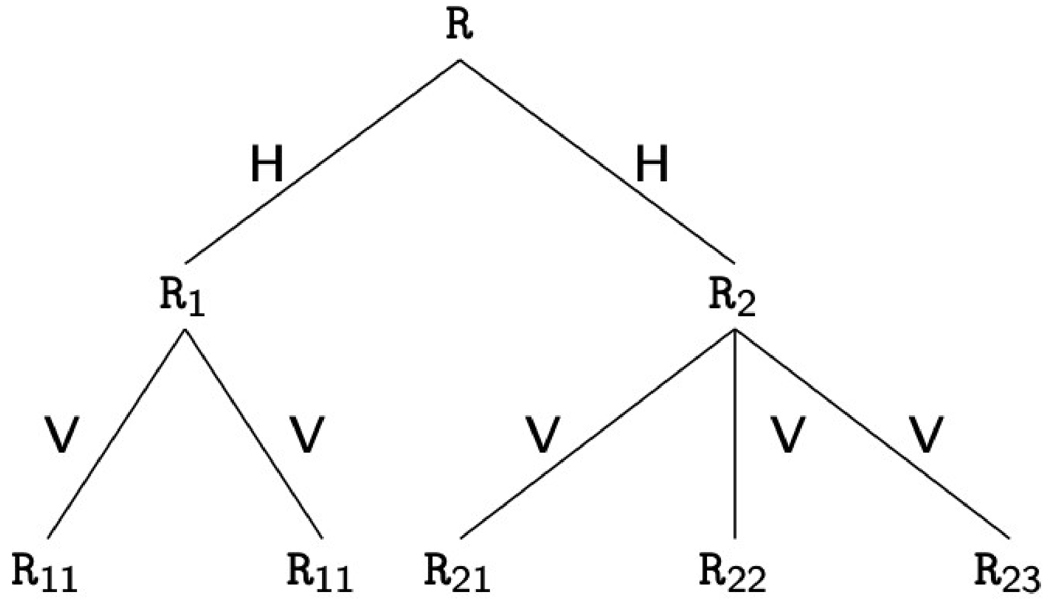
$$A = \bigcup A_{R_i}$$

- Reconstruction
  - Reconstruction can be achieved by

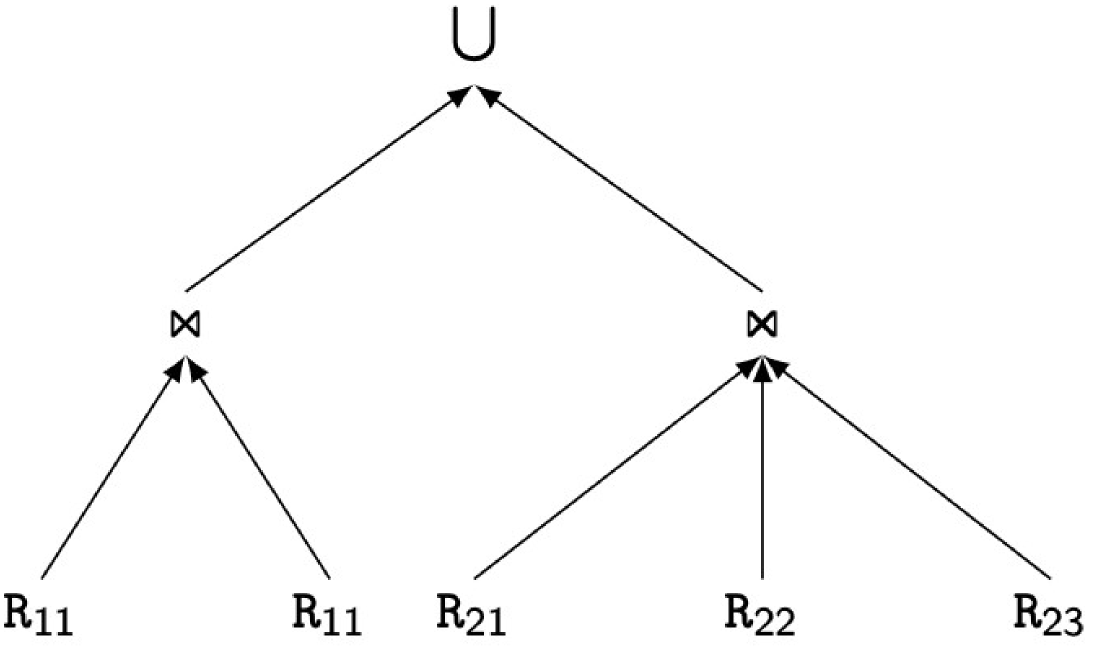
$$R = \bowtie_K R_i, \ \forall R_i \in F_R$$

