# Principles of Distributed Database Systems

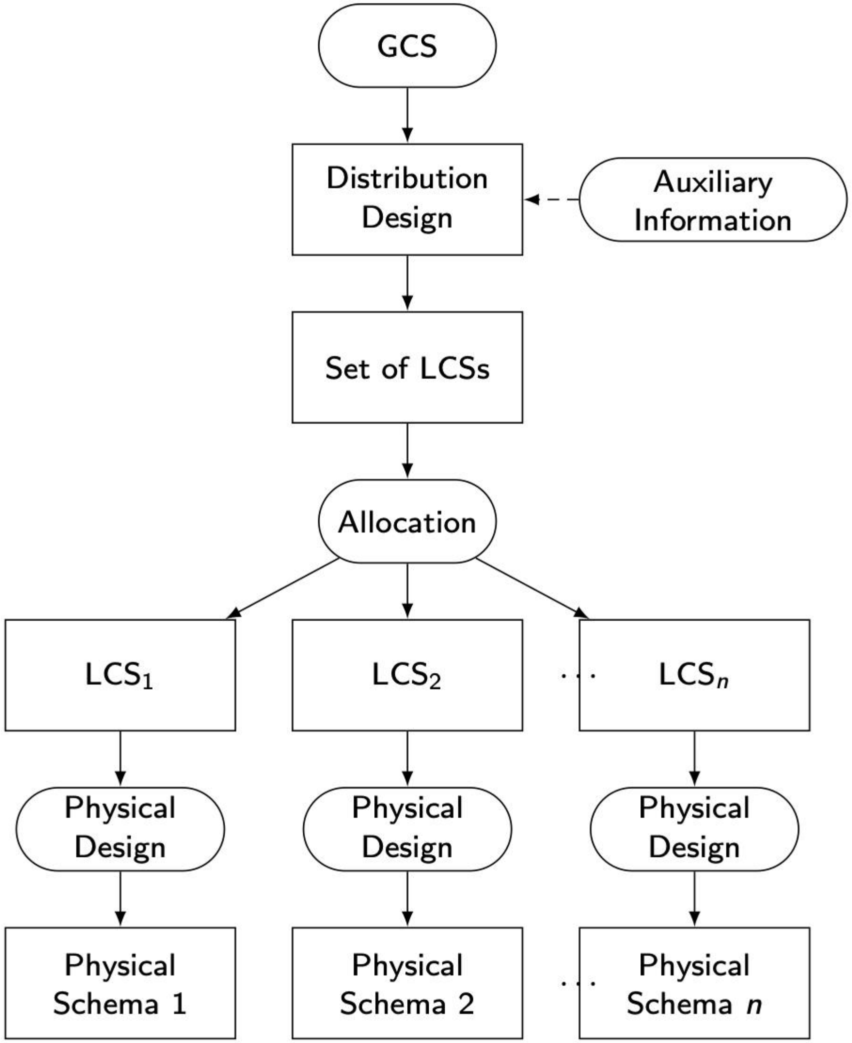
# Outline

- 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

# Outline

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

# 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 $\nabla$ such that

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

- 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:

$$\text{If } \frac{\text{read-only queries}}{\text{update queries}} << 1, \text{ replication is advantageous,}$$

