Supporting a Semantic Data Model in a Distributed Database System

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Abstract

Existing distributed database systems are based mostly on the relational model. Furthermore, it has been argued that the relational model is the model best suited for distributed databases. This paper describes an implementation approach for supporting logical pointers between distributed entities. This approach is being employed in a distributed database system that supports a semantically rich data model and that currently is under implementation. The access structures used to support entity-to-entity pointers in this data model facilitate the maintenance of referential integrity across sites. At the same time, they provide efficient access paths for distributed query processing. To make use of these access structures the extensions required of existing query processing techniques are quite straightforward.

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1. Introduction

Existing distributed database systems for the most part have been based on the relational data model [SN77] [RBFG80] [WDHL82]. Furthermore, it has been argued that the relational model is the model best suited for distribution [CODD82]. There are two properties of the relational model that facilitate its support for distribution. First, all of the relationships between records or types of objects are value-based; there is no need to support logical pointers across sites. Second, a high level language is available for specifying processing on sets of data; there is no need to follow record-at-a-time navigational links across sites.

This paper describes an implementation approach for supporting logical pointers across sites. This approach is currently being used in the implementation of the Distributed Database Manager (DDM) [CDFG83a] [CDFG83b], a distributed database system that supports the semantically rich Daplex data model [SHIP81]. Similar approaches could be used for distributed systems that support high level access based on the entity-relationship model [CHEN76] and the network model [MP82], or in relational systems that support physical links between tuples stored at different sites.

In order to extend effectively the relational distributed database technology to these models, three important problems should be addressed. First, it should be possible to control the placement of data that is based on relationships between data objects. Assume, for example, that information about university departments is distributed according to the building in which each department is housed. Now suppose we want to store information about each of the courses with information about the department that is offering the course. In relational systems such as distributed INGRES [SN77], SDD-1 [RBFG80], and R* [WDHL82], the course relation must include redundant information about the building that is housing the department offering the course, and the distribution criteria for the course relation would have to be based on the redundant building information. In the DDM, it is possible to fragment courses by department, and to group together related courses and departments.

The second problem is the maintenance of referential integrity across sites. If there is an integrity constraint that requires every course to have an offering department (i.e., the offering function from course to department is total), then even if course and department information are stored at different sites, the DDM will prevent the insertion of information for a new course for which there is no corresponding department. Similarly, the DDM will prevent the deletion of a department that is still referenced by an existing course. Furthermore, the DDM maintains this integrity constraint without requiring cross-site checking on each insertion or deletion. In a relational system, such integrity requirements would have to be specified by general integrity constraints [EC75] [HS78] [BCC81] [KP81]. The efficient support of such constraints for distributed relational databases remains an open problem.

The key to efficient distributed query processing in relational systems is the provision for set-at-a-time operations on distributed data. Thus, the third problem is how to use links that relate data across sites effectively. These links can augment physical access paths as in a single-site relational system like System R, or they can represent logical relationships. The DDM uses pointers across sites(1) to provide faster access to sets of records and to reduce data movement from one site to another during distributed query processing. These intersite pointers identify the logical entities and their residing sites only. Thus, they are unaffected by the relocation of physical records (representing entities) within a site. Furthermore, they are used by high level set-at-a-time operations. Hence, a network message is not incurred for following each such pointer.

Section 2 provides an overview of the semantic data model, Daplex, that is supported by the DDM. Section 3 addresses the first of the three problems stated above by describing the database fragmentation facilities of the DDM. Section 4 addresses the second problem by presenting the auxiliary data structures that are used to enforce referential integrity and to provide faster multi-site query processing. Section 5 addresses the third problem by discussing query processing operations that can make use of the presented structures. Finally, Section 6 summarizes our conclusions about data models and distributed databases.

(1) These pointers identify only the logical entity and the site where the entity is to be found. They do not have to be updated when an entity is relocated within a site.

2. The Daplex Data Model

The Daplex data model that is supported by the DDM originally was described in [SHIP81]. Its basic constructs are entities and functions. Entities are intended to represent conceptual objects and functions correspond to the properties of conceptual objects. Entities that have the same set of generic properties are grouped together into entity sets. Each function, when applied to an entity of an appropriate entity set, returns a specific property of that entity. Each property is represented either by a single value or a set of values. Such values can be drawn from scalar data types and character strings, or they can refer to other entities stored in the database as values.