- Disjointness
  - TID's are not considered to be overlapping since they are maintained by the system
  - Duplicated keys are not considered to be overlapping

Hybrid Fragmentation



Reconstruction of HF



Outline

- Distributed and Parallel Database Design
  - Fragmentation
  - Data distribution
  - Combined approaches

Fragment Allocation

- Problem Statement

Given

$F = \{F_1, F_2, \ldots, F_n\}$ fragments

$S = \{S_1, S_2, \ldots, S_m\}$ network sites

$Q = \{q_1, q_2, \ldots, q_q\}$ applications

Find the "optimal" distribution of F to S.

- Optimality
  - Minimal cost
    - Communication + storage + processing (read & update)
    - Cost in terms of time (usually)
  - Performance
    - Response time and/or throughput
  - Constraints
    - Per site constraints (storage & processing)

Information Requirements

- Database information
  - selectivity of fragments
  - size of a fragment
- Application information
  - access types and numbers
  - access localities
- Computer system information
  - unit cost of storing data at a site
  - unit cost of processing at a site
- Communication network information
  - bandwidth
  - latency
  - communication overhead

Allocation Model

General Form

min(Total Cost)

subject to

response time constraint

storage constraint

processing constraint

Decision Variable

$$x_{ij} = \begin{cases} 1 & \text{if fragment } F_i \text{ is stored at site } S_j \\ 0 & \text{otherwise} \end{cases}$$

Allocation Model

- Total Cost

$$\sum_{\text{all queries}} \text{query processing cost} +$$

$$\sum_{\text{all sites}} \quad \sum_{\text{all fragments}} \text{cost of storing a fragment at a site}$$

- Storage Cost (of fragment F_j at S_k)

  (unit storage cost at S_k) $\ast$ (size of F_j) $\ast$ x_{jk}

- Query Processing Cost (for one query)

  processing component + transmission component

Allocation Model

- Query Processing Cost

Processing component

access cost + integrity enforcement cost + concurrency control cost

- Access cost

$$\sum_{\text{all sites}} \sum_{\text{all fragments}} (\text{no. of update accesses+ no. of read accesses}) \ast x_{ij} \ast \text{local processing cost at a site}$$

- Integrity enforcement and concurrency control costs
    - Can be similarly calculated

Allocation Model

- Query Processing Cost

Transmission component

cost of processing updates + cost of processing retrievals

  - Cost of updates

$$\sum_{\text{all sites}} \sum_{\text{all fragments}} \text{update message cost} \; + \sum_{\text{all sites}} \sum_{\text{all fragments}} \text{acknowledgment cost}$$

  - Retrieval Cost

$$\sum_{\text{all fragments}} \min_{\text{all sites}} (\text{cost of retrieval command} \; + \text{cost of sending back the result})$$

Allocation Model

- Constraints
  - Response Time

execution time of query $\leq$ max. allowable response time for that query

  - Storage Constraint (for a site)

$$\sum_{\text{all fragments}} \text{storage requirement of a fragment at that site} \leq \text{storage capacity at that site}$$

  - Processing constraint (for a site)

$$\sum_{\text{all queries}} \text{processing load of a query at that site} \leq \text{processing capacity of that site}$$

Allocation Model

- Solution Methods
  - FAP is NP-complete
  - DAP also NP-complete
- Heuristics based on
  - single commodity warehouse location (for FAP)
  - knapsack problem
  - branch and bound techniques
  - network flow

Allocation Model

- Attempts to reduce the solution space
  - assume all candidate partitionings known; select the “best” partitioning
  - ignore replication at first
  - sliding window on fragments

