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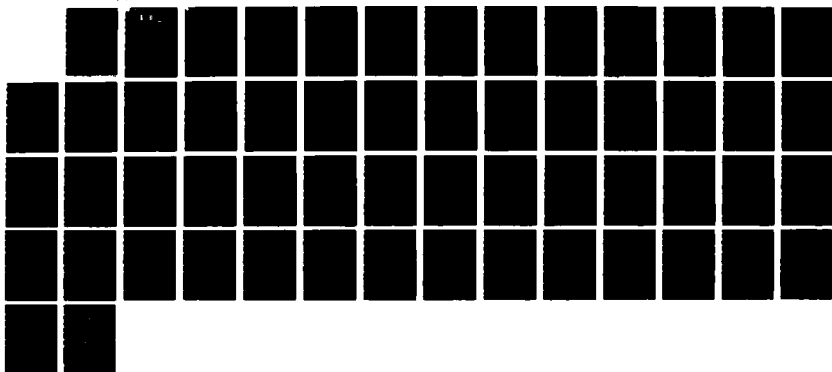
A GENERALIZED DBMS TO SUPPORT DIVERSIFIED DATA(US)
CALIFORNIA UNIV BERKELEY ELECTRONICS RESEARCH LAB
M STONEBRAKER ET AL 21 JUL 87 AFOSR-TR-87-1682
AFOSR-83-0254

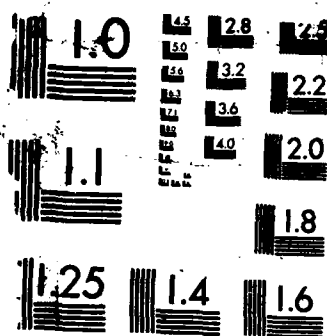
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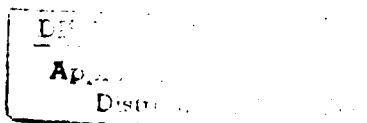
REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY NOV 30 1987			3. DISTRIBUTION / AVAILABILITY OF REPORT Unlimited		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE			5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR-87-1682		
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Der			7a. NAME OF MONITORING ORGANIZATION Air Force Office of Scientific Research		
6a. NAME OF PERFORMING ORGANIZATION Electronics Research Lab		6b. OFFICE SYMBOL (if applicable)	7b. ADDRESS (City, State, and ZIP Code) Bldg. 410, Bolling Air Force Base Washington, DC 20332		
6c. ADDRESS (City, State, and ZIP Code) University of California Berkeley, CA 94720		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-83-0254			
8a. NAME OF FUNDING / SPONSORING ORGANIZATION AFOSR		8b. OFFICE SYMBOL (if applicable) NM	10. SOURCE OF FUNDING NUMBERS		
8c. ADDRESS (City, State, and ZIP Code) 1700 S. 10th St Arlington, VA 22204 20588-6448		PROGRAM ELEMENT NO. 61102F	PROJECT NO. 2304	TASK NO. A2	WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) A Generalized DBMS to Support Diversified Data					
12. PERSONAL AUTHOR(S) Michael Stonebraker, Lawrence Rowe, Eugene Wong					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM 7/1/83 TO 3/31/87		14. DATE OF REPORT (Year, Month, Day) 7/21/87	
15. PAGE COUNT 4					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			

ABSTRACT (Continue on reverse if necessary and identify by block number)

This project supported an investigation into extending a relational system to support new kinds of data objects such as lines, points, polygons, bit maps, text, documents, vectors and arrays. Two important facts were studied:

use of an abstract data type system (ADT)
Use of procedural objects



87 11 17 038

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION	
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Stonebraker		22b. TELEPHONE (Include Area Code) (202) 767-5039	22c. OFFICE SYMBOL NM

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.

SECURITY CLASSIFICATION OF THIS PAGE

All other editions are obsolete.

87 11 17 038

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A GENERALIZED DBMS TO SUPPORT DIVERSIFIED DATA

AFOSR-TR- 87 - 1682

Final Technical Report
AFOSR Grant 83-0254
(July 1, 1983 — March 31, 1987)

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1. Problem Studied

→ This project supported an investigation into extending a relational system to support new kinds of data objects such as lines, points, polygons, bit maps, text, documents, vectors and arrays. Two important tactics were studied:

- 1) use of an abstract data type system (ADT); *and*
- 2) use of procedural objects.

Basically an ADT system allows new data types to be added to a relational system to augment the normal character strings, integers and floating point numbers traditionally provided. In addition, procedures provide a powerful data modeling capability that is especially useful for complex objects or objects that have unpredictable composition.

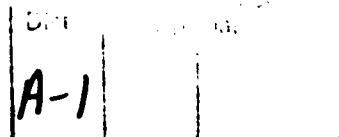
2. Results

the authors
→ The important results that ~~we~~ *the authors* achieved are twofold. First, ~~we~~ *they* obtained results on the integration of an ADT system into a general purpose DBMS. In particular, ~~we~~ *they* discovered how to integrate new data types with query optimization routines and how to allow new access methods to be constructed for the new data types. A paper on this subject entitled, "Inclusion of New Types in Relational Data Base Systems," was presented at the 1986 IEEE Data Engineering Conference and is included as an appendix to this report. Basically we showed how a query optimizer could be converted to one that is table driven off of processing information supplied by the designers of new data types and access methods.

→ Second, ~~we~~ *they* designed a syntax for efficient manipulation of procedural objects and then constructed query optimization algorithms to efficiently process this extended syntax. A report on this syntax, the algorithms that support it, and the performance of a prototype implementation will appear in the September 1987 issue of the *ACM Transactions on Data Bases*. This paper also appears in the appendix.