Consider a university database modelling students, instructors, departments, and courses. Figure 2.1 is a graphical representation of the logical definition for such a database in Daplex. The big rectangles depict entity types and the small rectangles indicate scalar data types and character strings. The single- and double-headed arrows represent respectively single-valued and set-valued functions that map entities from their domain types into their corresponding range types.

One notable difference between the Daplex data model and the relational data model is that referential constraints [DATE81], which are extremely fundamental in database applications (but not easily specifiable in relational contexts), are directly supported in Daplex. For example, in the above database, the database system will ensure that students are assigned valid instructors as advisors. Likewise, the database system will allow an update action that removes an instructor from the database to go through, but only if this will not result in dangling references from student entities that remain in the database. (Unlike general integrity constraints that are enforced only at the end of transactions, referential integrity is enforced at the data manipulation language statement level since it is considered an integral part of the data model.)

Another important semantic concept related to distribution is the notion of a generalization hierarchy of overlapping entity types. In relational systems, a real-world entity that plays several roles in an application environment typically is represented by tuples in a number of relations. In the university database, we might have an instructor named John Doe and a student also named John Doe, who are in fact the same person in real life. In this case, we might want to impose the constraint that the age of John Doe as an instructor should agree with the age of John Doe as a student. This constraint can be more succinctly expressed in Daplex by declaring a new entity type called person and indicating that student and instructor are subtypes of per-

