

An Approach to Querying Multiple Object Databases^{*}

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In a multidatabase system which consists of object databases, a global schema created by integrating schemas of the component databases provides a uniform interface and high level location transparency to help users retrieve data. The mapping between the global and component object schemas is complicated due to schema restructuring conducted to resolve various conflicts among component schemas before conducting schema integration. This mapping information is important for global query processing. In this paper, a mapping strategy is presented. A *mapping equation* is defined to denote the mappings for attributes and object instances between a virtual class and its constituent classes. In addition, a *mapping graph* is used to describe the mapping equation. Based on the mapping information, a mechanism for processing global queries in parallel is introduced. One processing unit is responsible for decomposing the global query into subqueries against the component databases. To handle the effects of schema restructuring, preprocessing and postprocessing units are also provided for each local DBMS. The results returned from component databases need to be integrated. The concept of *object isomerism*, where a real-world entity is represented by more than one object in different component databases, is considered for integrating query results.

Keywords: object database, multidatabase system, schema mapping strategy, global query processing, object isomerism

1. INTRODUCTION

Because of the rapid development of computer networks and the need for data sharing among multiple existing databases, issues related to heterogeneous database systems have become more and more important. In a heterogeneous database system, the autonomy of the component databases should be preserved. That is, the schemas and data in each component database should be designed and manipulated independently. In order to provide a uniform interface and high level location transparency so that users can retrieve data, a global schema is usually created by integrating component schemas in the heterogeneous database system.

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A variety of approaches to schema integration for multidatabase systems have been proposed [1-7]. Batini et al. discussed twelve methodologies for database or view integration [1]. Czejdo et al. used a language with a graphical user interface to perform schema integration in federated database systems [8]. Schema and domain incompatibilities were considered in [8, 9] and [10]. Issues related to implementing schema integration tools were reported in [11] and [12]. In [13], for automation of much of the integration process, tools for expressing similarities between structures in two schemas were embedded within the view integration process. A formal semantic model for specifying the correspondences between schemas was proposed in [14]. The integration strategy based on the operational mapping was provided in [15] for integrating heterogeneous data management systems. Other approaches defined a set of operators used to build a virtual integration of multiple databases or to customize virtual classes [16, 17].

In our previous work, we proposed a schema integration mechanism for deriving global object schemas from multiple existing object databases [18]. We first define *corresponding assertions* for the database administrator (DBA) to specify the semantic correspondences among component schemas. Based on these assertions, *integration rules* are designed, which use a set of primitive *integration operators* to perform the integration. The integration operators are used to virtually restructure or integrate the component schemas, and the rules specify which integration operators should be applied in which order in different situations.

The mapping between the global object schema and the component object schemas is complicated due to schema restructuring for resolving various conflicts among component object schemas before performing schema integration. The mapping information is important for processing of a global query against the global schema. However, most research on schema integration has not provided mapping strategies or query processing mechanisms for global queries, especially for the object data model. Class constructors for deriving view classes from underlying classes were provided in [6]. That work also proposed techniques for decomposing a query into subqueries and materializing the result. However, only query processing for class hierarchies was considered. Jeng et al. discussed query processing strategies for homogeneous distributed object database systems, but no schema conflicts were considered [19]. A message-based approach used to retrieve data in *class composition hierarchies* [20] was proposed in [21] but did not support the integration of results from subqueries.

In this paper, a strategy for mapping between global and component object schemas is discussed. The *mapping equation* is used to denote mappings of attributes and object instances between a virtual class and its constituent classes. Then, a *mapping graph* is employed to represent a corresponding mapping equation. For each class in the global schema, an attribute mapping graph and an object mapping graph are constructed to store the mapping information with component schemas. Via traversing mapping graphs, a parallel global query processing mechanism is introduced. Some processing units and auxiliary units are provided for query processing. One processing unit is responsible for decomposing a global query into the subqueries against the component databases. To handle the effects of schema restructuring, preprocessing and post processing units are also needed for each local DBMS. Both the class hierarchies and class composition hierarchies are considered in the strategies for query processing. Finally, the results returned from the component databases need to be integrated. In our query model, the

concept of *object isomerism* is considered; that is, the results for a real-world entity from different component databases are integrated to obtain a more informative query answer.

This paper is organized as follows. The next section presents some basic concepts used throughout the paper and briefly introduces our previous work. The mechanism for mapping between global and component object schemas is provided in section 3. Section 4 presents strategies for processing a query against the global schema. Finally, section 5 concludes this paper and includes a discussion of future work.

2. BACKGROUND

2.1 Basic Concepts

Inheritance model In a class hierarchy, classes are linked according to the IS-A relationships among them. There are two kinds of object inheritance models in a class hierarchy. In one model, the objects in subclasses are also in their super class. Thus, when a class is queried, all the objects in the class hierarchy rooted in the class are accessed. In the other model, the objects in a class are those objects which do not belong to its subclasses. When a class is queried, only the objects in the class are accessed unless some special notation is specified in the query; in this case, all the objects in the class hierarchy rooted in the class are accessed [22]. In this paper, we adopt the latter inheritance model.

Concept of object isomerism In a multidatabase system, a real-world entity may exist in different databases as different objects. We have discussed a strategy in [23] for finding such objects, called *isomeric objects*. The data for these isomeric objects need to be combined in query processing to provide complete information about the real-world entity. Since the process of identifying the isomeric objects is time-consuming, it is unrealistic to perform identification every time a global query is processed. In this paper, we assume that isomeric objects have been determined. To each object in the multidatabase system is assigned a *global object identifier (GOid)*, and the **GOids** for the isomeric objects are the same. It is easier to integrate the data of isomeric objects using **GOids**. The object identifiers defined in a component database are called *Oids*. The mappings among *Oids* and **GOids** are stored in the *GOid mapping table*. The process of identification is executed periodically to identify isomeric objects for newly added objects. The **GOid** mapping tables are also updated for each new identification.

We will use examples to show how the concept of object isomerism is applied to provide complete information about a real-world entity. Fig. 1 shows the schemas for class **Person** in DB_i and class **Person** in DB_j . Since these two classes are semantically equivalent, they are integrated to obtain a global class **G-Person** shown in the global schema. Suppose a person P is represented by object **p1** in **Person@ DB_i** . If there is an object **p2** in **Person@ DB_j** which also represents P , then **p1** and **p2** are assigned the same **GOid g1**. Therefore, the data in **p1** and **p2** can be combined during query processing to provide users with complete information about P , including its *ss#*, *name*, *salary*, *blood_type*, and *birthday*.

Similarly, Fig. 2 shows the schemas for class **Person** in DB_i and class **Student** in DB_k . There is an IS-A relationship in the semantics between these two classes. Thus, a

class hierarchy is constructed between them. Moreover, **Person@DB_i** and **Student@DB_k** are renamed **G-Person** and **G-Student**, respectively, in the global schema. Suppose a student *S* is represented by object **s1** in **Student@DB_k**, and that there is an object **p3** in **Person@DB_i** which also represents *S*. The **GOid g2** is assigned to both **s1** and **p3**. According to the global schema, an object in **G-Student** inherits attributes from **G-Person**. By combining **s1** with its isomeric object **p3** during query processing, users can get complete information about *S*.

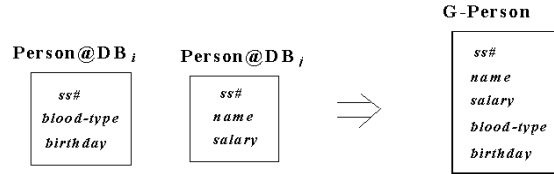


Fig. 1. Class **Person** in **Db_i**, class **Person** in **DB_j**, and global class **G-Person**.

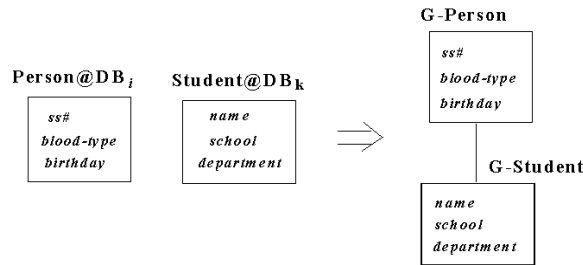


Fig. 2. Class **Person** in **Db_i**, class **Student** in **DB_k**, and the constructed global classes.

2.2 Previous Work

The mapping strategy is based on the integration operators defined in our previous work [18]. The resultant classes of these operations are called *virtual classes*. That is, no actual data are stored for the resultant classes. The data of the resultant classes are derived from the component databases and the mapping information. The attributes and objects associated with the virtual classes are called *virtual attributes* and *virtual objects*, respectively. For a virtual class C_v , the classes involved in the operations used to construct C_v are called the *constituent classes* of C_v . Each integration operator is briefly introduced in the following. These integration operators can be categorized as *class restructuring* or *class integration operators*.