3. Publications

- 1) Guttman, A. and M. Stonebraker, "R-Tree: A Dynamic Index Structure for Spatial Searching," Proc. 1984 ACM-SIGMOD Conference on Management of Data, Boston, Mass, June 1984.
- 2) Stonebraker, M., "Inclusion of New Types in Relational Data Base Systems," Proc. 1986 IEEE Data Engineering Conference, Los Angeles, CA, February 1986.
- 3) Stonebraker, M. and L. Rowe, "The Design of Postgres," Proc. 1984 ACM-SIGMOD Conference on Management of Data, Washington, D.C., May 1986.
- 4) Sellis, T. K., "Global Query Optimization," Proc. 1984 ACM-SIGMOD Conference on Management of Data, Washington, D.C., May 1986.
- 5) Stonebraker, M., J. Anton, and E. Hanson, "Extending a Data Base System with Procedures," to appear in ACM Transactions on Database Systems, September 1987.
- 6) Stonebraker, M., "Triggers and Inference in Data Base Systems," Electronics Research Laboratory memo M85/46, May 1985



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INCLUSION OF NEW TYPES IN RELATIONAL DATA BASE SYSTEMS

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Abstract

This paper explores a mechanism to support user-defined data types for columns in a relational data base system. Previous work suggested how to support new operators and new data types. The contribution of this work is to suggest ways to allow query optimization on commands which include new data types and operators and ways to allow access methods to be used for new data types.

1. INTRODUCTION

The collection of built-in data types in a data base system (e.g. integer, floating point number, character string) and built-in operators (e.g. +, -, *, /) were motivated by the needs of business data processing applications. However, in many engineering applications this collection of types is not appropriate. For example, in a geographic application a user typically wants points, lines, line groups and polygons as basic data types and operators which include intersection, distance and containment. In scientific application, one requires complex numbers and time series with appropriate operators. In such applications one is currently required to simulate these data types and operators using the basic data types and operators provided by the DBMS at substantial inefficiency and complexity. Even in business applications, one sometimes needs user-defined data types. For example, one system [RTI84] has implemented a sophisticated date and time data type to add to its basic collection. This implementation allows subtraction of dates, and returns "correct" answers, e.g.

This research was sponsored by the U.S. Air Force Office of Scientific Research Grant 83-0254 and the Naval Electronics Systems Command Contract N39-82-C-0235

"April 15" - "March 15" = 31 days

This definition of subtraction is appropriate for most users; however, some applications require all months to have 30 days (e.g. programs which compute interest on bonds). Hence, they require a definition of subtraction which yields 30 days as the answer to the above computation. Only a user-defined data type facility allows such customization to occur.

Current data base systems implement hashing and B-trees as fast access paths for built-in data types. Some user-defined data types (e.g. date and time) can use existing access methods (if certain extensions are made); however other data types (e.g. polygons) require new access methods. For example R-trees [GUTM84], KDB trees [ROBI81] and Grid files are appropriate for spatial objects. In addition, the introduction of new access methods for conventional business applications (e.g. extendible hashing [FAGI79, LITW80]) would be expedited by a facility to add new access methods.

A complete extended type system should allow:

- 1) the definition of user-defined data types
- 2) the definition of new operators for these data types
- 3) the implementation of new access methods for data types
- 4) optimized query processing for commands containing new data types and operators

The solution to requirements 1 and 2 was described in [STON83]; in this paper we present a complete proposal. In Section 2 we begin by presenting a motivating example of the need for new data types, and then briefly review our earlier proposal and comment on its implementation. Section 3 turns to the definition of new access methods and suggests mechanisms to allow the designer of a new data type to use access methods written for another data type and to implement his own access methods with as little work as possible. Then Section 4 concludes by showing how query optimization can be automatically performed in this extended environment.

2. ABSTRACT DATA TYPES

2.1. A Motivating Example

Consider a relation consisting of data on two dimensional boxes. If each box has an identifier, then it can be represented by the coordinates of two corner points as follows:

```
create box (id = i4, x1 = f8, x2 = f8, y1 = f8, y2 = f8)
```

Now consider a simple query to find all the boxes that overlap the unit square, ie. the box with coordinates (0, 1, 0, 1). The following is a compact representation of this request in QUEL:

```
retrieve (box.all) where not  
(box.x2 <= 0 or box.x1 >= 1 or box.y2 <= 0 or box.y1 >= 1)
```

The problems with this representation are:

The command is too hard to understand.

The command is too slow because the query planner will not be able to optimize something this complex.

The command is too slow because there are too many clauses to check.

The solution to these difficulties is to support a box data type whereby the box relation can be defined as:

```
create box (id = i4, desc = box)
```

and the resulting user query is:

```
retrieve (box.all) where box.desc !! "0, 1, 0, 1"
```

Here "!!" is an overlaps operator with two operands of data type box which returns a boolean. One would want a substantial collection of operators for user defined types. For example, Table 1 lists a collection of useful operators for the box data type.

Fast access paths must be supported for queries with qualifications utilizing new data types and operators. Consequently, current access methods must be extended to operate in this environment. For example, a reasonable collating sequence for boxes would be on

Binary operator	symbol	left operand	right operand	result
overlaps	!!	box	box	boolean
contained in	<<	box	box	boolean
is to the left of	<L	box	box	boolean
is to the right of	>R	box	box	boolean
intersection	??	box	box	box
distance	*	box	box	float
area less than	AL	box	box	boolean
area equals	AE	box	box	boolean
area greater	AG	box	box	boolean

Unary operator	symbol	operand	result
area	AA	box	float
length	LL	box	float
height	HH	box	float
diagonal	DD	box	line

Operators for Boxes

Table 1

ascending area, and a B-tree storage structure could be built for boxes using this sequence.

Hence, queries such as

retrieve (box.all) where box.desc AE "0.5,0.5"

should use this index. Moreover, if a user wishes to optimize access for the !! operator, then an R-tree [GUTM84] may be a reasonable access path. Hence, it should be possible to add a user defined access method. Lastly, a user may submit a query to find all pairs of boxes which overlap, e.g:

range of b1 is box
range of b2 is box
retrieve (b1.all, b2.all) where b1.desc !! b2.desc

A query optimizer must be able to construct an access plan for solving queries which contains user defined operators.

We turn now to a review of the prototype presented in [STON83] which supports some of the above function.

2.2. DEFINITION OF NEW TYPES

To define a new type, a user must follow a registration process which indicates the existence of the new type, gives the length of its internal representation and provides input and output conversion routines. e.g:

```
define type-name length = value.  
    input = file-name  
    output = file-name
```

The new data type must occupy a fixed amount of space, since only fixed length data is allowed by the built-in access methods in INGRES. Moreover, whenever new values are input from a program or output to a user, a conversion routine must be called. This routine must convert from character string to the new type and back. A data base system calls such routines for built-in data types (e.g. ascii-to-int, int-to-ascii) and they must be provided for user-defined data types. The input conversion routine must accept a pointer to a value of type character string and return a pointer to a value of the new data type. The output routine must perform the converse transformation.