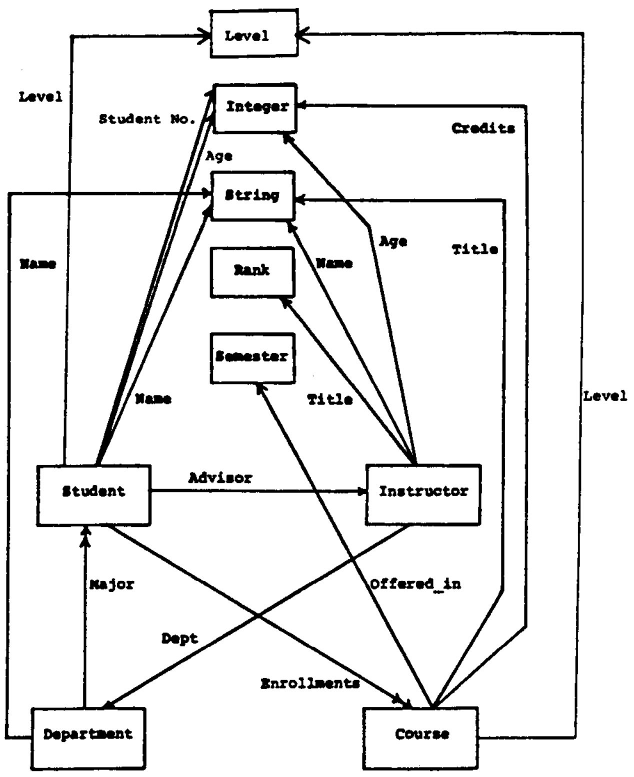


Figure 2.1 A Daplex Database

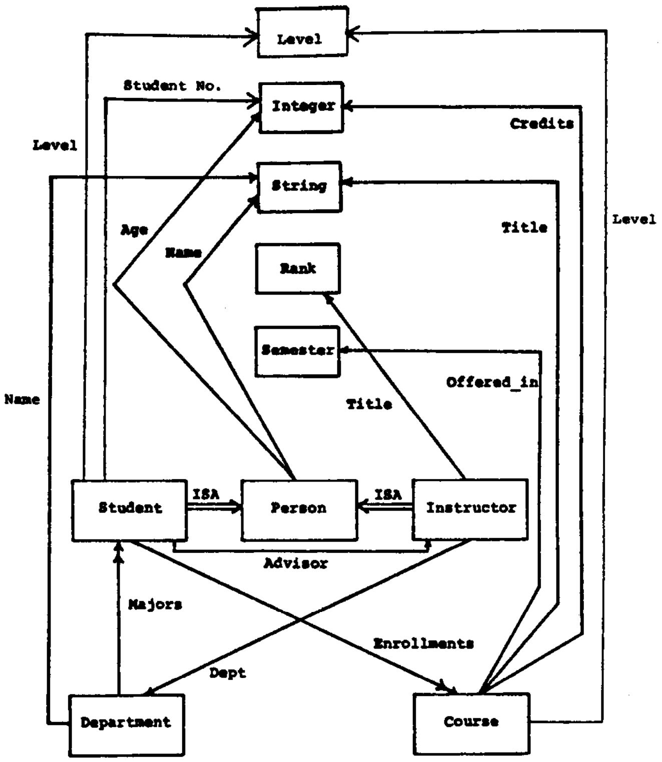


Figure 2.2 A Daplex Database with Type Overlap

son, and that age is a function applicable to person. The function inheritance semantics of Daplex automatically guarantee the consistency of age information on student and age information on instructor, since age is a function inherited from the supertype person. At the same time, inherited functions can be applied directly to an entity in data manipulation constructs in Daplex, without the need for tedious explicit joining operations. Figure 2.2 is a graphical representation of the revised database definition. The double-edged arrows represent is-a relationships (e.g., each student is-a person). The entity types person, student, and instructor are said to form a generalization hierarchy. Since every entity in this generalization hierarchy also must be a person, the type person is referred to as the root of the generalization hierarchy.

The implications of the need to efficiently enforce referential integrity and type overlap constraints on storage and access structures, for a centralized environment, have been discussed in [CDFL82]. In this paper, we focus on the implications of these fundamental integrity constraints for distributed database design.

3. Fragmentation and Grouping

The DDM provides complete physical data independence to end users. A separate interface is provided for database administrators (DBAs) for the purpose of specifying physical design parameters. An important design option available to DBAs is the allocation and replication of data to different sites in the network.(2) This section discusses the choice of allocation units in the DDM.

The database fragmentation options supported in the DDM are somewhat different from those found in previous systems like distributed INGRES [SN77], SDD-1 [RBFG80], and R* [WDHL82], which are based on the relational data model.(3) This

(2) The purpose of distributing and replicating data over different sites is to maximize locality of reference (i.e., to ensure that most transactions can be run using local data) and to provide resiliency against site failures.

(3) The typical unit for allocation in these systems is a fragment of a relation (i.e., a logically subset defined by a local predicate).

is necessitated by our support for entity-valued functions in Daplex. Essentially, Daplex allows for "direct" pointers that point from one entity to another. The semantics of Daplex requires that insertion and deletion of entities to and from the database do not result in dangling pointers. In order to simplify the maintenance of "direct" inter-entity pointers, we introduce the notion of a fragment group. A fragment group consists of a collection of fragments, each of which is a logically defined subset of a generalization hierarchy. Each fragment group is a unit for allocation and replication. Fragment groups can be designed to "localize" interentity references. This localization simplifies the enforcement of deletion dependencies and improves the efficiency of query processing. We expect that most databases can be designed in such a way that frequently followed interentity references (from entities within each fragment group) can be localized. This will eliminate the cumbersome maintenance of nonlocal pointers. It is important to note that we do not require fragment groups to be defined in such a way that all interentity references are localized.

Our support for generalization hierarchies in Daplex leads us to forgo vertical partitioning,(4) an option that is provided in SDD-1 [RBFG80] and R* [WDHL82]. Our decision here has been influenced mostly by simplicity and efficiency considerations. Had we supported vertical fragmentation, we would have the additional problem of deciding how interentity pointers should be represented. When accessing an entity of a given type, Daplex allows for access to attributes (functions) that are defined from the viewpoint of any overlapping type. In order to provide efficient support for such accesses, we require that all functions/attributes of an entity, regardless of being primitively defined or inherited, be accessible from the same site. Thus, our objects for fragmentation in the DDM are the generalization hierarchies within databases.

The fragmentation of entities within a generalization hierarchy may be defined in terms of function values, subtype memberships, subtype nonmemberships, and one-to-many relationships induced by single-valued entity functions. Since we have ruled out the possibility of vertical fragmentation of entities within a generalization hierarchy across sites, we permit the disjoint partitioning of base entity types (i.e., roots of generalization hierarchies) only. Partitioning of entities within a subtype can be implicitly defined by partitioning the corresponding base entity type. Each fragment of a base entity type is defined by a conjunction of conditions. The DBA assigns a unique identifier to each fragment in order to permit the definition of one fragment to be dependent on that of another fragment. Each defining condition can be in one of the following forms:

1. e is in "subtype" (where e is an entity in the base type and "subtype" is contained in the base type).

2. e not in "subtype" (where e is an entity in the base type and "subtype" is contained in the base type).