$$\text{otherwise replication may cause problems}$$

# Comparison of Replication Alternatives

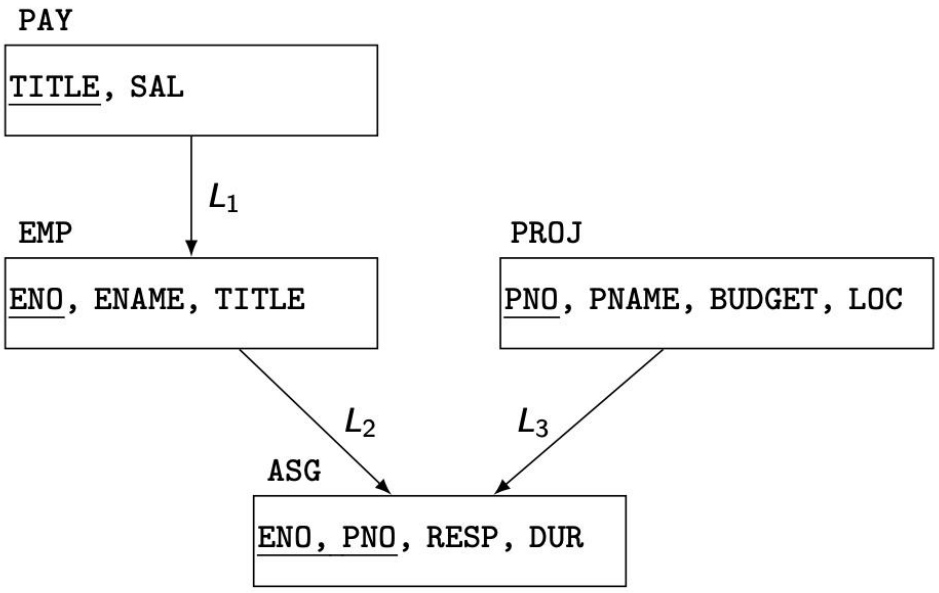
| | Full replication | Partial replication | Partitioning |
|---|---|---|---|
| QUERY PROCESSING | Easy | Same difficulty | |
| DIRECTORY MANAGEMENT | Easy or nonexistent | Same difficulty | |
| CONCURRENCY CONTROL | Moderate | Difficult | Easy |
| RELIABILITY | Very high | High | Low |
| REALITY | Possible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

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

    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 :

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

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 $m_i$.

$$\Downarrow$$

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*.

$$\frac{acc(m_i)}{card(f_i)} = \frac{acc(m_j)}{card(f_j)}$$

# 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

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

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

# 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 $\Rightarrow$ 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

$PAY_1$

| TITLE | SAL |
|---|---|
| Mech. Eng. | 27000 |
| Programmer | 24000 |

$PAY_2$

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

# PHF – Example

- Fragmentation of relation PROJ
  - Applications:
    - Find the name and budget of projects given their no.
      - 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") $\wedge$ (BUDGET $\leq$ 200000)

    $m_2$ : (LOC = "Montreal") $\wedge$ (BUDGET > 200000)

    $m_3$ : (LOC = "New York") $\wedge$ (BUDGET $\leq$ 200000)

    $m_4$ : (LOC = "New York") $\wedge$ (BUDGET > 200000)

    $m_5$ : (LOC = "Paris") $\wedge$ (BUDGET $\leq$ 200000)

    $m_6$ : (LOC = "Paris") $\wedge$ (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

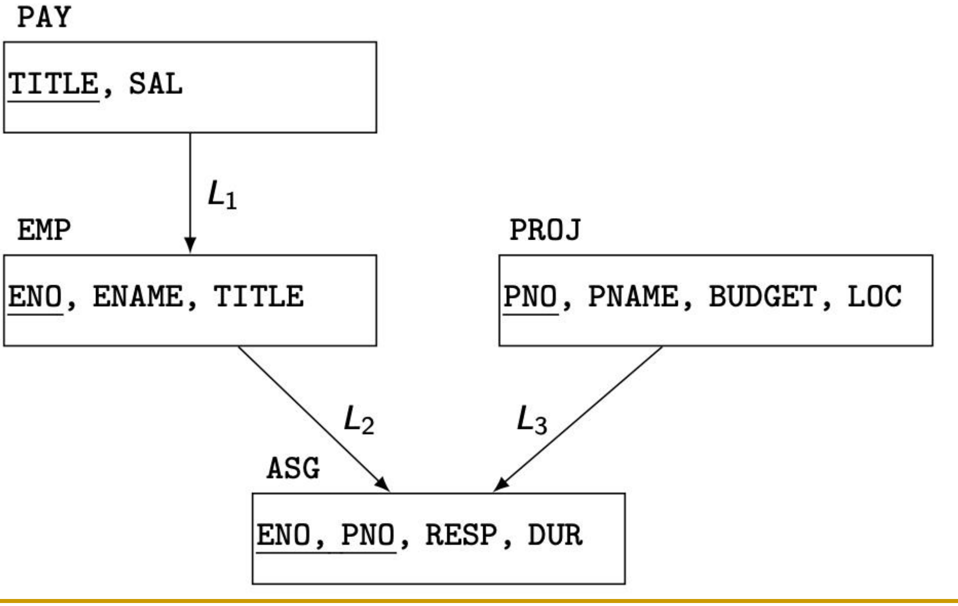
- Completeness
  - Since *Pr*' is complete and minimal, the selection predicates are complete
- Reconstruction
  - If relation $R$ is fragmented into $F_R = \{R_1, R_2, \ldots, R_r\}$

$$R = \bigcup_{\forall R_i \in F_R} R_i$$

- 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

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

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

$ASG_1$

| ENO | PNO | RESP | DUR |
|---|---|---|---|
| E3 | P3 | Consultant | 10 |
| E3 | P4 | Engineer | 48 |
| E4 | P2 | Programmer | 18 |
| E7 | P3 | Engineer | 36 |