Then, zero or more operators can be implemented for the new type. Each can be defined with the following syntax:

```
define operator token = value.  
    left-operand = type-name.  
    right-operand = type-name.  
    result = type-name.  
    precedence-level like operator-2.  
    file = file-name
```

For example:

```
define operator token = !!.  
    left-operand = box.  
    right-operand = box.  
    result = boolean.  
    precedence like *.  
    file = /usr/foobar
```

All fields are self explanatory except the precedence level which is required when several user defined operators are present and precedence must be established among them. The file /usr/foobar indicates the location of a procedure which can accept two operands of type box and return true if they overlap. This procedure is written in a general purpose programming language and is linked into the run-time system and called as appropriate during query processing.

2.3. Comments on the Prototype

The above constructs have been implemented in the University of California version of INGRES [STON76]. Modest changes were required to the parser and a dynamic loader was built to load the required user-defined routines on demand into the INGRES address space. The system was described in [ONG84].

Our initial experience with the system is that dynamic linking is not preferable to static linking. One problem is that initial loading of routines is slow. Also, the ADT routines must be loaded into data space to preserve sharability of the DBMS code segment. This capability requires the construction of a non-trivial loader. An "industrial strength" implementation might choose to specify the user types which an installation wants at the time the DBMS is installed. In this case, all routines could be linked into the run time system at system installation time by the linker provided by the operating system. Of course, a data base system implemented as a single server process with internal multitasking would not be subject to any code sharing difficulties, and a dynamic loading solution might be reconsidered.

An added difficulty with ADT routines is that they provide a serious safety loophole. For example, if an ADT routine has an error, it can easily crash the DBMS by overwriting DBMS data structures accidentally. More seriously, a malicious ADT routine can overwrite the entire data base with zeros. In addition, it is unclear whether such errors are due to bugs in the user routines or in the DBMS, and finger-pointing between the DBMS implementor and the ADT implementor is likely to result.

ADT routines can be run in a separate address space to solve both problems, but the performance penalty is severe. Every procedure call to an ADT operator must be turned into a round trip message to a separate address space. Alternately, the DBMS can interpret the ADT procedure and guarantee safety, but only by building a language processor into the run-time system and paying the performance penalty of interpretation. Lastly, hardware support for protected procedure calls (e.g. as in Multics) would also solve the problem.

However, on current hardware the preferred solution may be to provide two environments for ADT procedures. A protected environment would be provided for debugging purposes. When a user was confident that his routines worked correctly, he could install them in the unprotected DBMS. In this way, the DBMS implementor could refuse to be concerned unless a bug could be produced in the safe version.

We now turn to extending this environment to support new access methods.

3. NEW ACCESS METHODS

A DBMS should provide a wide variety of access methods, and it should be easy to add new ones. Hence, our goal in this section is to describe how users can add new access methods that will efficiently support user-defined data types. In the first subsection we indicate a registration process that allows implementors of new data types to use access methods written by others. Then, we turn to designing lower level DBMS interfaces so the access method designer has minimal work to perform. In this section we restrict our attention to access methods for a single key field. Support for composite keys is a straight forward extension. However, multidimensional access methods that allow efficient retrieval utilizing subsets of the collection of keys are beyond the scope of this paper.

3.1. Registration of a New Access Method

The basic idea which we exploit is that a properly implemented access method contains only a small number of procedures that define the characteristics of the access

method. Such procedures can be replaced by others which operate on a different data type and allow the access method to "work" for the new type. For example, consider a B-tree and the following generic query:

retrieve (target-list) where relation.key OPR value

A B-tree supports fast access if OPR is one of the set:

$\{=, <, \leq, >, \geq\}$

and includes appropriate procedure calls to support these operators for a data type (s). For example, to search for the record matching a specific key value, one need only descend the B-tree at each level searching for the minimum key whose value exceeds or equals the indicated key. Only calls on the operator " $\leq$ " are required with a final call or calls to the routine supporting " $=$ ".

Moreover, this collection of operators has the following properties.

- P1) $\text{key-1} < \text{key-2}$ and $\text{key-2} < \text{key-3}$ then $\text{key-1} < \text{key-3}$
- P2) $\text{key-1} < \text{key-2}$ implies not $\text{key-2} < \text{key-1}$
- P3) $\text{key-1} < \text{key-2}$ or $\text{key-2} < \text{key-1}$ or $\text{key-1} = \text{key-2}$
- P4) $\text{key-1} \leq \text{key-2}$ if $\text{key-1} < \text{key-2}$ or $\text{key-1} = \text{key-2}$
- P5) $\text{key-1} = \text{key-2}$ implies $\text{key-2} = \text{key-1}$
- P6) $\text{key-1} > \text{key-2}$ if $\text{key-2} < \text{key-1}$
- P7) $\text{key-1} \geq \text{key-2}$ if $\text{key-2} \leq \text{key-1}$

In theory, the procedures which implement these operators can be replaced by any collection of procedures for new operators that have these properties and the B-tree will "work" correctly. Lastly, the designer of a B-tree access method may disallow variable length keys. For example, if a binary search of index pages is performed, then only fixed length keys are possible. Information of this restriction must be available to a type designer who wishes to use the access method.