3. f(e) "comparison operator" "constant" (where e is an entity in the base type; f is a single-valued scalar function that is applicable to an entity that satisfies the type membership conjuncts forming part of the defining predicate in question; and "comparison operator" is one of "=", "/=", "<=", ">=", "<", ">").

4. f(e) is in F (where e is an entity in the base type; F is a previously defined fragment; and f is a single valued function that ranges over entities in F.(5)

Figure 3.1 illustrates one feasible fragmentation and grouping scheme for the example database from Section 2. Four fragment groups are defined under this particular scheme. The first fragment group stores department entities located on the first-floor, along with the courses offered by these first-floor departments and the instructors who work in these first-floor departments. The second fragment group stores second-floor departments and the associated courses and instructors. The third fragment group stores departments located on other(6) floors, along with the associated courses and instructors. Finally, the fourth fragment group stores only a single fragment that consists of persons who are not instructors.

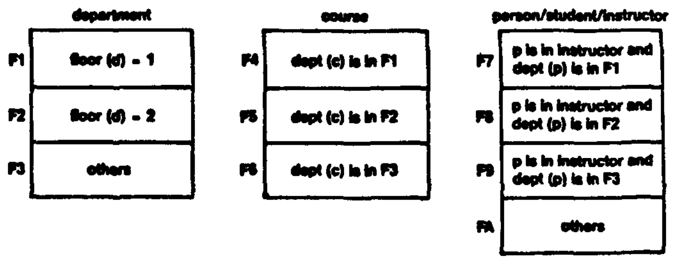
4. Access Structures

In this section, we discuss auxiliary data structures used in the DDM for supporting the maintenance of referential integrity constraints, and for facilitating the processing of transactions that span fragment group boundaries. Our

(4) That is, representing individual entities by multiple distributed records.

(5) We do impose the restriction that if fragment A's definition depends on that of fragment B, then fragment B must be assigned to the same fragment group as fragment A.

(6) The predicate "others" in Figure 3.1 is interpreted by the DDM system as a shorthand for the complement of the disjunction of the other fragment defining predicates on the generalization hierarchy in question.


department
course
person/student/instructor
F1
floor (d) = 1
F2
floor (d) = 2
F3
others
F4
dept (c) is in F1
F5
dept (c) is in F2
F6
dept (c) is in F3
F7
p is in instructor and dept (p) is in F1
F8
p is in instructor and dept (p) is in F2
F9
p is in instructor and dept (p) is in F3
FA
others

fragment group 1 = {F1, F4, F7}
fragment group 2 = {F2, F5, F8}
fragment group 3 = {F3 F6 F9}
fragment group 4 = {FA }

Figure 3.1 A Feasible Fragmentation and Grouping Scheme

principal objectives in designing these structures are:

1. To enforce referential integrity constraints that apply to entities stored across multiple sites without requiring updates across sites each time a reference is added or removed.

2. To provide fast access paths for traversals based on entity-valued functions.

3. To support efficient associative access to entities based on selection criteria that are orthogonal to those used in fragment definitions.

4. To facilitate the dynamic addition/removal of fragment group copies.

We have introduced two new types of access structures in the DDM. The first type of structure is a <u>fragment group entity directory</u>. One or more fragment group entity directories are automatically maintained for each fragment group. This is required to support semantics of the Daplex data model. Each directory is associated with a single fragment group. It is used to resolve references to entities stored in the fragment group and to identify the other fragment groups that store nonlocal entities referenced by entities in the fragment group. The second type of structure is a <u>distribution index</u>. Its maintenance is optional, and its applicability is not restricted to the Daplex data model. Each distribution index, whose maintenance is specified by the DBA, is associated with a single entity type and function. It pinpoints the fragment groups that contain entities that have specific values of that function.

Since each fragment group entity directory is associated with a single fragment group, it is actually considered part of the representation for entities in that fragment group. When specifying a distribution index for maintenance, a DBA can specify its placement in any previously defined fragment groups or in a new fragment group of its own. The replication of a distribution index is thus governed by the replication of the fragment group in which it is placed. The maintenance of these two types of structures are further explained below.