Class restructuring operators are used to virtually restructure the classes in a component schema in order to resolve structural conflicts among component schemas. They may virtually change the structure of the attributes in a class and the structure of a class hierarchy. Note that the first five *class restructuring operators* are used to restructure the attributes of a class. Also, all subclasses rooted in the class inherit the restructured attributes.

1. Refine (source-class.new-attribute, constant-value)

The *Refine* operator adds the *new-attribute* to the **source-class**. In addition, to the value of the *new-attribute* is assigned the *constant-value*.

2. *Hide* (**source-class**. *hidden-attribute*)

The *Hide* operator removes the *hidden-attribute* from the **source-class**.

3. *Rename* (**source-class**(.*source-attribute*), *new-name*)

The *Rename* operator renames the **source-class** or the *source-attribute* in the **source-class** as *new-name*.

4. *Aggregate* (**source-class**.*attribute-list*, *new-complex-attribute*, **new-domain-class**)

The *Aggregate* operator aggregates a set of primitive attributes (*attribute-list*) in the **source-class** into the *new-complex-attribute*. Moreover, a new virtual class **new-domain-class** is created to form the domain class of the *new-complex-attribute*.

Fig. 3 shows the schemas of two databases, **DB1** and **DB2**, in different schools. They are used to store personal information of students. This figure is used for the examples presented in this paper. When operation *Aggregate Student@DB2*. *city, street, no, address, V-Address* is performed, the set of primitive attributes *city, street, no* is restructured to form a complex attribute *address*. Moreover, a virtual class **V-Address** is constructed to form the domain class of *address*, whose values come from the sets of values of *city, street, no* in **Student@DB2**. The resultant virtual classes **V-Student2** and **V-Address** in **DB2** are shown in Fig. 4(a).

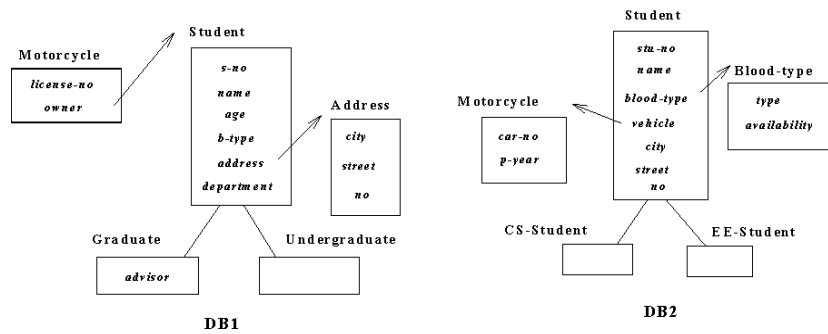


Fig. 3. Component schemas for **DB1** and **DB2**.

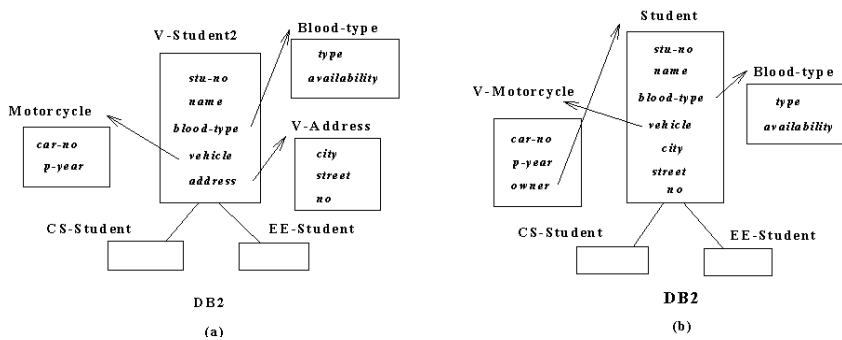


Fig. 4. The resultant schemas for the *Aggregate* and *Invert* operations.

5. *Invert (source-class, inverted-class.inverted-attribute, new-complex-attribute)*

For the **source-class** which is the domain class of the *inverted-attribute* in class **inverted-class**, the *Invert* operator adds the *new-complex-attribute* to the **source-class**, with **inverted-class** as its domain class. The *new-complex-attribute* is called the *inverse* of the *inverted-attribute*.

For example, the operation *Invert (Motorcycle@DB2, Student@DB2, vehicle, owner)* constructs a virtual attribute *owner* in **Motorcycle@DB2**. For each object **o1** in **Motorcycle@DB2**, the value of *owner* comes from the *Oid* of object **o2** in **Student@DB2** if the *vehicle* of **o2** is **o1**. If no such associated object exists in **Student@DB2**, then the value of *owner* of **o1** is a null value. The resultant virtual class **V_Motorcycle** is shown in Fig. 4(b).

6. *Demolish (source-class)*

The *division characteristic* of a class is defined as the property which distinguishes the subclasses of the class. We assume that there exists a division characteristic for each class. The *Demolish* operator demolishes all the subclasses of the *source-class* and adds all the attributes in the subclasses to the *source-class*. Moreover, a new attribute which denotes the division characteristic of the class is also added to the *source-class*. The objects in the resultant virtual class come from *source-class* and its subclasses. The added attribute is assigned a constant value for the objects in the same subclass. The values in the new attribute denote which subclass an object comes from.

After the operation *Demolish (Student@DB1)* is applied, the resultant virtual class **V-Student1** in **DB1** is that shown in Fig. 5(a). The attribute *degree*, which is the division characteristic of the class **Student@DB1**, is added, and its value is assigned as “graduate” for the objects in **Graduate@DB1** and as “undergraduate” for the objects in **Undergraduate@DB1**.

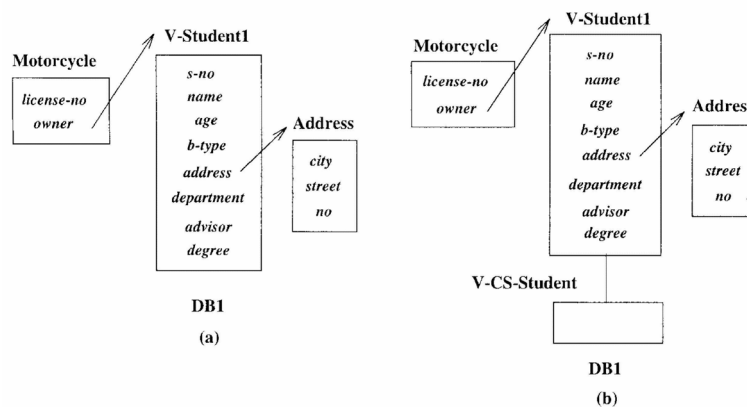


Fig. 5. The resultant schemas for the *Demolish* and *Build* operations.

7. *Build (source-class, new-class, predicate-clause)*

The *Build* operator creates a subclass (**new-class**) of the **source-class**, which contains virtual objects satisfying the *predicate-clause* in the **source-class**. The *predi-*

cate-clause is assumed to be a simple predicate on an attribute in the **source-class**.

For example, the resulting schema for the operation *Build* (**V-Student1**, **V-CS-Student**, *department = CS*) is that shown in Fig. 5(b).

After the restructuring process is performed, *class integration operators* are used to virtually integrate classes from different component databases.

1. *OUnion* (**source-class1**, **source-class2**, **new-class**)

The *OUnion* operator integrates **source-class1** and **source-class2** into a virtual class **new-class**. Only **new-class** will appear in the global schema.

2. *Generalize* (**source-class1**, **source-class2**, **common-superclass**)

The *Generalize* operator creates the virtual class **common-superclass**, which is the common superclass of **source-class1** and **source-class2**. Two more virtual classes corresponding to **source-class1** and **source-class2** produced as subclasses of the **common-superclass** in the global schema.

3. *Specialize* (**source-class1**, **source-class2**, **common-subclass**)

The *Specialize* operator creates the virtual class **common-subclass**, which is the common subclass of **source-class1** and **source-class2**. In addition, two more virtual classes corresponding to **source-class1** and **source-class2** produced as the superclasses of the **common-subclass** in the global schema.

4. *Inherit* (**source-subclass**, **source-superclass**)

The *Inherit* operator builds the IS-A relationship between **source-subclass** and **source-superclass**. The **source-superclass** is built as the superclass of the **source-subclass**. Two corresponding virtual classes are produced in the global schema.

Note that the database name is appended to the class names for the purpose of identification if the same class names exist in different component databases.

The *integration rules* provided in [18] comprise the major part that guides the schema integrator as it performs schema integration. The process guided by the integration rules resolves conflicts among the attributes or class-hierarchies of the component schemas. After that, the semantics-related classes in different component schemas are integrated into virtual classes in the global schema.

3. A MAPPING STRATEGY

3.1 Mapping Equation

Attributes and object instances are the major components of a class. Thus, the mapping information should include the mappings of attributes and object instances between a virtual class and the classes in the component schemas. *Attribute m_term* and *object m_term* represent the attributes and objects in a class, which are denoted by the class name with subscript “*a*” or “*o*,” respectively. For example, *attribute m_term* and *object m_term* for class **Student@DB1** shown in Fig. 3 are denoted as **Student@DB1_a** and **Student@DB1_o**, where **Student@DB1_a** = {*s_no*, *name*, *age*, . . . } and

Student@DB1_o contains all the objects belonging to **Student@DB1**. For each virtual class, the *m_terms* denote the virtual attributes and virtual objects in this virtual class. Therefore, the *m_terms* of virtual classes are called *virtual m_terms*. On the other hand, the classes existing in the component databases are called *actual classes*, whose *m_terms* are called *actual m_terms*.