The above information must be recorded in a data structure called an access method template. We propose to store templates in two relations called TEMPLATE-1 and TEMPLATE-2 which would have the composition indicated in Table 2 for a B-tree access method. TEMPLATE-1 simply documents the conditions which must be true for the

operators provided by the access method. It is included only to provide guidance to a human wishing to utilize the access method for a new data type and is not used internally in the system. TEMPLATE-2, on the other hand, provides necessary information on the data types of operators. The column "opt" indicates whether the operator is required or optional. A B-tree must have the operator " $\leftarrow$ " to build the tree; however, the other operators are optional. Type1, type2 and result are possible types for the left operand, the right operand, and the result of a given operator. Values for these fields should come from the following collection:

a specific type, e.g. int, float, boolean, char
 fixed, i.e. any type with fixed length
 variable, i.e. any type with a prescribed varying length format
 fix-var, i.e. fixed or variable
 type1, i.e. the same type as type1
 type2, i.e. the same as type2

After indicating the template for an access method, the designer can propose one or more collections of operators which satisfy the template in another relation, AM. In Table

TEMPLATE-1	AM-name	condition
	B-tree	P1
	B-tree	P2
	B-tree	P3
	B-tree	P4
	B-tree	P5
	B-tree	P6
	B-tree	P7

TEMPLATE-2	AM-name	opr-name	opt	left	right	result
	B-tree	=	opt	fixed	type1	boolean
	B-tree	<	opt	fixed	type1	boolean
	B-tree	$\leftarrow$	req	fixed	type1	boolean
	B-tree	>	opt	fixed	type1	boolean
	B-tree	$\rightarrow$	opt	fixed	type1	boolean

Templates for Access Methods

Table 2

AM	class	AM-name	opr	generic name	opr-id opr	Ntups	Npages
	int-ops	B-tree	=	=	id1	N / Ituples	2
	int-ops	B-tree	<	<	id2	F1 * N	F1 * NUMpages
	int-ops	B-tree	≤	≤	id3	F1 * N	F1 * NUMpages
	int-ops	B-tree	>	>	id4	F2 * N	F2 * NUMpages
	int-ops	B-tree	≥	≥	id5	F2 * N	F2 * NUMpages
	area-op	B-tree	AE	=	id6	N / Ituples	3
	area-op	B-tree	AL	<	id7	F1 * N	F1 * NUMpages
	area-op	B-tree	AG	>	id8	F1 * N	F1 * NUMpages

The AM Relation

Table 3

3 we have shown an AM containing the original set of integer operators provided by the access method designer along with a collection added later by the designer of the box data type. Since operator names do not need to be unique, the field opr-id must be included to specify a unique identifier for a given operator. This field is present in a relation which contains the operator specific information discussed in Section 2. The fields, Ntups and Npages are query processing parameters which estimate the number of tuples which satisfy the qualification and the number of pages touched when running a query using the operator to compare a key field in a relation to a constant. Both are formulas which utilize the variables found in Table 4, and values reflect approximations to the computations found in [SELI79] for the case that each record set occupies an individual file. Moreover, F1 and F2 are surrogates for the following quantities:

$$F1 = (\text{value} - \text{low-key}) / (\text{high-key} - \text{low-key})$$

$$F2 = (\text{high-key} - \text{value}) / (\text{high-key} - \text{low-key})$$

With these data structures in place, a user can simply modify relations to B-tree using any class of operators defined in the AM relation. The only addition to the modify command is a clause "using class" which specifies what operator class to use in building and accessing the relation. For example the command

modify box to B-tree on desc using area-op

Variable	Meaning
N	number of tuples in a relation
NUMpages	number of pages of storage used by the relation
Ituples	number of index keys in an index
Ipages	number of pages in the index
value	the constant appearing in: rel-name.field-name OPR value
high-key	the maximum value in the key range if known
low-key	the minimum value in the key range if known

Variables for Computing Ntups and Npages

Table 4

will allow the DBMS to provide optimized access on data of type box using the operators {AE,AL,AG}. The same extension must be provided to the index command which constructs a secondary index on a field, e.g:

index on box is box-index (desc) using area-op

To illustrate the generality of these constructs, the AM and TEMPLATE relations are shown in Tables 5 and 6 for both a hash and an R-tree access method. The R-tree is assumed to support three operators, contained-in ($\subset$), equals ($=$) and contained-in-or-equals ($\subset\supseteq$). Moreover, a fourth operator (UU) is required during page splits and finds the box which is the union of two other boxes. UU is needed solely for maintaining the R-tree data structure, and is not useful for search purposes. Similarly, a hash access method requires a hash function, H, which accepts a key as a left operand and an integer number of buckets as a right operand to produce a hash bucket as a result. Again, H cannot be used for searching purposes. For compactness, formulas for Ntups and Npages have been omitted from Table 6.

3.2. Implementing New Access Methods

In general an access method is simply a collection of procedure calls that retrieve and update records. A generic abstraction for an access method could be the following:

TEMPLATE-1	AM-name	condition
	hash	Key-1 = Key-2 implies H(key1) = H(key-2)
	R-tree	Key-1 << Key-2 and Key-2 << Key-2 implies Key-1 << key-3
	R-tree	Key-1 << Key-2 implies not Key-2 << Key-1
	R-tree	Key-1 <<= Key-2 implies Key-1 << Key-2 or Key-1 == Key-2
	R-tree	Key-1 == Key-2 implies Key-2 == Key-1
	R-tree	Key-1 << Key-1 UU Key-2
	R-tree	Key-2 << Key-1 UU Key-2

TEMPLATE-2	AM-name	opr-name	opt	left	right	result
	hash	=	opt	fixed	type1	boolean
	hash	H	req	fixed	int	int
	R-tree	<<	req	fixed	type1	boolean
	R-tree	=	opt	fixed	type1	boolean
	R-tree	<<=	opt	fixed	type1	boolean
	R-tree	UU	req	fixed	type1	boolean

Templates for Access Methods

Table 5

AM	class	AM-name	opr name	generic opr	opr-id	Ntups	Npages
	box-ops	R-tree	=	=	id10		
	box-ops	R-tree	<<	<<	id11		
	box-ops	R-tree	<<=	<<=	id12		
	box-ops	R-tree	UU	UU	id13		
	hash-op	hash	=	=	id14		
	hash-op	hash	H	H	id15		

The AM Relation

Table 6

open (relation-name)

This procedure returns a pointer to a structure containing all relevant information about a relation. Such a "relation control block" will be called a descriptor. The effect is to make the relation accessible.

close (descriptor)

This procedure terminates access to the relation indicated by the descriptor.

get-first (descriptor, OPR, value)

This procedure returns the first record which satisfies the qualification

..where key OPR value

get-next (descriptor, OPR, value, tuple-id)	This procedure gets the next tuple following the one indicated by tuple-id which satisfies the qualification.
get-unique (descriptor, tuple-id)	This procedure gets the tuple which corresponds to the indicated tuple identifier.
insert (descriptor, tuple)	This procedure inserts a tuple into the indicated relation
delete (descriptor, tuple-id)	This procedure deletes a tuple from the indicated relation.
replace (descriptor, tuple-id, new-tuple)	This procedure replaces the indicated tuple by a new one.
build (descriptor, keyname, OPR)	Of course it is possible to build a new access method for a relation by successively inserting tuples using the insert procedure. However, higher performance can usually be obtained by a bulk loading utility. Build is this utility and accepts a descriptor for a relation along with a key and operator to use in the build process.