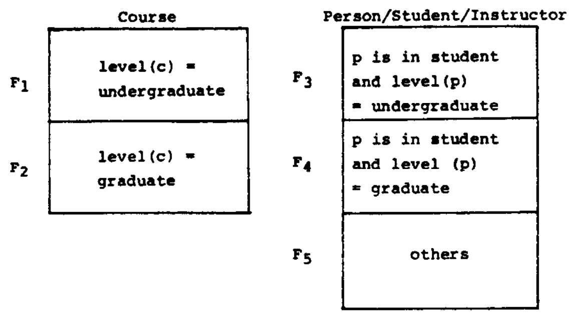
4.1 <u>Fragment Group Entity Directory</u>

Like the Local Database Manager [CFLR81] [CDFL82] which supports centralized Daplex databases, we maintain entity directories in the DDM in order to facilitate the resolution of interentity references and the enforcement of referential and type overlap constraints. In general, for a given fragment group we maintain a fragment group entity directory for each generalization hierarchy that is either stored in the fragment group or potentially referenced (as specified in the logical schema) by entities stored within the fragment group.

Two kinds of entries may be stored in a fragment group entity directory. A <u>primary</u> entry is one that pertains to an entity that is stored in the fragment group. A <u>secondary</u> entry is for an entity that is referenced but not stored in the fragment group.

A primary entry for an entity contains typing information, local reference count(s), physical record pointer(s), and one or more sets of nonlocal fragment group identifiers. A fragment group's identifier is in one set if it contains entities that reference the given entity from the viewpoint of a specific entity type in the generalization hierarchy. The local reference counts keep track of local references from within the fragment group, one for each entity type to which the entity belongs. A secondary entry contains typing information and a reference count for each entity type to which the nonlocally stored (but referenced) entity belongs. This reference count indicates the number of times the designated entity is being referenced (from the viewpoint of a specific type) from entities stored within this fragment group.

Figure 4.1 illustrates a fragmentation and grouping scheme for the course and person entity types. Note that the entity to entity references are not completely localized. In this scheme, undergraduate courses are grouped with undergraduate students in FG_1, and graduate courses are grouped with graduate students in FG_2. However,


Course
F1
level(c) = undergraduate
F2
level(c) = graduate
Person/Student/Instructor
F3
p is in student and level(p) = undergraduate
F4
p is in student and level (p) = graduate
F5
others

fragment group 1 = {F1, F3}
fragment group 2 = {F2, F4}
fragment group 3 {F5 }

Figure 4.1 A Course/Person Fragmentation Schema

undergraduates can take graduate courses and graduates can take undergraduate courses. Figure 4.2 shows the set of courses taken by each student in the database. Figure 4.3 shows the corresponding fragment group entity directories for the (degenerate) course generalization

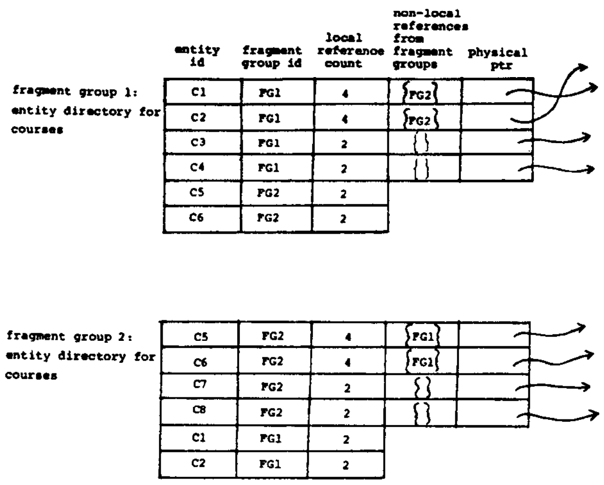
$S_1, \ldots, S_4$ = undergrad students
$S_5, \ldots, S_8$ = graduate students

S_1 (C_1, C_2, C_5, C_6)	S_5 (C_5, C_6, C_1, C_2)
S_2 (C_1, C_2, C_5, C_6)	S_6 (C_5, C_6, C_1, C_2)
S_3 (C_1, C_2, C_3, C_4)	S_7 (C_5, C_6, C_7, C_8)
S_4 (C_1, C_2, C_3, C_4)	S_8 (C_5, C_6, C_7, C_8)

Figure 4.2 Enrollment of Students in Courses

hierarchy. Courses C_1 through C_4 are undergraduate courses and have primary entries in FG_1's directory for course entities. For these courses, the directory maintains local reference counts, local physical pointers, and indicates that some entities in FG_2 point to C_1 and C_2 (i.e., graduate students are taking these courses). Graduate courses C_5 and C_6 are not stored in FG_1 but are referenced (twice) by entities stored within FG_1.