In the process of schema integration, virtual classes are produced after each integration operation. A *mapping equation* is used to represent the mapping between a virtual class and its constituent classes. The left-hand side of a *mapping equation* is an *m_term* of the virtual class. The right-hand side is a *mapping expression*, which consists of a sequence of *m_terms*, for the constituent classes, connected by *mapping operators*. The *mapping operators* are used to perform different kinds of combining operations among *m_terms*.

In a mapping expression, in addition to the actual *m_terms* and virtual *m_terms*, another kind of *m_term* called a *derived attributes* may appear. A derived attribute is a virtual attribute which is added to a class after class restructuring operations are performed; examples are *new-attribute* in the *Refine* operator, *new-name* in the *Rename* operator, and *new-complex-attribute* in the *Aggregate* operator. A derived attribute *a'* associates with a *deriving function* (enclosed in a pair of square brackets), which is used to represent the value or the source of the derived attribute. There are five deriving functions, as discussed in the following.

- $a' [= c]$: *c* is a constant value. The notation denotes the constant value assigned to the *refined* attribute *a'*.
- $a' [a]$: *a* is an attribute name which denotes the old name for the *renamed* attribute *a'*.
- $a' [a_1, a_2, \dots, a_n]$: A set of primitive attributes are listed, which denote the source attributes for the complex attribute *a'* produced by the *Aggregate* operation.
- $a' [(D.a)]$: *a* is an attribute in class **D**. The notation represents the source of an attribute *a'*, which is the inverse of *a* and is produced by the *Invert* operation.
- $a' [C1.a' = d1, C2.a' = d2, \dots, Cn.a' = dn]$: **C1** to **Cn** are class names, and *d1* to *dn* are constant values. The notation denotes the values of the division characteristic attribute *a'* when it is added due to the *Demolish* operation.

According to the kinds of operands they have, mapping operators are classified as *attribute mapping operators* or *object mapping operators* as shown in Table 1. Four attribute mapping operators can be performed on attribute *m_terms*. Those attributes having the same semantics in different component schemas [24] are assumed to be the same. Alternately, eight object mapping operators are operated on object *m_terms*. In particular, π is applied to retrieve the data of the virtual objects in the *new-domain-class* for the *Aggregate* operation. Therefore, each of projection result is considered a virtual object and assigned a *virtual Oid*. For operations on \cup_o , \cap_o and $-_o$, isomeric objects should be treated as the same object. In addition, $X \uplus_o Y$ means that the objects represented by *X* inherit the information from the objects represented by *Y*.

Among these mapping operators, \cup_a , \cap_a , \cup_o , \cap_o , $-_o$, and \uplus_o are for the *m_terms* whose corresponding classes come from different component schemas. Therefore, they are called *external mapping operators*. The other mapping operators are called *internal mapping operators*.

Table 1. The mapping operators.

Mapping operators	Semantics
attribute mapping operators	
\cup	Perform <i>set-union</i> on two sets of attributes defined in the same component schema.
$-$	Perform <i>set-difference</i> on two sets of attributes defined in the same component schema.
\cup_a	Perform <i>set-union</i> on two sets of attributes defined in different component schema.
\cap	Perform <i>set-intersection</i> on two sets of attributes defined in different component schema.
object mapping operators	
σ	Perform <i>selection</i> on a set of objects represented by an object m-term
π	Perform <i>projection</i> on a set of objects represented by an object m term.
\cup	Perform <i>set-union</i> on two sets of objects in the same component database.
$-$	Perform <i>set-difference</i> on two sets of objects in the same component database.
\cup_o	Perform <i>set-union</i> on two sets of objects in different component databases.
\cap_o	Perform <i>set-intersection</i> on two sets of objects in different component databases.
$-_o$	Perform <i>set-difference</i> on two sets of objects in different component databases
\uplus_o	Perform on two sets of objects in different component databases. The result of $X \uplus_o Y$ contains the objects in X . Moreover, if the objects represented by X have isomeric objects represented by Y , then the objects in X will contain the additional information in their isomeric objects.

The formal definition of the mapping equation is given as follows:

Attribute mapping equation:

$$\langle \text{vir-att-m_term} \rangle = \langle \text{a-m_expression} \rangle,$$

where the left-hand side is a virtual attribute m_term. In addition, the right-hand side, $\langle \text{a-m_expression} \rangle$, is an *attribute mapping expression* which is a sequence of attribute m_terms connected by attribute mapping operators. All the attribute mapping operators are left-associative and have the same precedence. However, parentheses can be used to force grouping. $\langle \text{vir-att-m_term} \rangle$ and $\langle \text{a-m_expression} \rangle$ are defined by a BNF grammar as shown below. The notations contained in $\langle \rangle$ are nonterminal symbols, and the others are terminal symbols:

$$\begin{aligned}
\langle a\text{-}m\text{-}expression \rangle &\rightarrow \langle a\text{-}m\text{-}expression \rangle | \langle a\text{-}m\text{-}expression \rangle \langle a\text{-}m\text{-}op \rangle \langle a\text{-}m\text{-}term \rangle \\
\langle a\text{-}m\text{-}term \rangle &\rightarrow \langle der\text{-}att\text{-}m\text{-}term \rangle | \langle act\text{-}att\text{-}m\text{-}term \rangle | \\
&\quad \langle vir\text{-}att\text{-}m\text{-}term \rangle | (\langle a\text{-}m\text{-}expression \rangle) \\
\langle der\text{-}att\text{-}m\text{-}term \rangle &\rightarrow \textit{derived-attribute} [\textit{deriving-function}] \\
\langle act\text{-}att\text{-}m\text{-}term \rangle &\rightarrow \mathbf{actual-class-name}_a \\
\langle vir\text{-}att\text{-}m\text{-}term \rangle &\rightarrow \mathbf{virtual-class-name}_a \\
\langle a\text{-}m\text{-}op \rangle &\rightarrow \cup | - | \cup_a | \cap_a.
\end{aligned}$$

Object mapping equation:

$$\langle vir\text{-}obj\text{-}m\text{-}term \rangle = \langle o\text{-}m\text{-}expression \rangle,$$

where the left-hand side is a virtual object m_term. The right-hand side, $\langle o\text{-}m\text{-}expression \rangle$, is an *object mapping expression* which is a sequence of object m_terms connected by object mapping operators. The unary object mapping operators, σ and π , have higher precedence than the binary object mapping operators. In addition, the unary operators are right-associative and have the same precedence. The binary operators are left-associative and have the same precedence. Furthermore, parentheses can also be used to force grouping. $\langle vir\text{-}obj\text{-}m\text{-}term \rangle$ and $\langle o\text{-}m\text{-}expression \rangle$ are defined by a BNF as follows:

$$\begin{aligned}
\langle o\text{-}m\text{-}expression \rangle &\rightarrow \langle o\text{-}m\text{-}factor \rangle | \langle o\text{-}m\text{-}expression \rangle \langle o\text{-}m\text{-}op2 \rangle \langle o\text{-}m\text{-}factor \rangle \\
\langle o\text{-}m\text{-}factor \rangle &\rightarrow \langle o\text{-}m\text{-}term \rangle | \langle o\text{-}m\text{-}op1 \rangle \langle o\text{-}m\text{-}term \rangle \\
\langle o\text{-}m\text{-}term \rangle &\rightarrow \langle act\text{-}obj\text{-}m\text{-}term \rangle | \langle vir\text{-}obj\text{-}m\text{-}term \rangle | \\
&\quad (\langle o\text{-}m\text{-}expression \rangle | \phi \\
\langle act\text{-}obj\text{-}m\text{-}term \rangle &\rightarrow \mathbf{actual-class-name}_o \\
\langle vir\text{-}obj\text{-}m\text{-}term \rangle &\rightarrow \mathbf{virtual-class-name}_o \\
\langle o\text{-}m\text{-}op1 \rangle &\rightarrow \sigma | \pi \\
\langle o\text{-}m\text{-}op2 \rangle &\rightarrow \cup | - | \cup_o | \cap_o | -_o | \cup_o.
\end{aligned}$$

The situation $\langle o\text{-}m\text{-}term \rangle \rightarrow \phi$ will be explained in the next subsection.

Consider a mapping equation, in which each virtual m_term on the right-hand side can be replaced by the right-hand side of its corresponding mapping equation enclosed in a pair of parentheses. After a sequence of replacements, we can get a mapping equation with a virtual m_term on the left-hand side and only actual m_terms, derived attributes, or ϕ on the right-hand side. This means that we can get an equation to denote the mapping between a virtual class and the actual classes in a component database.