$ASG_2$

| ENO | PNO | RESP | DUR |
|---|---|---|---|
| E1 | P1 | Manager | 12 |
| E2 | P1 | Analyst | 24 |
| E2 | P2 | Analyst | 6 |
| E5 | P2 | Manager | 24 |
| E6 | P4 | Manager | 48 |
| E8 | P3 | Manager | 40 |

# 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

$$\begin{array}{c} \\ q_1 \\ q_2 \\ q_3 \\ q_4 \end{array} \begin{array}{c} \begin{array}{cccc} \text{PNO} & \text{PNAME} & \text{BUDGET} & \text{LOC} \end{array} \\ \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$$

# 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)

$$
\begin{array}{c}
 \\ \text{PNO} \\ \text{PNAME} \\ \text{BUDGET} \\ \text{LOC}
\end{array}
\begin{array}{c}
\begin{array}{cccc} \text{PNO} & \text{PNAME} & \text{BUDGET} & \text{LOC} \end{array} \\
\begin{bmatrix} - & 0 & 45 & 0 \\ 0 & - & 5 & 75 \\ 45 & 5 & - & 3 \\ 0 & 75 & 3 & - \end{bmatrix}
\end{array}
$$

# 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.

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

# Bond Energy Algorithm

Input: The *AA* matrix

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

❶ *Initialization*: Place and fix one of the columns of *AA* in *CA*.

❷ *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.

❸ *Row order*: Order the rows according to the column ordering.

# Bond Energy Algorithm

"Best" placement? Define contribution of a placement:

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

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 and PNAME have been placed. Place BUDGET:

$$\begin{array}{r|cccc|}
 & \text{PNO} & \text{PNAME} & \text{BUDGET} & \text{LOC} \\
\hline
\text{PNO} & - & 0 & 45 & 0 \\
\text{PNAME} & 0 & - & 5 & 75 \\
\text{BUDGET} & 45 & 5 & - & 3 \\
\text{LOC} & 0 & 75 & 3 & -
\end{array}
\qquad
\begin{array}{r|cccc|}
 & \text{PNO} & \text{PNAME} & & \\
\hline
\text{PNO} & 45 & 0 & & \\
\text{PNAME} & 0 & 80 & & \\
\text{BUDGET} & 45 & 5 & & \\
\text{LOC} & 0 & 75 & &
\end{array}$$

Ordering (0-3-1) :

$$cont(A_0,\text{BUDGET},\text{PNO}) = 2bond(A_0, \text{BUDGET}) + 2bond(\text{BUDGET}, \text{PNO}) - 2bond(A_0, \text{PNO}) = 8820$$

Ordering (1-3-2) :

$cont(\text{PNO},\text{BUDGET},\text{PNAME}) = 10150$

Ordering (2-3-4) :