Essentially, we have separated the reference counts for an entity from different fragment groups and stored the counts with the fragment groups where the references are made. Our motivation is to minimize update cost. The primary entry will be affected by nonlocal updates (on another fragment group) only if the update results in the addition of a "new" secondary entry or the removal of an "old" secondary entry in the foreign fragment group's corresponding entity directory (i.e., if the nonlocal reference count goes from 0 to 1, or from 1 to 0, in a secondary entry).



fragment group 1: entity directory for courses

entity id	fragment group id	local reference count	non-local references from fragment groups	physical ptr
C1	FG1	4	{FG2}	
C2	FG1	4	{FG2}	
C3	FG1	2	{ }	
C4	FG1	2	{ }	
C5	FG2	2		
C6	FG2	2		

fragment group 2: entity directory for courses

C5	FG2	4	{FG1}	
C6	FG2	4	{FG1}	
C7	FG2	2	{ }	
C8	FG2	2	{ }	
C1	FG1	2		
C2	FG1	2		

Figure 4.3 Fragment Group Entity Directories

Similarly, the entity directory for courses in FG_2 contains primary entries for graduate courses C_5 through C_8 and secondary entries for C_1 and C_2. If another graduate student enrolls in C_1, only the reference count in FG_2 needs to be incremented. If graduate students were no longer enrolled in C_7 as a result of updates, its local reference count would become zero. Since C_7 is not referenced by entities in any other fragment group, the deletion of C_7 would be allowed. The legality of the deletion can always be determined by checking only the appropriate primary entry in the local entity directory.

4.2 Distribution Index

In distributed databases, it is often necessary to access all entities with a specific function value: entities that potentially could be stored in any fragment group. In order to facilitate such accesses, we introduce the notion of a distribution index. Each entry in a distribution index identifies the logical fragment groups that store entities that have a given indexed value. In order to maintain a distribution index efficiently, we require that corresponding local secondary indices be maintained for each fragment group where entities of the indexed entity type reside. (A local secondary index contains only entries for entities that are locally stored within a fragment group.) Without such local indices, it would be difficult to determine if an insertion or deletion operation has any effect on the distribution index. With the local indices, we know that the distribution index has to be updated whenever an update operation causes the creation or deletion of an entry in a local secondary index.

Figure 4.4 illustrates a distribution index that could be maintained for the students in the fragment groups identified in figure 4.1. While this example distribution index is based on a unique function (i.e., each student has a unique student number), distribution indices in general can involve nonunique functions and combinations of functions.

Student No.	F G
77446	{FG1}
78550	{FG2}
79450	{FG2}
---	--
---	--
---	--

Student No. Index

Figure 4.4 A Distribution Index

The distribution index on student number can be used to locate a specific student regardless of whether the student is a graduate or an undergraduate. That index is updated only when students enter or leave the university or change undergraduate/graduate status. No specific physical location information is maintained in the distribution index to shield it from changes of the student record within a fragment group.

In systems such as SDD-1, R*, and Distributed INGRES, both fragments would have to be searched based on student number. Alternately, these systems would allow a fragmentation criterion based on student number. However, the specification of ranges of student numbers as fragmentation criteria violates the important principle of separating logical and physical database designs: student numbers would have to be assigned based on where the records should be stored. On the other hand, the specification of an individual distribution criterion for each student number is cumbersome and would require updates to the distribution criteria (which normally can be performed only by a DBA) for each change in student status. The distribution index seems like a more natural extension to single-site secondary indices for locating data.

4.3 Implications of Replication

The DDM supports data replication [CDFG83a] [CDFG83b], and fragment groups are used as the units for allocation to sites in the system. However, it is important to note that all nonlocal references used in the representation of entity functions, in entity directories, and in distribution indices, refer to logical fragment groups and not to sites that stores copies of those fragment groups. This serves to simplify pointer maintenance significantly. At the same time, it facilitates our compilation approach to the generation of access plans for repetitive transactions. The same plan would be usable, regardless of which copy of a given fragment group is dynamically selected for executing the transaction. At run time, each logical fragment group must be bound to a physically available site for reading purposes. (That is, for each logical fragment group that must be read during the execution of the transaction, a site that stores a copy of the fragment group must be used.)