Some useful properties among the internal object mapping operators σ , π , $-$, and \cup are described in the following. These properties can be used for query transformation in query processing.

- The commutativity and associativity properties of \cup
 - P1:** $m_exp_i \cup m_exp_j = m_exp_j \cup m_exp_i$;
 - P2:** $(m_exp_i \cup m_exp_j) \cup m_exp_k = m_exp_i \cup (m_exp_j \cup m_exp_k)$.
- The distributivity property among \cup , σ , π , and $-$

- P3:** $\sigma_p(m_exp_i \cup m_exp_j) = (\sigma_p m_exp_i) \cup (\sigma_p m_exp_j)$;
- P4:** $\pi_s(m_exp_i \cup m_exp_j) = (\pi_s m_exp_i) \cup (\pi_s m_exp_j)$;
- P5:** $(m_exp_i \cup m_exp_j) - m_exp_k = (m_exp_i - m_exp_k) \cup (m_exp_j - m_exp_k)$;
- P6:** $\sigma_p(m_exp_i - m_exp_j) = (\sigma_p m_exp_i) - (\sigma_p m_exp_j)$;
- P7:** $\pi_s(m_exp_i - m_exp_j) = (\pi_s m_exp_i) - (\pi_s m_exp_j)$.

- An equivalence for degrading the $-$ operation to σ operation

P8: $m_exp_i - (\sigma_p m_exp_i) = \sigma_p^- m_exp_i$

- Other equivalences among the internal object mapping operators

P9: $m_exp_k - (m_exp_i \cup m_exp_j) = m_exp_k - m_exp_i - m_exp_j$;

P10: $(m_exp_i - m_exp_j) \cup m_exp_k = (m_exp_i \cup m_exp_k) - m_exp_j$;

P11: $\sigma_p(\pi_s m_exp_i) = \pi_s(\sigma_p m_exp_i)$.

m_exp_i , m_exp_j and m_exp_k shown above denote object mapping expressions which only consist of internal object mapping operations.

3.2 Mapping Equations for Integration Operators

For an integration operator, the mappings between the produced virtual classes and their constituent classes can be represented by mapping equations. The m_term of each produced virtual class appears on the left-hand side of a mapping equation, with the right-hand side being a mapping expression which consists of the m_terms of the operands involved in the operator. In the following, we will introduce mapping equations for the virtual classes produced after each integration operation.

Class restructuring operators:

- $C' = Refine(C.a', c)$

Class C is *refined* by an attribute a with a constant value c in order to get a virtual class C' . The m_terms of C' are

$$C'_a = C_a \cup \{a' [= c]\}, \quad C'_o = C_o.$$

- $C' = Hide(C.a)$

The attribute a in class C is *hidden* in order to get a virtual class C' . The m_terms of C' are

$$C'_a = C_a - \{a\}, \quad C'_o = C_o.$$

- $C' = Rename(C, C')$

The Class C is *renamed* in order to get a virtual class C' . The m_terms of C' are

$$C'_a = C_a, \quad C'_o = C_o.$$

- $C' = Rename(C.a, a')$

The attribute a in class \mathbf{C} is *renamed* to a' in order to get a virtual class \mathbf{C}' . The m_terms of \mathbf{C}' are

$$\mathbf{C}'_a = \mathbf{C}_a \cup \{a'[a]\} - \{a\}, \quad \mathbf{C}'_o = \mathbf{C}_o.$$

- $\mathbf{C}' = \text{Aggregate}(\mathbf{C}, \{a_1, a_2, \dots, a_n\}, a', \mathbf{A})$

The set of primitive attributes $\{a_1, a_2, \dots, a_n\}$ in class \mathbf{C} are *aggregated* to obtain a complex attribute a' , which results in a virtual class \mathbf{C}' . A new virtual class \mathbf{A} is created in order to get the domain class of a' . Since the added attribute a' should be inherited by the subclasses in the class hierarchy H rooted in \mathbf{C} , the virtual class \mathbf{A} should contain the virtual objects from the projection on $\{a_1, a_2, \dots, a_n\}$ on the objects in H . To each object in the result of the project on $\{a_1, a_2, \dots, a_n\}$ is assigned a virtual *OID*. Such a virtual *OID* is useful when processing queries against the virtual class \mathbf{A} . Assuming that classes $\mathbf{C1}$ to \mathbf{Cn} are the subclasses in the class hierarchy rooted in class \mathbf{C} , the m_terms of \mathbf{C}' and \mathbf{A} are

$$\begin{aligned} \mathbf{C}'_a &= \mathbf{C}_a \cup \{a'[\{a_1, a_2, \dots, a_n\}]\} - \{a_1, a_2, \dots, a_n\}, & \mathbf{C}'_o &= \mathbf{C}_o, \\ \mathbf{A}_a &= \{a_1, a_2, \dots, a_n\}, & \mathbf{A}_o &= \pi_{a_1, a_2, \dots, a_n}(\mathbf{C}_o \cup \mathbf{C1}_o \cup \dots \cup \mathbf{Cn}_o). \end{aligned}$$

- $\mathbf{C}' = \text{Invert}(\mathbf{C}, \mathbf{D}.a, a')$

The attribute a' is added to class \mathbf{C} , where a' is the inverse of attribute a , in order to get a virtual class \mathbf{C}' . The m_terms of \mathbf{C}' are

$$\mathbf{C}'_a = \mathbf{C}_a \cup \{a'[(\mathbf{D}.a)]\}, \quad \mathbf{C}'_o = \mathbf{C}_o.$$

- $\mathbf{C}' = \text{Demolish}(\mathbf{C})$

The subclasses of class \mathbf{C} are demolished in order to get a virtual class \mathbf{C}' . Assume that classes $\mathbf{C1}$ to \mathbf{Cn} are the subclasses of \mathbf{C} , that a' is the division characteristic of \mathbf{C} , and that $d1$ to dn are the values assigned to a' for the objects in $\mathbf{C1}$ to \mathbf{Cn} , respectively. The m_terms of \mathbf{C}' are

$$\begin{aligned} \mathbf{C}'_a &= \mathbf{C}_a \cup \mathbf{C1}_a \cup \mathbf{C2}_a \cup \dots \cup \mathbf{Cn}_a \cup \{a'[\mathbf{C1}.a' = d1, \mathbf{C2}.a' = d2, \dots, \mathbf{Cn}.a' = dn]\}, \\ \mathbf{C}'_o &= \mathbf{C}_o \cup \mathbf{C1}_o \cup \mathbf{C2}_o \cup \dots \cup \mathbf{Cn}_o. \end{aligned}$$

- $\mathbf{C}' = \text{Build}(\mathbf{C}, \text{Sub}_\mathbf{C}, p)$

A new virtual class $\text{Sub}_\mathbf{C}$ is created from \mathbf{C} , in which all the virtual objects satisfy the predicate p . Furthermore, another virtual class \mathbf{C}' corresponding to \mathbf{C} is created. The m_terms of $\text{Sub}_\mathbf{C}$ and \mathbf{C}' are

$$\begin{aligned} \mathbf{C}'_a &= \mathbf{C}_a, & \mathbf{C}'_o &= \mathbf{C}_o - (\sigma_p \mathbf{C}_o), \\ \text{Sub}_\mathbf{C}_a &= \mathbf{C}_a, & \text{Sub}_\mathbf{C}_o &= \sigma_p \mathbf{C}_o. \end{aligned}$$

By observing the object mapping equations for class restructuring operators, the following properties can be found.

P12: \cup is the only object mapping operator used to combine different object m_terms as shown in the object mapping equations for *Aggregate* and *Demolish* operators.

P13: The object mapping operator $-$ is only used in the mapping equation for class C' produced in the *Build* operator.

These properties will be used in the next section in strategies for global query processing.

Class integration operators:

• *OUnion(C1, C2, GC)*

Class $C1$ and $C2$ are *ouioned*. Only a virtual class GC is created. The m_terms of GC are

$$GC_a = C1_a \cup_a C2_a, \quad GC_o = C1_o \cup_o C2_o.$$

• *Generalize(C1, C2, Super_C)*

Class $C1$ and $C2$ are *generalized* in order to produce a virtual class $Super_C$ as their common subclass. In addition, two virtual classes $C1'$ and $C2'$ are created, corresponding to classes $C1$ and $C2$, respectively. The m_terms of $C1'$, $C2'$ and $Super_C$ are

$$\begin{aligned} Super_C_a &= C1_a \cap_a C2_a, & Super_C_o &= \phi, \\ C1'_a &= C1_a, & C1'_o &= C1_o, \\ C2'_a &= C2_a, & C2'_o &= C2_o. \end{aligned}$$

ϕ denotes an empty object set. According to the inheritance model adopted in this paper, class $Super_C$ contains objects which do not belong to class $C1'$ or $C2'$. Thus, to the object m_term of $Super_C$ is assigned ϕ .