Outline

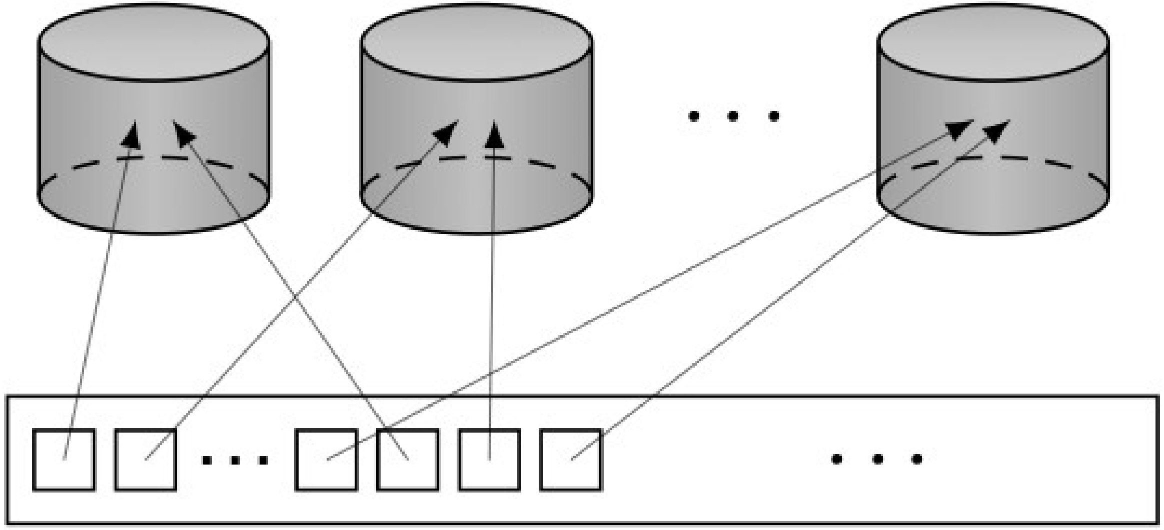
- Distributed and Parallel Database Design
  - Fragmentation
  - Data distribution
  - Combined approaches

Combining Fragmentation & Allocation

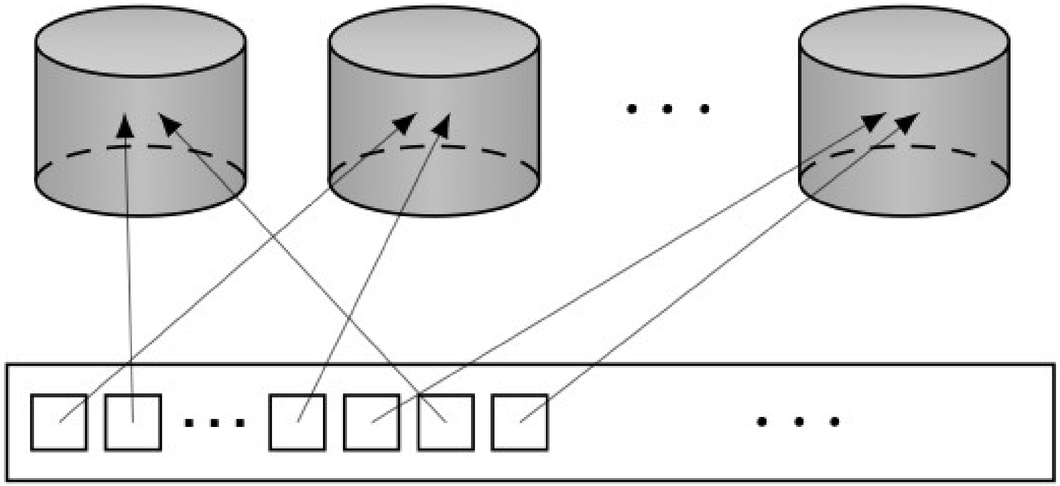
Partition the data to dictate where it is located

- Workload-agnostic techniques
  - Round-robin partitioning
  - Hash partitioning
  - Range partitioning
- Workload-aware techniques
  - Graph-based approach