In fact, our implementation scheme for fragment group entity directories has been influenced strongly by the desire for the capability to add and remove fragment group copies dynamically. The allocation and replication parameters of a fragment group can be changed without requiring update operations on entity directories. For example, a new fragment group copy can be added simply by obtaining an image of an existing copy. Conceivably, we could have chosen a more compact representation for the fragment group entity directories by collapsing the directories for different fragment group copies if they happened to be stored at the same site. However, this would have brought major upheavals when the allocation and replication parameters of fragment groups have to be changed for performance reasons.

5. Distributed Query Processing

An overview of our two-stage approach to optimizing repetitive transactions has been presented in [CDFG83b]. The selection of a processing strategy treats each fragment group as a logical site and is performed at compile time. The result of compilation is a plan that prescribes the local operations to be performed on data stored within individual fragment groups and the movement of data resulting from these local operations. Optimization at compile time is essentially based on a worst case analysis, since it assumes that different fragment groups are stored at different sites. At run time, the binding of logical fragment groups to physical sites is performed. That is, a set of sites is selected for following the compile time plan. The optimization during site selection for each fragment group takes into consideration which sites are operational (and thus which copies of a needed fragment group are accessible), and which fragment groups are potentially needed for running the transaction.

The presence of distributed access structures discussed in Section 4 affects the set of cross-site operations that are included in the access plan generated at compile time. At run time, they are used to reduce the set of fragment groups that potentially contain the desired data to the set of fragment groups that are actually required. We discuss the uses of fragment group entity directories and distribution indices for query processing below.

5.1 Use of Fragment Group Entity Directories

In addition to providing direct support for referential integrity maintenance, fragment group entity directories support fast access from individual entities to the entities they reference. Consider the fragmentation and grouping scheme illustrated in Figure 4.1. The enrollments function of a given student is represented by a collection of pointers to course entities. As explained in [CDFL82], either logical pointers or hybrid pointers can be used for the representation of entity functions. A logical pointer consists of the entity's unique identifier that was assigned at the time of its creation. A hybrid pointer combines a logical pointer with a physical pointer. The physical pointer portion of a hybrid pointer depends on whether the referenced entity is local or foreign. The physical pointer to a local entity points to a single local record representing the entity from a specific viewpoint (i.e., the range type of the entity-valued function). The physical pointer to a foreign entity is represented as an indirection flag only. It simply indicates that the entity is foreign, and that an appropriate entry in the local fragment group entity directory should be consulted to determine the fragment group that stores the foreign entity. (See [CDFL82] for discussions on hybrid pointer maintenance and validation.) A request can then be passed on to the site chosen during site binding for the identified fragment group in order to access the desired entity. The fragment group entity directory at this foreign fragment group is used to obtain the physical pointer(s) to the record(s) that represent the referenced entity. Thus, fragment group entity directories provide efficient support for "small" transactions that typically access a single entity of one type, along with related entities from other types.

At the same time, it is possible to make use of entity directories to process "large" transactions that perform joining operations on entire entity types. Consider a joining operation between student and course types based on the enrollments function. Assume that students who are not enrolled in any course, and courses that are not taken by any student, do not qualify for output in this transaction.

Now, assume that the database is fragmented as shown in Figure 4.1, that FG_1 and FG_2 are available at different sites, and that the transaction is originated at a third site. The most straightforward processing strategy is to transfer all student and course information from both FG_1 and FG_2 to the transaction's home site, reconstruct the student entity type by taking the union of undergraduate students and graduate students, reconstruct the course entity type by taking the union of undergraduate courses and graduate courses, and then compute the desired join between students and courses.

An often used strategy for reducing the amount of data that have to be transferred to the transaction's home site is to make use of semi-join operations [BGWR81]. Typically, this would involve projecting one of the operands on its joining field, and transferring this projection to the site of the second operand in order to reduce the size of the latter. With fragmented operands, the semi-join operation becomes more complicated. (For example, see [YCTB83] for discussions on how semi-joins can be performed on fragmented operands.)

However, with the presence of fragment group entity directories, a faster processing strategy is readily available. Let SU and CU represent undergraduate students and undergraduate courses in FG_1. Let SG and CG represent the graduate students and graduate courses in FG_2. A possible processing strategy, selected at compile time, is illustrated in figure 5.1.