• *Specialize(C1, C2, Sub_C)*

Class $C1$ and $C2$ are *specialized* in order to produce a virtual class Sub_C as their common subclass. In addition, two virtual classes $C1'$ and $C2'$ are created, corresponding to classes $C1$ and $C2$, respectively. The m_terms of $C1'$, $C2'$ and Sub_C are

$$\begin{aligned} Sub_C_a &= C1_a \cup_a C2_a, & Sub_C_o &= C1_o \cap_o C2_o, \\ C1'_a &= C1_a, & C1'_o &= C1_o -_o Sub_C_o, \\ C2'_a &= C2_a, & C2'_o &= C2_o -_o Sub_C_o. \end{aligned}$$

• *Inherit(C1, C2)*

Class $C1$ is specified as a subclass of class $C2$, and the attributes of $C2$ are *inherited* by $C1$. Two $C1'$ and $C2'$ are created, corresponding to classes $C1$ and $C2$, respectively, where $C2'$ is the superclass of $C1'$. The m_terms of $C1'$, $C2'$ are

$$\mathbf{C1}'_a = \mathbf{C1}_a \cup_a \mathbf{C2}_a,$$

$$\mathbf{C1}'_o = \mathbf{C1}_o \uplus_o \mathbf{C2}_o,$$

$$\mathbf{C2}'_a = \mathbf{C2}_a,$$

$$\mathbf{C2}'_o = \mathbf{C2}_o -_o \mathbf{C1}_o.$$

If the objects in $\mathbf{C1}$ have isomeric objects in $\mathbf{C2}$, then the values of the newly inherited attributes from $\mathbf{C2}$ are taken from $\mathbf{C2}$ and integrated in $\mathbf{C1}'$. The inherited attributes are filled with null values for the other objects in $\mathbf{C1}'$.

Note that the mapping equations for the virtual classes created by the class restructuring operators only contain the internal mapping operators. Similarly, for the class integration operators, the mapping equations for the created virtual classes only contain the external mapping operators. These properties will be used in the next subsection.

3.3 Mapping Graph

Each virtual m_term can be transformed into a mapping expression exp_m which is a sequence of actual m_terms or derived attributes connected by mapping operators. The exp_m can be represented by a *mapping graph*. The mapping graph is similar to the expression *DAG* (directed acyclic graph) used in a compiler [25]. It is a generalized binary tree structure in which a node may have more than one parent. Any node that has no child nodes is a *terminal node*; the terminal nodes in a mapping graph are actual m_terms or derived attributes. The nodes which are not terminal nodes are called *non-terminal* node N can be labeled with a virtual m_term m ; this indicates that the expression represented by N is the mapping expression for m . Among the nonterminal nodes, any node which has no parent node is a root node.

For each global class, an object mapping graph and an attribute mapping graph are constructed. The root nodes in the mapping graphs are labeled using the m_terms of the global class. The mapping graphs of a virtual class \mathbf{C}_v which is produced in the integration process are subgraphs rooted in the nonterminal nodes labeled using the m_terms of \mathbf{C}_v .

According to the integration rules proposed in [18] and the properties stated in section 3.2, the internal mapping operators are performed before the external mapping operators in a mapping expression. Thus, nodes representing internal mapping operators will be located below the nodes representing external mapping operators in a mapping graph.

3.4 Example

We will consider here the previous example shown in Fig. 3 to explain the mapping strategy. The two component schemas are integrated using the class restructuring and class integration operators as follows. Those classes whose names begin with **V-** are the virtual classes produced in the integration process, and those whose names begin with **G-** are the final global virtual classes.

1. Integrate **Student@DB1**, **Student@DB2** and their subclasses:

V-S1 = *Demolish* (**Student@DB1**);

V-S2 = *Invert* (**V-S1**, **Motorcycle@DB1.owner, vehicle**);

V-S3 = *Aggregate* (**V-S2**.{*b-type*}, *blood-type*, **V-B1**);

- V-S4** = Refine (**V-S3.school**, "NTHU");
V-S5 = Build (**V-S4, V-CS-S1**, "department=CS");
V-S6 = Build (**V-S5, V-EE-S1**, "department=EE");
V-S1' = Aggregate (**Student@DB2**, {city, street, no}, address, **V-A1'**);
V-S2' = Rename (**V-S1'.stu-no**, s-no);
V-S3' = Refine (**V-S2'.school**, "NCTU");
OUnion (**V-S6, V-S3', G-Student**);
OUnion (**V-CS-S1, CS-Student@DB2, G-CS-Student**);
OUnion (**V-EE-S1, EE-Student@DB2, G-EE-Student**);
OUnion (**Address@DB1, V-A1', G-Address**);
V-B1' = Rename (**Blood@DB2.type**, b-type);
OUnion (**V-B1, V-B1', G-Blood-type**).
 2. Integrate **Motorcycle@DB1** and **Motorcycle@DB2**:
V-M1' = Invert (**Motorcycle@DB2, Student@DB2.vehicle, owner**);
V-M2' = Rename (**V-M1', car-no, license-no**);
OUnion (**Motorcycle@DB1, V-M2', G-Motorcycle**).

The constructed global schema is shown in Fig. 6. Furthermore, the m_terms of **V-S6** and **V-S3'** are those listed below:

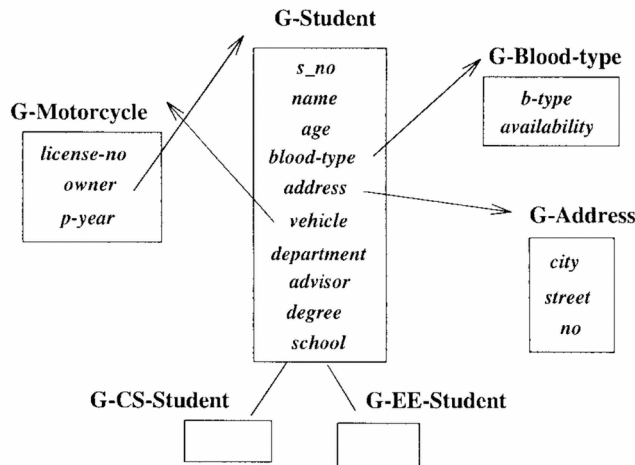


Fig. 6. The constructed global schema.

- V-S6_o** = (**Student@DB1_o ∪ Graduate@DB1_o ∪ Undergraduate@DB1_o**)
 - $\sigma_{\text{department=CS}}$ (**Student@DB1_o ∪ Graduate@DB1_o ∪ Undergraduate@DB1_o**)
 - $\sigma_{\text{department=EE}}$ ((**Student@DB1_o ∪ Graduate@DB1_o ∪ Undergraduate@DB1_o**)
 - $\sigma_{\text{department=CS}}$ (**Student@DB1_o ∪ Graduate@DB1_o ∪ Undergraduate@DB1_o**)).
V-S6_a = (**Student@DB1_a ∪ Graduate@DB1_a ∪ Undergraduate@DB1_a**)
 ∪ {degree [**Graduate.degree** = graduate, **Undergraduate.degree** = undergraduate]}
 ∪ {vehicle [(**Motorcycle@DB1.owner**)]} ∪ {blood-type [{b-type}]} - {b-type}

$$\cup \{school [=NTHU]\}.$$

$$\mathbf{V-S3}'_o = \mathbf{Student@DB2}_o.$$

$$\mathbf{V-S3}'_a = \mathbf{Student@DB2}_a \cup \{address [\{city, street, no\}] - \{city, street, no\} \cup \{s-no [stu-no]\} - \{stu-no\} \cup \{school [=NCTU]\}.$$

The mapping graphs for the virtual class **G-Student** constructed in the global schema are shown in Fig. 7. Note that the parentheses around the mapping expressions are not shown in the mapping graphs because the precedence of each operator is represented by the tree structure.

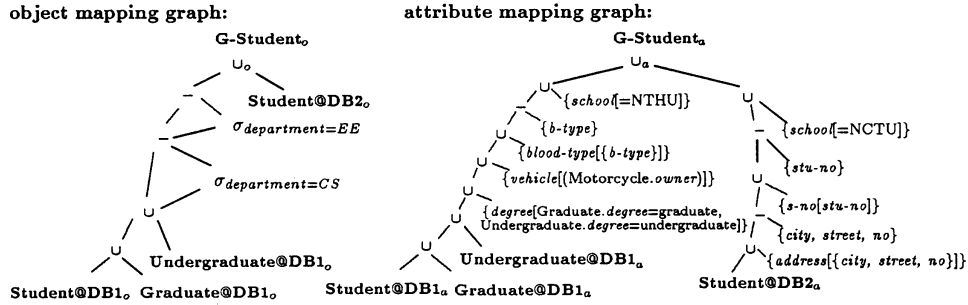


Fig. 7. The mapping graphs for class **G-Student**.

4. GLOBAL QUERY PROCESSING

In this section, we will discuss strategies for processing global queries against the global schema, which include decomposing a global query into executable subqueries for local DBMSs and integrating the results of these subqueries. The format of global queries is similar to that used in XSQL [22]. A query consists of three parts: *Select*, *From* and *Where* clauses as shown below:

Select <target attributes>,
From <range classes>,
Where <predicate clause>,

where the *predicate clause* is assumed to be in conjunctive form.