There are many different (more or less similar) access method interfaces; see [ASTR76, ALLC80] for other proposals. Each DBMS implementation will choose their own collection of procedures and calling conventions.

If this interface is publicly available, then it is feasible to implement these procedures using a different organizing principle. A clean design of open and close should make these routines universally usable, so an implementor need only construct the remainder. Moreover, if the designer of a new access method chooses to utilize the same physical page layout as some existing access method, then replace and delete do not require modification, and additional effort is spared.

The hard problem is to have a new access method interface correctly to the transaction management code. (One commercial system found this function to present the most difficulties when a new access method was coded.) If a DBMS (or the underlying operating system) supports transactions by physically logging pages and executing one of the

popular concurrency control algorithms for page size granules. (e.g. [BROW81, POPE81, SPEC83, STON85]) then the designer of a new access method need not concern himself with transaction management. Higher level software will begin and end transactions, and the access method can freely read and write pages with a guarantee of atomicity and serializability. In this case the access method designer has no problems concerning transactions, and this is a significant advantage for transparent transactions. Unfortunately, much higher performance will typically result if a different approach is taken to both crash recovery and concurrency control. We now sketch roughly what this alternate interface might be.

With regard to crash recovery, most current systems have a variety of special case code to perform logical logging of events rather than physical logging of the changes of bits. There are at least two reasons for this method of logging. First, changes to the schema (e.g. create a relation) often require additional work besides changes to the system catalogs (e.g. creating an operating system file in which to put tuples of the relation). Undoing a create command because a transaction is aborted will require deletion of the newly created file. Physical backout cannot accomplish such extra function. Second, some data base updates are extremely inefficient when physically logged. For example, if a relation is modified from B-tree to hash, then the entire relation will be written to the log (perhaps more than once depending on the implementation of the modify utility). This costly extra I/O can be avoided by simply logging the command that is being performed. In the unlikely event that this event in the log must be undone or redone, then the modify utility can be rerun to make the changes anew. Of course, this sacrifices performance at recovery time for a compression of the log by several orders of magnitude.

If such logical logging is performed, then a new access method must become involved in logging process and a clean event-oriented interface to logging services should be provided. Hence, the log should be a collection of events, each having an event-id, an associated event type and an arbitrary collection of data. Lastly, for each event type, T, two procedures, REDO(T) and UNDO(T) are required which will be called when the log

manager is rolling forward redoing log events and rolling backward undoing logged events respectively. The system must also provide a procedure.

LOG (event-type, event-data)

which will actually insert events into the log. Moreover, the system will provide a collection of built-in event types. For each such event, UNDO and REDO are available in system libraries. Built-in events would include:

- replace a tuple
- insert a tuple at a specific tuple identifier address
- delete a tuple
- change the storage structure of a relation
- create a relation
- destroy a relation

A designer of a new access method could use the built-in events if they were appropriate to his needs. Alternately, he could specify new event types by writing UNDO and REDO procedures for the events and making entries in a system relation holding event information. Such an interface is similar to the one provided by CICS [IBM80].

We turn now to discussing the concurrency control subsystem. If this service is provided transparently and automatically by an underlying module, then special case concurrency control for the system catalogs and index records will be impossible. This approach will severely impact performance as noted in [STON85]. Alternately, one can follow the standard scheduler model [BERN81] in which a module is callable by code in the access methods when a concurrency control decision must be made. The necessary calls are:

- read (object-identifier)
- write (object-identifier)
- begin
- abort
- commit
- savepoint

and the scheduler responds with yes, no or abort. The calls to begin, abort, commit and savepoint are made by higher level software, and the access methods need not be concerned with them. The access method need only make the appropriate calls on the schedule.

when it reads or writes an object. The only burden which falls on the implementor is to choose the appropriate size for objects.

The above interface is appropriate for data records which are handled by a conventional algorithm guaranteeing serializability. To provide special case parallelism on index or system catalog records, an access method requires more control over concurrency decisions. For example, most B-tree implementations do not hold write locks on index pages which are split until the end of the transaction which performed the insert. It appears easiest to provide specific lock and unlock calls for such special situations, i.e:

```
lock (object, mode)
unlock (object)
```

These can be used by the access method designer to implement special case parallelism in his data structures.

The last interface of concern to the designer of an access method is the one to the buffer manager. One requires five procedures:

```
get (system-page-identifier)
fix (system-page-identifier)
unfix (system-page-identifier)
put (system-page-identifier)
order (system-page-identifier, event-id or system-page-identifier)
```

The first procedure accepts a page identifier and returns a pointer to the page in the buffer pool. The second and third procedures pin and unpin pages in the buffer pool. The last call specifies that the page holding the given event should be written to disk prior to the indicated data page. This information is necessary in write-ahead log protocols. More generally, it allows two data pages to be forced out of memory in a specific order.

An access method implementor must code the necessary access method procedures utilizing the above interfaces to the log manager, the concurrency control manager and the buffer manager. Then, he simply registers his access method in the two TEMPLATE relations.

3.3. Discussion

A transparent interface to the transaction system is clearly much preferred to the complex collection of routines discussed above. Moreover, the access method designer who utilizes these routines must design his own events, specify any special purpose concurrency control in his data structures, and indicate any necessary order in forcing pages out of the buffer pool. An open research question is the design of a simpler interface to these services that will provide the required functions.

In addition, the performance of the crash recovery facility will be inferior to the recovery facilities in a conventional system. In current transaction managers, changes to indexes are typically not logged. Rather, index changes are recreated from the corresponding update to the data record. Hence, if there are n indexes for a given object, a single log entry for the data update will result in $n+1$ events (the data update and n index updates) being undone or redone in a conventional system. Using our proposed interface all $n+1$ events will appear in the log, and efficiency will be sacrificed.