$cont(\text{PNAME},\text{BUDGET},\text{LOC}) = 1780$

# BEA – Example

- Therefore, the CA matrix has the form

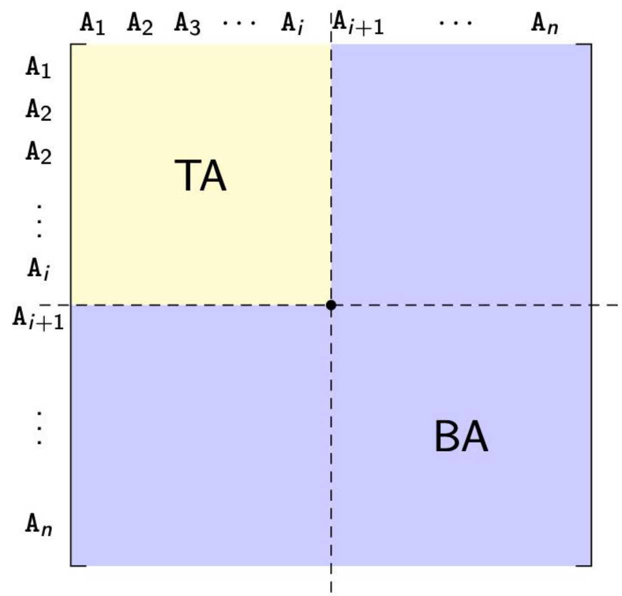
$$
\begin{array}{c|ccc}
 & \mathtt{PNO} & \mathtt{BUDGET} & \mathtt{PNAME} \\
\mathtt{PNO} & 45 & 45 & 0 \\
\mathtt{PNAME} & 0 & 5 & 80 \\
\mathtt{BUDGET} & 45 & 53 & 5 \\
\mathtt{LOC} & 0 & 3 & 75
\end{array}
$$