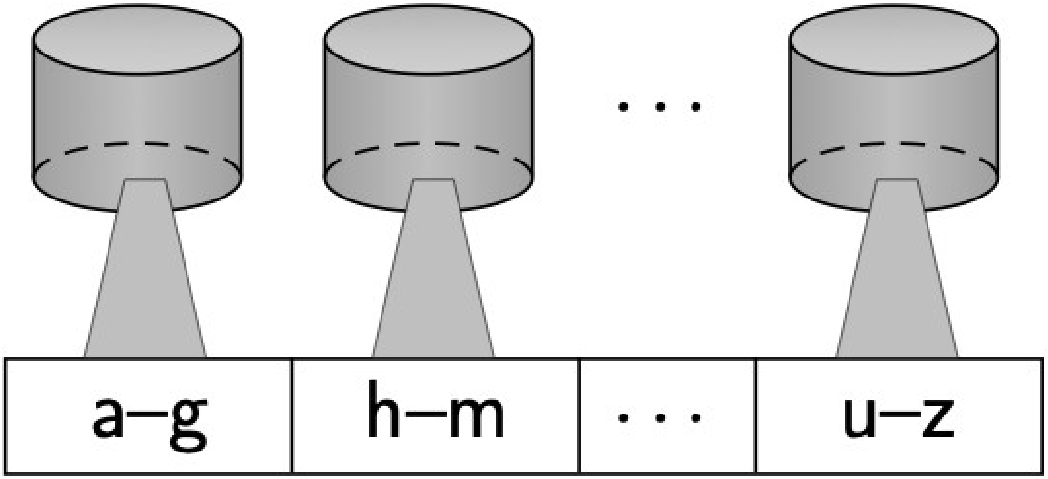
Round-robin Partitioning



Hash Partitioning

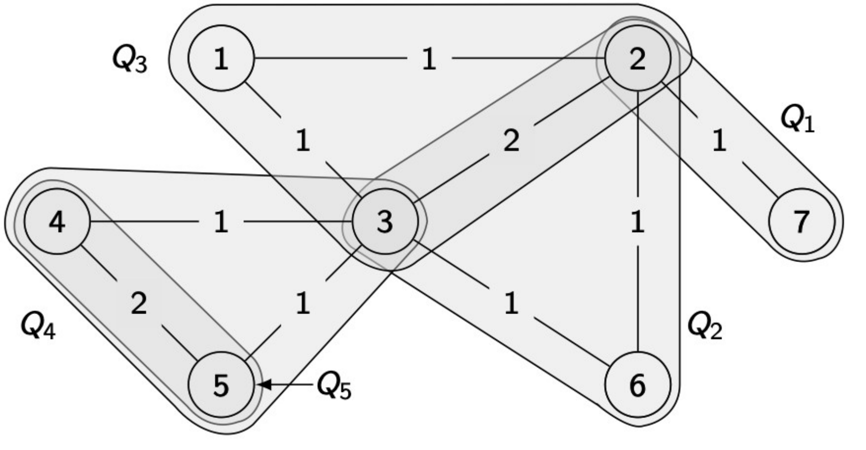


Range Partitioning



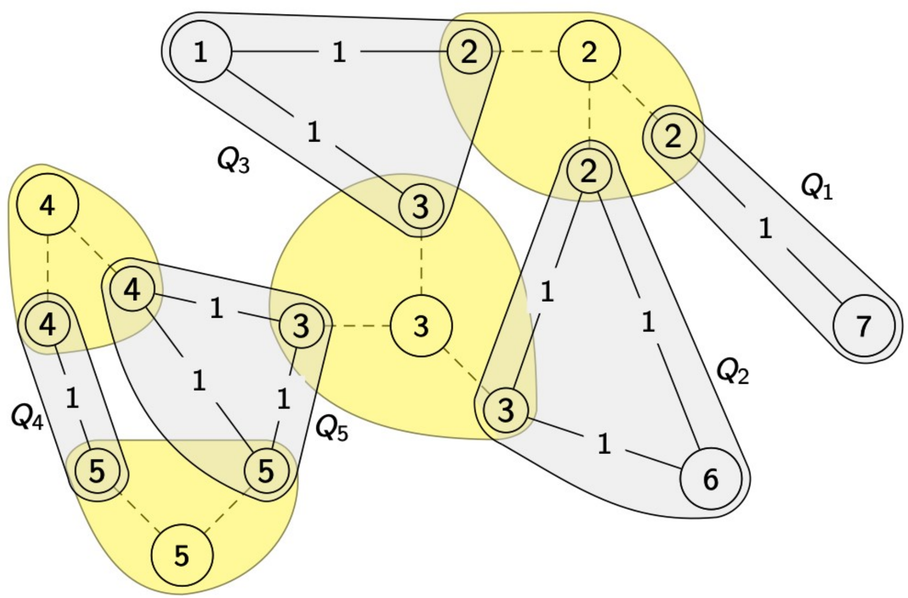
Workload-Aware Partitioning

- Examplar: Schism
  - Graph $G=(V,E)$ where
    - vertex $v_i \in V$ represents a tuple in database,
    - edge $e=(v_i,v_j) \in E$ represents a query that accesses both tuples v_i and v_j;
    - each edge has weight counting the no. of queries that access both tuples
  - Perform vertex disjoint graph partitioning
    - Each vertex is assigned to a separate partition



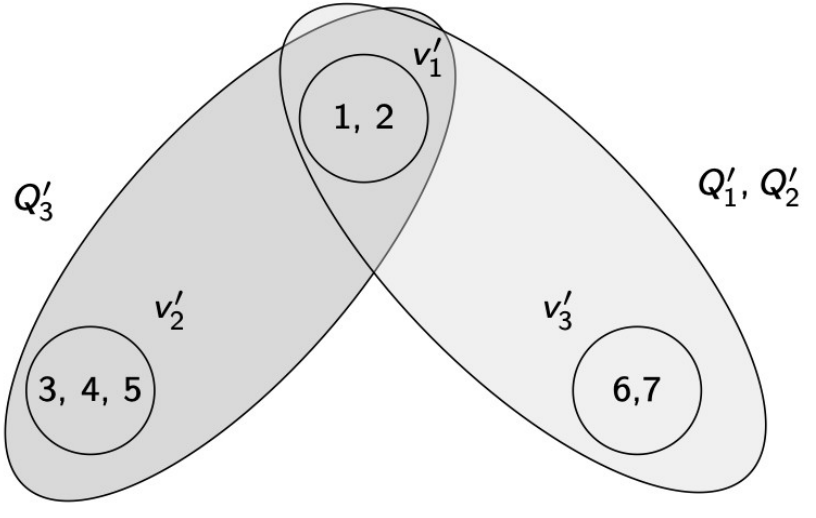
Incorporating Replication

- Replicate each vertex based on the no. of transactions accessing that tuple each transaction accesses a separate copy



Dealing with graph size

- Each tuple a vertex graph too big directory too big
- SWORD
  - Use hypergraph model
  - Compress the directory



Adaptive approaches

- Redesign as physical (network characteristics, available storage) and logical (workload) changes occur.
- Most focus on logical
- Most follow combined approach
- Three issues:
  1. How to detect workload changes?
  2. How to determine impacted data items?
  3. How to perform changes efficiently?

Detecting workload changes

- Not much work
- Periodically analyze system logs
- Continuously monitor workload within DBMS
  - SWORD: no. of distributed queries
  - E-Store: monitor system-level metrics (e.g., CPU utilization) and tuple-level access

Detecting affected data items

- Depends on the workload change detection method
- If monitoring queries queries will identify data items
  - Apollo: generalize from “similar” queries

```
SELECT PNAME FROM PROJ WHERE BUDGET>20000 AND LOC=‘LONDON’
```

⇩

```
SELECT PNAME FROM PROJ WHERE BUDGET>? AND LOC=‘?’
```

- If monitoring tuple-level access (E-Store), this will tell you

Performing changes

- Periodically compute redistribution
  - Not efficient
- Incremental computation and migration
  - Graph representation look at changes in graph
    - SWORD and AdaptCache: Incremental graph partitioning initiates data migration for reconfiguration
  - E-Store: determine hot tuples for which a migration plan is prepared determine; cold tuple reallocation as well
    - Optimization problem; real-time heuristic solutions
  - Database cracking: continuously reorganize data to match query workload
    - Incoming queries are used as advice
    - When a node needs data for a local query, this is hint that data may need to be moved