The access method designer has the least work to perform if he uses the same page layout as one of the built-in access methods. Such an access method requires get-first, get-next, and insert to be coded specially. Moreover, no extra event types are required, since the built-in ones provide all the required functions. R-trees are an example of such an access method. On the other hand, access methods which do not use the same page layout will require the designer to write considerably more code.

4. QUERY PROCESSING AND ACCESS PATH SELECTION

To allow optimization of a query plan that contains new operators and types, only four additional pieces of information are required when defining an operator. First, a selectivity factor, *Stups*, is required which estimates the expected number of records satisfying the clause:

...where rel-name.field-name OPR value

A second selectivity factor, S , is the expected number of records which satisfy the clause

...where $\text{relname-1.field-1 OPR relname-2.field-2}$

Stups and S are arithmetic formulas containing the predefined variables indicated earlier in Table 4. Moreover, each variable can have a suffix of 1 or 2 to specify the left or right operand respectively.

Notice that the same selectivity appears both in the definition of an operator (Stups) and in the entry (Ntups) in AM if the operator is used in an index. In this case, Ntups from AM should be used first, and supports an if-then-else specification used for example in the [SEL179] for the operator "=" as follows:

selectivity = (1 / Ituples) ELSE 1/10

In this example selectivity is the reciprocal of the number of index tuples if an index exists else it is 1/10. The entry for Ntups in AM would be (N / Ituples) while Stups in the operator definition would be N / 10.

The third piece of necessary information is whether merge-sort is feasible for the operator being defined. More exactly, the existence of a second operator, OPR-2 is required such that OPR and OPR-2 have properties P1-P3 from Section 3 with OPR replacing "=" and OPR-2 replacing "<". If so, the relations to be joined using OPR can be sorted using OPR-2 and then merged to produce the required answer.

The last piece of needed information is whether hash-join is a feasible joining strategy for this operator. More exactly, the hash condition from Table 6 must be true with OPR replacing "=".

An example of these pieces of information for the operator, AE, would be:

```
define operator token = AE.  
    left-operand = box.  
    right-operand = box.  
    result = boolean.  
    precedence like *.  
    file = /usr/foobar.  
    Stups = 1.  
    S = min (N1, N2).
```

merge-sort with AL.
hash-join

We now turn to generating the query processing plan. We assume that relations are stored keyed on one field in a single file and that secondary indexes can exist for other fields. Moreover, queries involving a single relation can be processed with a scan of the relation, a scan of a portion of the primary index, or a scan of a portion of one secondary index. Joins can be processed by iterative substitution, merge-sort or a hash-join algorithm. Modification to the following rules for different environments appears straightforward.

Legal query processing plans are described by the following statements.

- 1) Merge sort is feasible for a clause of the form:

relname-1.field-1 OPR relname-2.field-2

if field-1 and field-2 are of the same data type and OPR has the merge-sort property. Moreover, the expected size of the result is S. The cost to sort one or both relations is a built-in computation.

- 2) Iterative substitution is always feasible to perform the join specified by a clause of the form:

relname-1.field-1 OPR relname-2.field-2

The expected size of the result is calculated as above. The cost of this operation is the cardinality of the outer relation multiplied by the expected cost of the one-variable query on the inner relation.

- 3) A hash join algorithm can be used to perform a join specified by:

relname-1.field-1 OPR relname-2.field-2

if OPR has the hash-join property. The expected size of the result is as above, and the cost to hash one or both relations is another built-in computation.

- 4) An access method, A for relname can be used to restrict a clause of the form

relname.field-name OPR value

only if relname uses field-name as a key and OPR appears in the class used in the modify command to organize relname. The expected number of page and tuple accesses are given by the appropriate row in AM.

- 5) A secondary index, I for relname can be used to restrict a clause of the form:

relname.field-name OPR value

only if the index uses field-name as a key and OPR appears in the class used to build the index. The expected number of index page and tuple

accesses is given by the appropriate row in AM. To these must be added 1 data page and 1 data tuple per index tuple.

6) A sequential search can always be used to restrict a relation on a clause of the form:

relname.field-name OPR value

One must read NUMpages to access the relation and the expected size of the result is given by Stups from the definition of OPR.

A query planner, such as the one discussed in [SELI79] can now be easily modified to compute a best plan using the above rules to generate legal plans and the above selectivities rather than the current hard-wired collection of rules and selectivities. Moreover, a more sophisticated optimizer which uses statistics (e.g. [KOOI82, PIAT84] can be easily built that uses the above information.

5. CONCLUSIONS

This paper has described how an abstract data type facility can be extended to support automatic generation of optimized query processing plans, utilization of existing access methods for new data types, and coding of new access methods. Only the last capability will be difficult to use, and a cleaner high performance interface to the transaction manager would be highly desirable. Moreover, additional rules in the query optimizer would probably be a useful direction for evolution. These could include when to cease investigating alternate plans, and the ability to specify one's own optimizer parameters, e.g. the constant W relating the cost of I/O to the cost of CPU activity in [SELI79].

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EXTENDING A DATA BASE SYSTEM WITH PROCEDURES

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Abstract

This paper suggests that more powerful data base systems (DBMS) can be built by supporting data base procedures as full fledged data base objects. In particular, allowing fields of a data base to be a collection of queries in the query language of the system is shown to allow complex data relationships to be naturally expressed. Moreover, many of the features present in object-oriented systems and semantic data models can be supported by this facility.

In order to implement this construct, extensions to a typical relational query language must be made and considerable work on the execution engine of the underlying DBMS must be accomplished. This paper reports on the extensions for one particular query language and data manager and then gives performance figures for a prototype implementation. Even though the performance of the prototype is competitive with that of a conventional system, suggestions for improvement are presented.

1. INTRODUCTION

Most current data base systems store information only as data. However, older data base systems (e.g. [DBTG71]) specifically allowed data base procedures written in a general purpose programming language to be called during command execution. Moreover, LISP [WILE84] supports objects which are interchangeably either procedures or data. In this paper we suggest that supporting a restricted form of data base procedures in a DBMS allows complex data base problems to be easily and naturally addressed. In particular, we propose that a field in a data base be allowed to have a value which is a collection of commands in the query language supported by the DBMS (e.g. SQL [SORD84] or QUEL).