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

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

# 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

$$CTQ * CBQ - COQ^2$$

# 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 $A$:

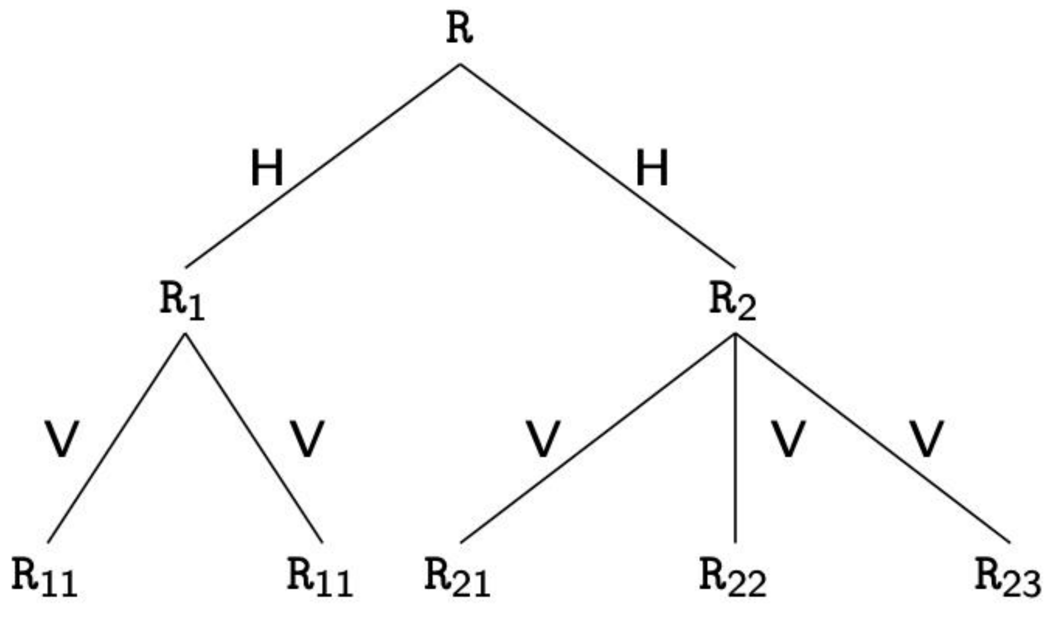
$$A = \bigcup A_{R_i}$$

- Reconstruction
  - Reconstruction can be achieved by

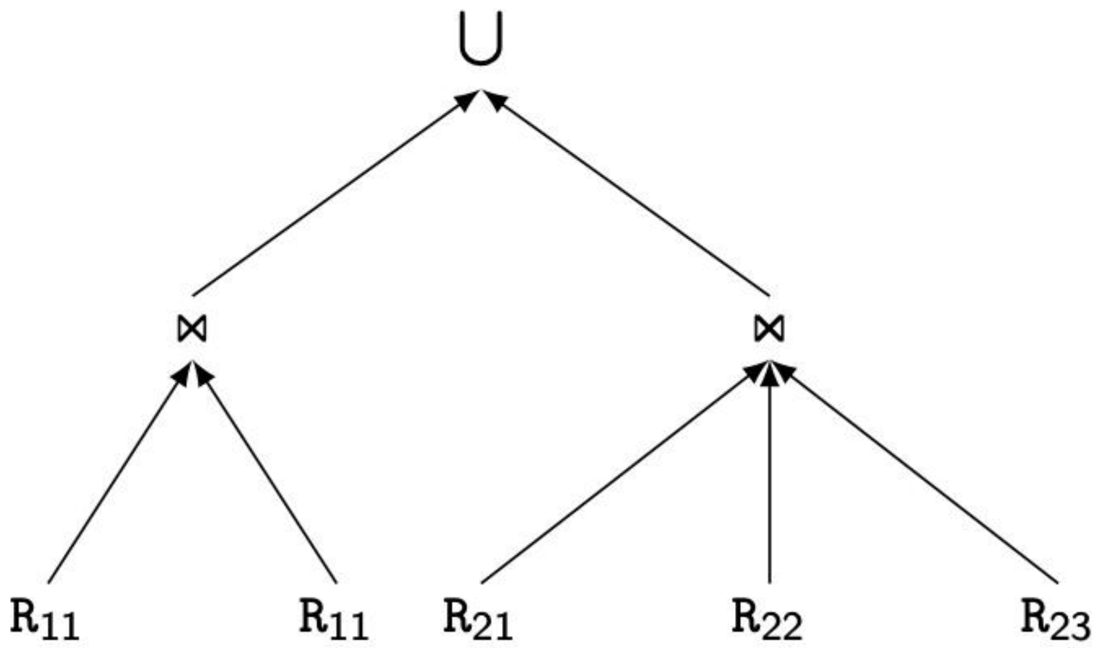
$$R = \bowtie_K R_i, \ \forall R_i \in F_R$$

- 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
- Communication network information
  - unit cost of storing data at a site
  - unit cost of processing at a site
- Computer system information
  - bandwidth
  - latency
  - communication overhead

# Allocation

File Allocation (FAP) vs Database Allocation (DAP):

- Fragments are not individual files
  - relationships have to be maintained
- Access to databases is more complicated
  - remote file access model not applicable
  - relationship between allocation and query processing
- Cost of integrity enforcement should be considered
- Cost of concurrency control should be considered

# 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

$$\sum_{\text{all queries}} \text{query processing cost} + \sum_{\text{all sites}} \sum_{\text{all fragments}} \text{cost of storing a fragment at a site}$$

- Storage Cost (of fragment $F_j$ at $S_k$)