At a site that stores FG_1, we perform the join based on enrollments between SU and CU and store the result in a temporary T_1. By examining entities in SU and the entity directory for courses in FG_1, we also can determine locally those undergraduate students who are taking graduate courses (SU semi-joined by CG) and those undergraduate courses being taken by graduate students (CU semi-joined by SG). These operations result in temporaries T_2 and T_3 respectively. Similarly, the temporaries T_4, T_5, and T_6 can be formed locally at a site that contains FG_2. At step 2, only some of the courses and students need to be joined. T_7 represents undergraduates taking graduate courses, and T_8 represents graduates taking undergraduate courses. The unions at step 3 thus do not need to remove duplicates.

	Site FG1	Site FG2
Step 1:	T1 = SU Join CU	T4 = SG Join CG
	T2 = SU Semi-Join CG	T5 = SG Semi-Join CU
	T3 = CU Semi-Join SG	T6 = CG Semi-Join SU

	Site X
Step 2:	T7 = T2 Join T6
	T8 = T5 Join T3

	Site X
Step 3:	Result = T1 U T4 U T7 U T8

Figure 5.1 Use of Entity Directories

We say that this compile time plan specifies that the join is to be distributed over the union operations and that double semi-join reductions are to be used to reduce the amount of data that has to be transferred. At run time further reductions become apparent automatically (T_7 (or T_8) would be empty if T_2 and T_6 (or T_5 and T_3) were empty). Note that T_2 would be empty if and only if T_6 were empty.

With the above processing strategy, we are minimizing the amount of computation cost that will have to be incurred during step 2. If the intermediate results obtained during step 1 must individually be transferred to a different final site before step 2 is carried out, then it may be preferrable to perform semi-joins between SU and CU to form temporaries T_{1a} and T_{1b}, and between SG and CG to form temporaries T_{2a} and T_{2b}, and postpone all joining operations until step 2. At the same time, since T_{1a} may overlap with T_2, and T_{1b} may overlap with T_3, it may be preferrable to represent these temporaries with sets of entity identifiers, and to send information concerning entities that belong to multiple overlapping temporaries to the final site only once.(7)

5.2 Use of Distribution Indices

As previously mentioned, one obvious use for distribution indices is processing selection operations. Assume a distribution index on the age of students is kept for the previous example database. Consider a query that asks for all students who are 17 years old. Without a distribution index, it would be necessary to issue two subqueries, one on each of the two fragment groups, in order to retrieve all of the desired students. However, a distribution index may indicate that there are no 17 year old students in FG_2, thus eliminating the futile access to FG_2 that otherwise would have to be made.

Another potential use for distribution indices is for the processing of valued-based joining operations. Consider a query that joins suppliers and projects based on their respective cities. If we have available distribution indices on both the city function of suppliers and on the city function of projects, we can use the distribution index to identify the fragment groups that actually have matching entities. For each supplier fragment we can identify the cities for which there will be a matching project. We can then use the list of cities to perform a semi-join on that supplier fragment. Similarly, we can collect a list of qualifying cities for each project fragment. At compile time, the optimizer will decide to use neither, one, or both of the semi-join reductions. At run time, it may be determined that entire fragments need not be accessed.

6. Conclusions

The design of the DDM has led us to three important conclusions. The first conclusion is that it is indeed possible to build distributed database systems that support a semantically rich data model like Daplex, the entity-relationship model, and other models that support explicit relationships between different types of objects. The distributed database management system that supports these models must support a high level, set-at-a-time data manipulation facility. With such a facility, the support for distribution should allow for the placement of data that is based on the relationships between the types of data, maintain referential integrity between data stored at different sites, and use distribution access paths along with relational like operations to support query processing.

The second conclusion we have reached is that in addition to the increased functionality of the semantically rich data model, a distributed system like the DDM actually can improve performance over a distributed relational database system. The distributed access structures used to maintain referential integrity also can be used in query processing to locate and limit the number of fragments that need to be accessed and to reduce the amount of data that needs to be shipped between sites. Furthermore, these structures can be designed so that multiple-site checking and updating is not required for individual entity insertions and deletions.

The third conclusion we have reached is that the required extension to relational distributed database technology is straightforward. The extensions described in this paper do not seem significantly more difficult than the implementa-

(7) Likewise, T_{4a} may overlap with T_5, and T_{4b} may overlap with T_6.

tions required for a distributed relational system. In fact, the extensions, particularly the query processing extensions, are built on relational query processing techniques. Furthermore, these extensions are orthogonal to other aspects of the DDM implementation such as directory management, (inter-transaction) concurrency control, reliability, and recovery.

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