We will discuss global query processing based on the assumption that the result of a query is represented as a table with attribute *Oid* and the complex attribute storing the *Oid* values of the associated objects. Some query processing may need to join the complex attribute with the *Oid* attribute of another class, and some may need to join the *Oid* attributes of two classes. Data inconsistencies among component databases will not be discussed in this paper.

4.1 The Flow of Global Query Processing

The flow of global query processing is shown in Fig. 8. There are four main processing units, which are depicted by ellipses. There is one *query decomposer*, one *result integrator*, and a pair of consisting of a *local preprocessor* and *local postprocessor* for each local DBMS. The bold lines with arrows show the flow of the query and the result.

First, the global query against the global object schema is sent to the *query decomposer*. The query decomposer is responsible for checking if the global query needs to be decomposed into several subqueries, each against a single component database. Then, the subqueries are sent to the *local preprocessors* of the corresponding local DBMSs. The range class in the query sent to the local preprocessor may be a virtual class constructed from more than one actual class. In this situation, the local preprocessor needs to further decompose the query into subqueries whose *From* clauses contain a single actual class. Moreover, it has to process the derived attributes in the *Select* and *Where* clauses in order to produce executable queries for the local DBMS. The *local postprocessor* has to integrate the results of the subqueries which are produced by the local preprocessor. Before the result is returned to the result integrator, the derived attributes appearing in the *Select* clause whose values cannot be obtained from the local DBMS should be processed. Finally, the result integrator integrates the results from the local postprocessors to get the final result.

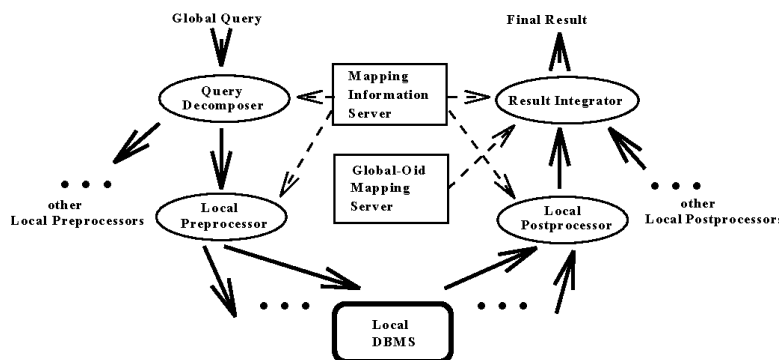


Fig. 8. The flow of global query processing.

In addition to the processing units, two auxiliary units are provided, which are depicted by rectangles. The *mapping information server* stores the mapping graph for each virtual class in the global schema. The mapping and the type or scale conversion functions for attributes having the same semantics in different component schemas are also provided. Moreover, function $V_to_O()$ is used to assign an associated virtual *Oid* to the result of a projection. The *Global-Oid mapping server* manages the *GOid mapping table*. Function $L_to_G()$ is used to find the corresponding *GOid* of an object when an *Oid* is specified. The dashed lines with arrows show the auxiliary units used by the processing units.

4.2 Strategies for Global Query Processing

The details of the four main processing units will be introduced in this subsection. However, due to page limitations, for detailed algorithms, please refer to [26].

4.2.1 Query decomposer

The tasks involved in query decomposition are divided into two phases: **QD_1** and **QD_2**. In phase **QD_1**, if more than one range class is specified in the *From* clause for *explicit joins* [27], the global query should be decomposed into subqueries, each containing a single range class. Moreover, a modified global query for processing explicit joins on the results of the subqueries needs to be constructed. After phase **QD_1** is completed, although only one range class is contained in each subquery, the range class may be a virtual class consisting of actual or virtual classes in different component schemas. Therefore, the task of phase **QD_2** is to check the object mapping graph of the range class for each subquery produced during phase **QD_1** and to perform further decomposition if possible. After the query decomposer finishes its work, the range class of each resultant subquery should be an actual or virtual class located in a single component databases. Then, the subqueries are sent to the *local preprocessors* of the corresponding local DBMSs.

Phase QD_1:

If only one range class is specified in the *From* clause of the global query, then phase **QD_1** is skipped, and the global query is passed on to be processed in phase **QD_2**. Otherwise, suppose there are n range classes. Let each range class be denoted by R_i , $1 \leq i \leq n$. For each R_i , P_i denotes its associated predicates in the *Where* clause, which connected by **and**, and S_i denotes its associated target attributes. In addition, the predicates for processing explicit joins are called *explicit join predicates*. The attributes belonging to R_i and appearing in explicit join predicates are denoted by J_i . Then, the global query is decomposed into n subqueries. The i th subquery is shown as follows, where $1 \leq i \leq n$:

```
Select  Si, Ji,
From    Ri,
Where   Pi.
```

Moreover, the global query is modified to obtain the following, where t_i denotes the table for storing the result of the i th subquery:

```
Select  S1, S2, ..., Sn,
From    t1, t2, ..., tn,
Where   explicit join predicates.
```

The modified global query is sent to the result integrator and will be used to integrate the results of the subqueries.

Phase QD_2:

Suppose the subquery produced during phase **QD_1** is denoted as:

```

Select  S,
From    R,
Where   P.

```

Then the object mapping graph of **R** is traversed from its root. When an external object mapping operator is visited, we know that **R** is created by integrating two actual or virtual classes from different component databases. Let **LC_o** and **RC_o** denote the left and right operands of the external mapping operator, respectively. Two subqueries are then constructed as follows:

```

Select  S,          Select  S,
From    LC,        From    RC,
Where   P,          Where   P.

```

The results of these two subqueries are then integrated in the result integrator to obtain the result of the original query. The subqueries are further decomposed by calling algorithm **QD_2** recursively until no external mapping operator can be visited. That is, each From clause in the newly constructed subqueries contains an actual class or a virtual class defined in a single component database. These subqueries are sent to the local preprocessor of the associated component database.

4.2.2 Local preprocessor

The range class of the subquery sent to a local preprocessor is an actual class or a virtual class produced by the class restructuring operations. If the range class is a virtual class constructed from more than one actual class, the local preprocessor has to further perform a subquery on each actual class. Moreover, it has to process the derived attributes in the *Select* and *Where* clauses in order to produce executable queries for the local DBMS. These queries are then sent to the underlying local DBMS for execution. The tasks of the local preprocessor are performed in the three phases described below.

Phase **LPR_1**:

Let the query sent to phase **LPR_1** be denoted as:

```

Select  S,
From    C,
Where   P.

```

The object mapping subgraph rooted in the *m_tern* if **C** is checked. The object mapping expression represented by the mapping subgraph is a sequence of internal object mapping operations composed of \cup , σ , π , and/or $-$ operations.

According to property **P13**, the only situation in which the internal object mapping operator $-$ appears in our mapping model is that shown on the left hand side of property **P8** (produced after a *Build* operation). Therefore, all the $-$ operations in the mapping expression can be degraded to σ operations according to property **P8**.

From property **P12**, if there is a sequence of \cup operations in the resultant expression, then the range class **C** must have been constructed from more than one actual class. According to **P3** and **P4**, the mapping expression is transformed into a sequence of subexpressions linked by the \cup operator. Each subexpression contains a single actual m_term corresponding to a terminal node. The resultant subexpression is, thus, only composed of σ and/or π operations. A subquery is then constructed for each subexpression.

Suppose the i th subexpression is denoted as $\pi_{s_{i_1}, s_{i_2}, \dots, s_{i_m}} \sigma_{p_{i_1}} \sigma_{p_{i_2}} \dots \sigma_{p_{i_k}} \mathbf{C}_i$. \mathbf{C}_i is specified as the range class, which is the associated actual class of \mathbf{C}_o . p_{i_1}, p_{i_2}, \dots , and p_{i_k} are added to the *Where* clause as predicates and are combined with boolean **and** operations. As mentioned previously, π is used to retrieve the virtual objects produced after the *Aggregate* operation. Therefore, $s_{i_1}, s_{i_2}, \dots, s_{i_m}$ are added to the target attributes for retrieval of values from the underlying DBMS. The constructed subquery for the i th subexpression is

```

Select      S, si1, si2, ..., sim,
From        Ci,
Where       P and pi1 and pi2 and ... and pik.

```

Phase LPR_2:

For each subquery produced in phase **LPR_1**, the *Select* and *Where* clauses need to be modified if different derived attributes are specified in the subquery. The derived attributes in the query are processed in phase **LPR_2**. Let the query submitted to phase **LPR_2** be called **q**. The derived attributes can be recognized by referring to the attributed mapping graph.