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

- 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

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

  - 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

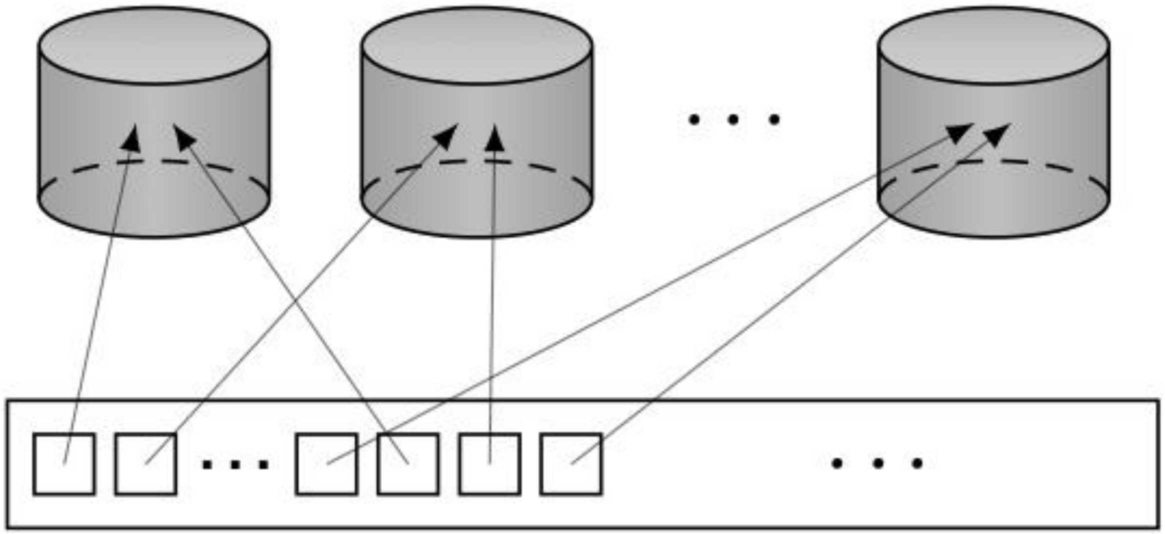
# Combining Fragmentation & Allocation

Partition the data to dictate where it is located

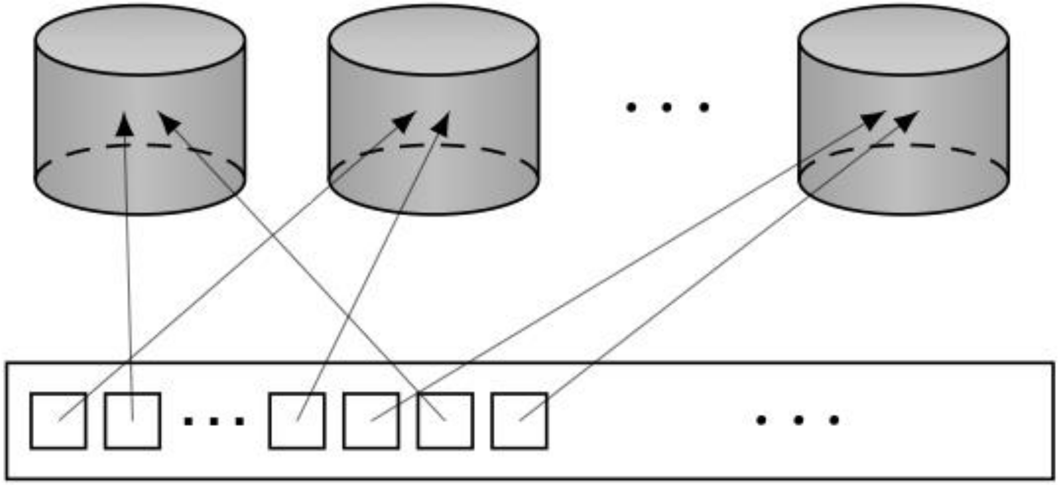
- Workload-agnostic techniques
  - Round-robin partitioning
  - Hash partitioning
  - Range partitioning
- Workload-aware techniques
  - Graph-based approach