Our proposal should augment a field-oriented abstract data type (ADT) facility (e.g. [ONG84]). Such an ADT capability appears useful for supporting relatively simple objects which do not require shared subobjects (e.g. lines, points, complex numbers, etc.). On the other hand, data base procedures are attractive for more

This research was sponsored by the U.S. Air Force Office of Scientific Research Grant 83-0254 and the Naval Electronics Systems Command Contract N39-82-C-0235

complex objects, possibly with shared subobjects (e.g. forms, icons, reports, etc.).

We begin in Section 2 by presenting the data definition facilities for procedural data along with several examples of the use of this construct. Then, in Section 3 we review briefly how to extend one query language with necessary facilities to use procedures. Our choice is QUEL [STON76], but the extensions are easy to map into most other relational query languages. The definition of this language, QUEL+, is indicated in Section 3 and is based on suggestions in [STON84]. Substantial changes to the query execution code of a data base system are required to process QUEL+. In Section 4 we indicate the changes that were necessary to support our constructs in the University of California version of INGRES [STON76]. Then, in Section 5 the performance of our prototype on several problems with complex data relationships is indicated. Lastly, Section 6 discusses ways in which the performance of the prototype could be improved.

2. DATA BASE PROCEDURES

The motivation behind using procedures as full-fledged data base objects was to retain the "spartan simplicity" of the relational model, while allowing it to address situations where it has been found inadequate. Such situations include generalization, aggregation, referential integrity, transitive closure, complex objects with shared subobjects, stored queries, and objects with unpredictable composition. The main advantage of our approach is that a single mechanism can address a large class of recognized deficiencies. We discuss the data definition capabilities of our proposal along with examples of its application to some of the above problems in the remainder of this section.

2.1. Objects with Unpredictable Composition

The basic concept is that a field in a relation can have a value consisting of a collection of query language commands. Consider, for example, a conventional EMP relation with the requirement of storing data on the various hobbies of employees. Three relations containing hobby data might be:

SOFTBALL (emp-name, position, average)

SAILING (emp-name, rating, boat-type, marina)

JOGGING (emp-name, distance, best-time, shoe-type, number-of-races)

Each gives relevant data for a particular hobby. For example, Smith could be added as the catcher of the softball team by:

append to SOFTBALL (name = "Smith", position = "catcher", average = 0)

The desired form of the EMP relation would be:

create EMP (name = c10, age = i4, salary = f8, hobbies = procedure)

Then, for example, Smith could be added as an employee by:

```
append to EMP (
    name = "Smith"
    age = 40
    salary = 10000,
    hobbies = "retrieve (SOFTBALL.all)
              where SOFTBALL.name = "Smith""
)
```

In this case, the first three values are conventional fields while the fourth is a field of data type "collection of commands in the query language". The value of this last field is obtained by executing the command(s) in the field. As such the ultimate value of each hobby's object is an arbitrary collection of records of arbitrary composition. A procedural field has the flexibility to model environments where there is no predetermined structure to objects. A second example of the need for procedural fields is indicated in the next subsection.

2.2. Stored Queries

Most data base systems which preprocess commands in advance of execution (e.g. System R [ASTR76] and the IDM [EPST80]) store access plans or compiled code in the data base system. Such systems already manage a data base of compiled queries. Their implementations would become somewhat cleaner if data base commands became full-fledged data base objects. For example, the precompiler for a programming language could run a conventional APPEND command to insert a tuple into the following relation for each data base command found in a user program:

TODO (id, command)

Then, at run time the program would use the EXECUTE command to be introduced in Section 3:

execute (TODO.command) where TODO.id = value

To substitute parameters into such a command, one requires an additional operator "with" to specify:

execute (TODO.command with param-list) where TODO.id = value

In this way, the compile-time and run-time interfaces to the data base system are the same, resulting in a more compact implementation.(**) Moreover, in Section 6 we discuss how to asynchronously build query processing plans for user commands between the time that the preprocessor inserts them in the TODO relation and the time that the user executes them. Hence, there is no performance penalty to our approach compared to current technology. In fact, our approach may well run faster because in Section 6 we also propose caching the answers to commands as well as their execution plan.

A second use of stored queries is to support the definition of relational views. Each view can be stored as a row in a VIEW relation as follows:

VIEW (name, query)

Here, the retrieval command that defines the view can be stored in the "query" field while the name of the view is stored in the "name" field. The query modification facilities of [STON75] are needed to support the extensions that we propose to a query language in the next section; consequently, it will be seen that

** Of course, authorization must be done for the above command to support access control. It would be beneficial to avoid reauthorizing a command each time it is executed from an application program. A mechanism to accomplish this task is beyond the scope of this paper.

views require very little special case code if implemented as procedural fields.

Lastly, many applications require the ability to store algorithms made up of data base commands in the data base. An example of this kind of application is [KUNG84]. Our proposal contains exactly the facilities needed in such environments.

2.3. Complex Objects with Shared Subobjects

Another example where procedures are helpful is in the modeling of complex objects. Suppose an object is composed of text, line segments, and polygons and is represented in the following relations:

```
OBJECT (Oid, text, shape)
LINE   (Lid, l-desc)
TEXT   (Tid, t-desc)
POLYGON (Pid, p-desc)
```

Subcomponents of objects would be inserted into the LINE, TEXT or POLYGON relation, and we assume that l-desc and p-desc are of type "line" and "point" respectively and utilize a field-oriented ADT facility (e.g. [ONG84]). For example:

```
append to LINE (Lid = 22,
                  l-desc = "(0,0) (14,28)")
append to POLYGON (Pid = 44,
                   p-desc = "(1,10) (14,22) (6,19) (12,22)")
append to TEXT (Tid = 16,
                t-desc = "the fox jumped over the log")
```

Then, the "text" and "shape" fields of OBJECT would be of type procedure, and each tuple in OBJECT would contain queries to assemble a specific object from pieces stored in the other relations. For example, the following query would make object 6 be composed of all line segments with identifiers less than 20, polygon 44, and the first 9 text fragments.

```
append to OBJECT( Oid = 6,
                  shape = "retrieve (LINE.all) where LINE.Lid < 20
                           retrieve (POLYGON.all) where POLYGON.Pid = 44",
                  text = "retrieve (TEXT.all) where TEXT.Tid < 10")
```

Notice that sharing is easily accomplished by inserting queries into multiple "shape" or "text" fields which reference the same subobject.