1. attribute a' is a *Refined* or *division characteristic* attribute

The value of attribute a' is the constant value in its deriving function. If a' appears in the *Where* clause of **q**, then let p' denote an associated predicate. Each p' is evaluated by checking its constant value:

- (1) If p' is true, then p' is removed from the predicate clause.
- (2) If p' is false, then the whole predicate clause is false no matter what the other predicates are. **q** is eliminated without the need for it to the result integrator. If a' is specified in the *Select* clause of **q**, then it is removed because its value is not retrievable from the underlying DBMS. Such value will be appended to the result in the postprocessor.

2. complex attribute a' produced by an *Invert* operation

For query **q**, let P denote the predicates, and let T denote the target attributes, which contain a nested attribute rooted at a' . Since a' is a virtual attribute, P and T cannot be processed directly by the local DBMS, so they are removed from **q**. Let attribute $\mathbf{D}.a$ be the inverse of a' (that is, the domain class of a' is \mathbf{D}). This implies that the nested attributes rooted at a' come from the attributes of \mathbf{D} . Therefore, an additional new subquery should be constructed on \mathbf{D} for retrieving T and evaluation P . Let P' and T' denote P and T , respectively, after the path expression " $a'.X$ " is replaced with X . The new subquery is

Select *T*, *a*,
From *D*,
Where *P*.

Not that *D.a* is retrieved such that the results of the new subquery and *q* can be integrated later. (In this case, the *Oid* of the range class of *q* must also be retrieved.)

3. attribute *a'* produced by an *Rename* operation

Let the deriving function of *a'* be [*a*]. The attribute *a'* should be replaced with the old name *a* when *a'* exists in the *Select* and/or the *Where* clause of *q*.

4. complex attribute *a'* produced by an *Aggregate* operation

The path expression *a'*. *a_i* is replaced with the primitive attribute *a_i*, where *a_i* is one of primitive attributes specified in the deriving function of *a'*. The replacement action is performed when *a'* exists in the *Select* and/or the *Where* clause of *q*.

Phase LPR_3:

The attributes of a global class are the union of the attributes belonging to its constituent classes. An attribute appearing in the global class may not be defined in a constituent class, in which case it is called a *missing attribute* of the constituent class [28]. Let the query passed to phase **LPR_3** be denoted by *q*. Predicates involving missing attributes of the range class are called *unsolved predicates*. The missing attributes and the unsolved predicates should be removed from the *Select* clause and the *Where* clause, respectively, since they cannot be processed by the underlying DBMS. If the missing attributes appear in the *Where* clause, the result of *q* will be marked with *maybe result* [29] because the unsolved predicates are not evaluated. Otherwise, the result will be *certain result*. The data for the isomeric objects need to be combined in the result integrator to provide complete information about the isomeric objects. Therefore, the *Oid* is also specified in the *Select* clause for integration of isomeric objects later. The maybe result of *q* may be changed into a *certain result* due to the integration of isomeric objects. In [30], we studied global query processing that involves missing attributes.

4.2.3 Local postprocessor

Suppose the results of queries sent from a local preprocessor to the local DBMS have been returned to the local postprocessor. There are two phases of tasks to be performed in the local postprocessor, and they are called **LPO_1** and **LPO_2**. Phase **LPO_1** is responsible to processing the results if the derived attributes appear in the associated queries. The results of the subqueries, which are constructed in phase **LPR_1**, are integrated in phase **LPO_2**.

Phase LPO_1:

Given a query result *r*, suppose its associated query is *q*. Further processing on *r* is needed in the following situations.

1. *q* has a subquery *q'* for processing the derived attribute *a'* generated by an *Invert* operation. Let the result of *q'* be denoted by *r'*. If *a'* appears in the *Where* clause of *q*, then *r* and *r'* will be joined over the join attributes *Oid* and *a*, respectively. If *a'* is

only specified in the *Select* clause of \mathbf{q} , then a *left outer join* from \mathbf{r} to \mathbf{r}' will be performed.

2. \mathbf{q} has target attributes which are *Refined* or *division characteristic* attributes. The values of these attributes cannot be retrieved from the local DBMSs. Therefore, the values obtained from the associated deriving function are appended to the result. It is necessary to convert the attribute values so that they are of the data type shown in the global schema when necessary.
3. \mathbf{q} has target attributes s_1, s_2, \dots, s_m as a result of the Aggregate operator that appears in phase **LPR_1**. For each result tuple which represents the value of a virtual object, the attribute values of s_1, s_2, \dots, s_m will be used by function **V_to_OO** to assign a virtual *Oid*. These *Oids* may be used to obtain further information from their isomeric objects.
4. If \mathbf{q} has unsolved predicates, then \mathbf{r} is marked with a maybe result. Otherwise, \mathbf{r} is a certain result.

Phase LPO_2:

The union operator is used to integrate the results of subqueries constructed in phase **LPR_1**. Then, the results are returned to the result integrator.

4.2.4 Result integrator

For integration of the results of subqueries produced by the query decomposer, there are two phases of processing in the result integrator. The first phase, phase **RI_1**, is responsible for integrating the results of subqueries constructed in phase **QD_2**. In addition, the second phase, called **RI_2**, executes the modified global query constructed in phase **QD_1**.

Phase RI_1:

Each object \mathbf{o} in the maybe result can be turned into a certain result if its isomeric objects satisfy the associated unsolved predicates. This situation can be stated by the following two conditions.

- (1) The missing attributes A_m involved in the query used to obtain \mathbf{o} exist in another component schema ξ .
- (2) The isomeric objects of \mathbf{o} are also in the result returned from the component database with schema ξ .

The maybe result is eliminated when the first condition is satisfied and when its isomeric objects exist but are not in the result of the subqueries. For more details about global query processing concerning missing attributes, please refer to [30].

The order for integrating the results of subqueries is the opposite of the order for constructing subqueries in phase **QD_2**. Let a query \mathbf{q}_{qd2} have two subqueries $\mathbf{q1}$ and $\mathbf{q2}$ constructed in phase **QD_2**. This implies that the range class of $\mathbf{q1}$ and $\mathbf{q2}$. \mathbf{O}_m is used to decide \mathbf{o} the best way to integrate the results of these two subqueries in order to obtain the result of \mathbf{q}_{qd2} . Let $\mathbf{cr1}$ and $\mathbf{cr2}$ denote the certain results of $\mathbf{q1}$ and $\mathbf{q2}$, respectively. In addition, $\mathbf{mr1}$ and $\mathbf{mr2}$ are used to denote the maybe results. In the following, different ways of integrating the results are presented. Note that the join attribute is the associated **GOid** of the *Oid* for the result.

- case1: $\mathbf{O}_m = \cup_o$
 $\langle \text{certain result} \rangle = \mathbf{cr1} \overset{o}{\bowtie} \mathbf{cr2}$,
 $\langle \text{maybe result} \rangle = \mathbf{mr1} \overset{o}{\bowtie} \mathbf{mr2}$,
 where $\overset{o}{\bowtie}$ is an *outer join*.
- case2: $\mathbf{O}_m = \cap_o$
 $\langle \text{certain result} \rangle = \mathbf{cr1} \bowtie \mathbf{cr2}$,
 $\langle \text{maybe result} \rangle = \mathbf{mr1} \bowtie \mathbf{mr2}$,
 where \bowtie is a *join*.
- case3: $\mathbf{O}_m = -_o$
 $\langle \text{certain result} \rangle = \mathbf{cr1} - (\mathbf{cr2} \bowtie \mathbf{cr2})$,
 $\langle \text{maybe result} \rangle = \mathbf{mr1} - (\mathbf{mr2} \bowtie \mathbf{mr2})$,
 where \bowtie is an *semijoin*.
- case4: $\mathbf{O}_m = \uplus_o$
 $\langle \text{certain result} \rangle = \mathbf{cr1} \overset{o}{\ltimes} \mathbf{cr2}$,
 $\langle \text{maybe result} \rangle = \mathbf{mr1} \overset{o}{\ltimes} \mathbf{mr2}$,
 where $\overset{o}{\ltimes}$ is a *left outer join*.

Phase RI_2:

If a modified global query was sent from phase **QD_1**, this modified global query is executed to get the final result.

4.3 Example

In the following, based on the global schema constructed in the previous example, a query is given to illustrate the procedure for global query processing. Consider query **Q**: “Retrieve the name, school, and the availability of the blood type of the graduate students living in Taipei, who are younger than 30 years old and whose motorcycles were produced after 1990.” **Q** is shown in Fig. 9(a).