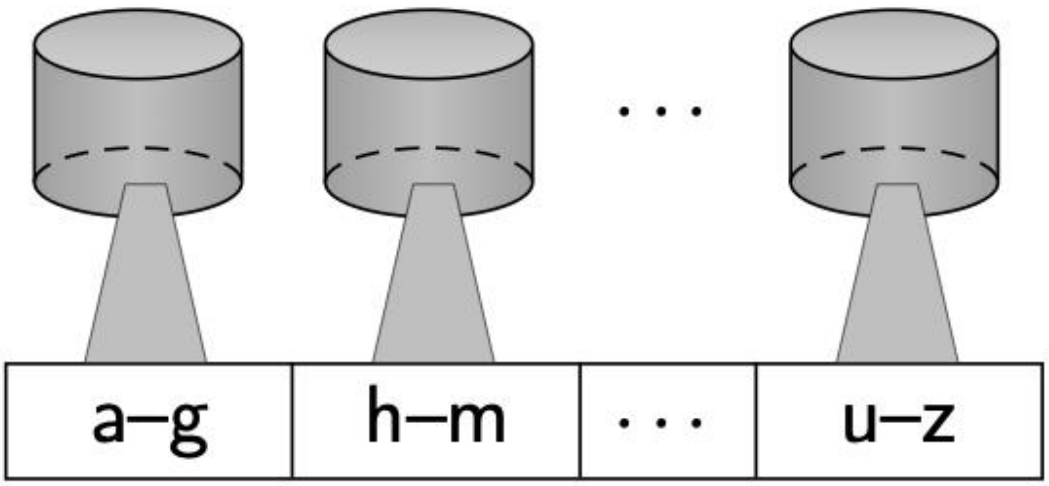
# Round-robin Partitioning



# Hash Partitioning

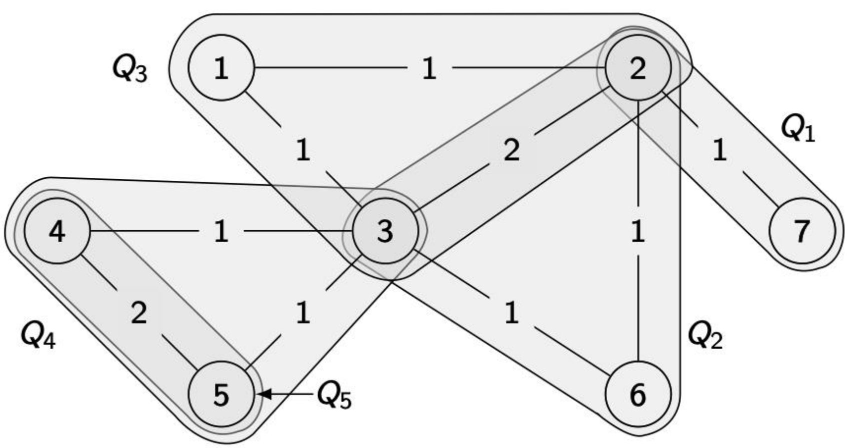


# Range Partitioning



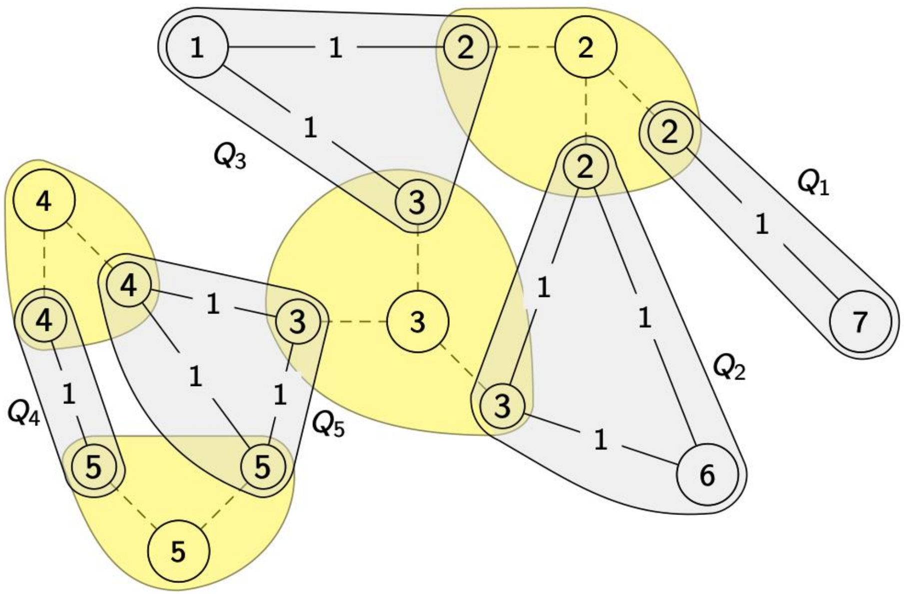
# Workload-Aware Partitioning

- 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



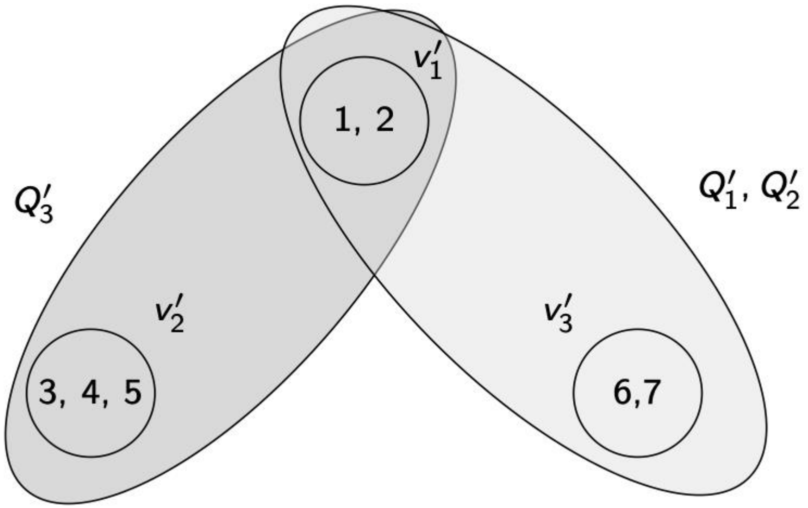
# Incorporating Replication

- 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