When **Q** is processed by the global decompose, phase **QD_1** is skipped because no explicit join exists in **Q**. Phase **QD_2** examines the mapping graph of the range class **G-student**. The external mapping operator \cup_o appearing in the mapping graph shows that **G-student** is constructed from **V-S6** and **V-S3'**, which come from different component databases. Thus, **Q** is decomposed into **Q1** and **Q2** as shown in Fig. 9(b) and Fig. 9(c), and is sent to the preprocessors of **DB1** and **DB2**, respectively.

```

Q:  Select  name, school, blood-type.availability
      From    G-Student
      Where   degree = graduate    and age < 30
            and   address.city = Taipei
            and   vehicle.p-year > 1990
            (a)
  
```

Q1: *Select* *name, school, blood-type.availability*
From **V-S6**
Where *degree = graduate* **and** *age < 30*
and *address.city = Taipei*
and *vehicle.p-year > 1990*

(b)

Q2: *Select* *name, school, blood-type.availability*
From **V-S3'**
Where *degree = graduate* **and** *age < 30*
and *address.city = Taipei*
and *vehicle.p-year > 1990*

(c)

Q1-1: *Select* *name, school, blood-type.availability*
From **Student@DB1**
Where *degree = graduate* **and** *age < 30*
and *address.city = Taipei*
and *vehicle.p-year > 1990*
and *department ≠ CS*
and *department ≠ EE*

(d)

Q1-2: *Select* *name, school, blood-type.availability*
From **Graduate@DB1**
Where *degree = graduate* **and** *age < 30*
and *address.city = Taipei*
and *vehicle.p-year > 1990*
and *department ≠ CS*
and *department ≠ EE*

(e)

Q1-3: *Select* *name, school, blood-type.availability*
From **Undergraduate@DB1**
Where *degree = graduate* **and** *age < 30*
and *address.city = Taipei*
and *vehicle.p-year > 1990*
and *department ≠ CS*
and *department ≠ EE*

(f)

Fig. 9. The global query and the subqueries produced during processing.

Q1-2-1: *Select* *Oid, name*
From **Graduate@DB1**
Where *age < 30*
and *address.city = Taipei*
and *vehicle.p-year > 1990*
and *department ≠ CS*
and *department ≠ EE*

(g)

Q1-2-2: *Select* *owner*
From **Motorcycle@DB1**
Where *p-year > 1990*

(h)

Q2-1: *Select* *Oid, name, blood-type.availability*
From **Student@DB2**
Where *vehicle.p-year > 1990*
and *city = Taipei*

(i)

Fig. 9. (Cont'd) The global query and the subqueries produced during processing.

The preprocessor in **DB1** is responsible for processing **Q1**. From the \cup operations performed on **Student@DB1_o**, **Graduate@DB1_o**, and **Undergraduate@DB1_o** as shown in the object mapping graph, we know that **V-S6** is a virtual class consisting of three actual classes. Therefore, additional decomposition of **Q1** is needed in phase **LPR_1**. The object mapping expression which is used to represent the object m-term of **V-S6** requires some transformation to get a sequence of subexpressions connected by \cup operations as follows.

$$\begin{aligned}
 \mathbf{V-S6}_o &= (\mathbf{Student@DB1}_o \cup \mathbf{Graduate@DB1}_o \cup \mathbf{Undergraduate@DB1}_o) \\
 &- \sigma_{\text{department}=CS} (\mathbf{Student@DB1}_o \cup \mathbf{Graduate@DB1}_o \cup \mathbf{Undergraduate@DB1}_o); \\
 &- \sigma_{\text{department}=EE} ((\mathbf{Student@DB1}_o \cup \mathbf{Graduate@DB1}_o \cup \mathbf{Undergraduate@DB1}_o)); \\
 &- \sigma_{\text{department}=CS} (\mathbf{Student@DB1}_o \cup \mathbf{Graduate@DB1}_o \cup \mathbf{Undergraduate@DB1}_o). \\
 &= \sigma_{\text{department} \neq EE} ((\mathbf{Student@DB1}_o \cup \mathbf{Graduate@DB1}_o \cup \mathbf{Undergraduate@DB1}_o); \\
 &- \sigma_{\text{department}=CS} (\mathbf{Student@DB1}_o \cup \mathbf{Graduate@DB1}_o \cup \mathbf{Undergraduate@DB1}_o)); \\
 &= \sigma_{\text{department} \neq CS \text{ and } \text{department} \neq EE} (\mathbf{Student@DB1}_o \cup \mathbf{Graduate@DB1}_o \cup \mathbf{Undergraduate@DB1}_o); \\
 &= \sigma_{\text{department} \neq CS \text{ and } \text{department} \neq EE} \mathbf{Student@DB1}_o) \\
 &\cup (\sigma_{\text{department} \neq CS \text{ and } \text{department} \neq EE} \mathbf{Graduate@DB1}_o) \\
 &\cup (\sigma_{\text{department} \neq CS \text{ and } \text{department} \neq EE} \mathbf{Undergraduate@DB1}_o).
 \end{aligned}$$

Then, the three subqueries **Q1-1**, **Q1-2**, and **Q1-3** against classes **Student@DB1**, **Graduate@DB1** and **Undergraduate@DB1** can be constructed as shown in Figs. 9(d), 9(e), and 9(f), respectively. In phase **LPR_2**, the derived attributes in the *Select* and *Where* clauses are then considered. In order to process a predicate involving the *division characteristic* attribute *degree*, the value in the deriving function is checked. **Q1-1**

and **Q1-3** can, thus, be eliminated, and the predicate “*degree = graduate*” in **Q1-2** is true and can be removed. The *refined* attribute *school* in the *Select* clause is also removed because its value will be appended to the result in the postprocessor. A new subquery **Q1-2-2** is constructed against **Motorcycle@DB1** as shown in Fig. 9(h) so that the predicate on the derived attribute *vehicle.p-year* can be processed. Then, the predicate for *vehicle.p-year* is removed from **Q1-2**. Finally, the target attribute *blood-type.availability*, which is a missing attribute, is removed from **Q1-2** in phase **LPR_3**. In addition, *Oid* should be appended to the *Select* clause in **Q1-2** for further result integration. **Q1-2** is modified to obtain **Q1-2-1** as shown in Fig. 9(g). Both **Q1-2-1** and **Q1-2-2** are submitted to **DB1** for execution.

Now, we will consider local preprocessing for **Q2**. **V-S3'** is constructed from only one actual class **Student@DB2**. Thus, no further decomposition is needed in phase **LPR_1**. Only the range class is replaced with **Student@DB2**. In phase **LPR_2**, the *refined* attribute *school* is removed from **Q2**. Then, the path expression *address.city* which is produced from the *Aggregate* operation is replaced with *city*. The predicates for the missing attributes *degree* and *age* in **Q2** are removed in phase **LPR_3** because they are not defined in **Student@DB2**. Moreover, the result of **Q2** is marked with a maybe result. Finally, *Oid* also needs to be added to the *Select* clause. **Q2** is modified to obtain **Q2-1** as shown in Fig. 9(i) and is submitted to **DB2** for execution.

After the subqueries sent to the local DBMSs are executed, the results are sent back to the corresponding postprocessors. The postprocessor of **DB1** joins the results of **Q1-2-1** and **Q1-2-2** over the joining attributes *Oid* and *owner* in phase **LPO_1** to get the results of **Q1-2**. Then, the constant value “NTHU” for the attribute *school* and null values for the missing attribute *blood-type.availability* are appended to the results of **Q1-2**. Since the results of **Q1-1** and **Q1-3** are empty sets, the results of **Q1** are the results of **Q1-2** after the processing of phase **LPO_2**. Similarly, the postprocessor of **DB2** appends the constant value “NCTU” for the attribute *school* to the results of **Q2-1** in phase **LPO_1**. Then, the results of **Q2** are obtained. Finally, the results of **Q1** and **Q2**, called **r1** and **r2**, are returned to the result integrator.

Since the results in **r2** are maybe results, their isomeric objects in **r1**, which are certain results, should be checked. The function **L-to-G()** is used to identify isomeric objects which have the same **GOid**. For each objec in **r2**, if its isomeric object is in **r1**, it can be turned into a certain result. If its isomeric object can be found in **DB1** but is not in **r1**, then this maybe result is eliminated from the results. Otherwise, it remains as a maybe result. Therefore, the certain result **cr2** and maybe result **mr2** of **r2** are obtained after processing in phase **RI_1**. Finally, the certain result of the global query is **r1** \bowtie **cr2**. Since there is no maybe result in **r1**, the global maybe result is **mr2**. Phase **RI_2** is omitted because no explicit join is specified in query **Q**.

5. CONCLUSIONS

The mapping information between a global schema and its associated component schemas is important when a global query against the global schema is processed. In this paper, we have extended our previous research on integrating multiple object schemas to consider mapping information and query processing strategies. The mapping

equation has been defined and used to denote the mappings of attributes and object instances among a virtual class and its constituent classes. In addition, a mapping equation is described by a mapping graph. These mechanisms provide mapping information between the global and component object schemas. The query processing flow for the global query based on the localized approach has been presented. Based on mapping information, strategies for query decomposition and result integration have been discussed. Moreover, preprocessing and postprocessing units have been provided to enable each local DBMS to handle virtual classes and virtual attributes produced in schema restructuring. Finally, the concept of object isomerism has been applied to derive more informative query answers.

There are many ways to decompose a global query; thus, many different query execution plans can be produced. In this paper, we have only provided one way to decompose a global query. For a defined cost model, query transformation based on the estimated cost can provide a method to find an efficient query execution plan. Alternatively, increased intersite parallelism can reduce the response time of query processing. The query optimization strategies will be subjects of future research.

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