Additional examples of complex objects include forms (such as found in a system like FADS [ROWE82]), icons, reports, and complex geographic objects (e.g. a plumbing fixture which makes a right angle bend).

When objects can have a variety of subobjects and those subobjects can be shared, most contemporary modeling ideas are flawed. For example, the proposal of [HASK82, LORI83] does not easily allow shared subobjects. Semantic data models (e.g. [HAMM81, MYLO80, SHIP81, SMIT77, ZANI83]) lack the flexibility to deal with uncertain structure. The proposal of [COPE84] allows sharing by storing subobjects as separate records and connecting them with pointer chains. Our sharing is accomplished without requiring a specialized low level storage manager, and we will show in Section 6 how caching can be used to make performance

competitive with pointer based proposals

2.4. Generalizations to Arbitrary Procedures

Our proposal should be easily generalizable to procedures written in a general purpose programming language. An example that can utilize more general procedures is a graphics application that wishes to store icons in the data base (e.g. [KALA85]). Icons should be stored in human readable form, so their description can be browsed easily. However, display software requires icons to be converted into a display list for a particular graphics terminal. An icon could be a complex object, and its components assembled by a query. However, the components must then be turned into a display list by a procedure in a general purpose programming language which appears in an application program. Efficiency can be gained by caching icons as noted in Section 6; however, further efficiency results from caching the actual display list. Such a capability requires general procedures rather than just data base procedures.

A second example of the need for general procedures is in the support for extended data type proposals (e.g. [ONG84]). They require user-defined procedures to implement new operators. Such procedures must be called by the DBMS as appropriate, and it would be more natural if they were full-fledged data base objects.

A last example of the use of general procedures would be in the system catalogs of a typical relational data base system where the following two relations appear:

RELATION (relation-name, owner, ...)

ATTRIBUTE (relation-name, attribute-name, position, data-type, ...)

Whenever a relation with N attributes is "opened", a "descriptor" must be built by accessing one tuple in RELATION plus N tuples from the ATTRIBUTE relation. In order to allow "browsing" of the system catalogs, it is desirable to store the catalogs in the above fashion; however, the penalty is the lengthy time required to open a relation.

An alternate solution is to add a procedural field to RELATION, e.g:

RELATION (relation-name, owner, ... , descriptor)

The "descriptor" field contains queries to retrieve the appropriate tuples from the ATTRIBUTE relation and the current tuple from the RELATION relation. These queries are surrounded by code in a general purpose programming language to build the actual descriptor in the format desired by the run time system.

In Section 6 we will discuss a technique that allows the value for a procedural field to be cached in the field itself. If this is accomplished, then the N accesses to the ATTRIBUTE relation are avoided, and the descriptor can be accessed directly from the RELATION relation. Writes to tuples in the ATTRIBUTE relation which make up an object (an infrequent event) will cause the cached value to be invalidated as explained in Section 6. The next time a relation is opened, the contents of the cached value must be reassembled.

Alternate implementations of complex objects (e.g. [COPE84]) store subobjects as individual records. Hence, pointers must be followed to assemble a composite

object. Sophisticated clustering will be required to avoid extra disk reads in this environment. Moreover, if subobjects are shared, it will be impossible to guarantee clustering. Our caching implementation should offer superior performance to one based on pointers when updates are infrequent. It should be noted, however, that our caching idea can be applied to any DBMS to improve performance. Hence, a pointer based DBMS that also implemented caching might be an attractive alternative.

We now turn to a special case of procedural data types and indicate its utility.

2.5. Referential Integrity

Consider the standard EMP and DEPT example as follows:

EMP (name, age, salary, dept)

DEPT (dname, floor, budget)

Here, one often wants to guarantee that the values that occur in the column "dept" of EMP are a subset of the values that occur in the field "dname" in DEPT. This concept has been termed *referential integrity* in [DATE81] and occurs because "dept" is, in effect, a pointer to a tuple in DEPT and is represented by a foreign key.

Procedural data can alleviate the need for special case syntax and implementation code to support referential integrity in the following way. Suppose the "dept" field for each employee in the EMP relation contains the following procedure:

retrieve (DEPT.all) where DEPT.dname = "the-appropriate-dept"

In this case the following semantics are automatically enforced. Whenever an employee is hired and assigned to a non-existent department, then the procedure in the "dept" field evaluates to null, and the employee is effectively placed in the null department. Moreover, whenever a department is deleted from the DEPT relation, then all employees who were previously in that department now have a procedural field which evaluates to null and are thereby placed in the null department. Although [DATE81] has several other options, procedural data captures the main thrust of that proposal.

Notice that all fields in the "dept" column have the same basic query as their value, differing only in the constant used in the qualification. Consider an implementation of this special case whereby the parameterized command(s) is stored in the system catalogs and only the parameter(s) stored in the field itself. Hence, in the example above, only the department name of the employee's department would appear in the field "dept", while the remainder of the query:

retrieve (DEPT.all) where DEPT.dname = parameter-1

would appear in the system catalogs. Moreover, an update to the "dept" field would only need to specify the parameter and not the entire query, e.g:

append to EMP (name = "Joe", age = 25, salary = 10000, dept = "shoe")

To specify this special case syntactically, one could proceed in two steps. First, one could register the procedure containing the parameter(s) with the data manager and give it some internal name, say DEPARTMENT, with the following

command:

define DEPARTMENT as retrieve (DEPT.all) where DEPT.dname = parameter-1

Then, one could create the EMP relation as:

create EMP (name = c10, age = i4, salary = f8, dept = DEPARTMENT)

Alternatively, one could avoid the registration step for commonly used procedures such as the one above by accepting the following syntax:

create EMP (name = c10, age = i4, salary = f8, dept = DEPT[dname])

The syntactic token DEPT[dname] signifies that the procedure

retrieve (DEPT.all) where DEPT.dname = parameter-1

should be automatically defined and associated with the "dept" field.

The data type "pointer to a tuple" suggested in [POWE83, ZANI83] can be effectively supported by another special case. Suppose each relation automatically contains a unique identifier (UID), a feature commonly requested in some environments. Moreover, suppose in the syntax:

create EMP (name = c10, age = i4, salary = f8, dept = DEPT)

the DEPT token is automatically associated with the query:

retrieve (DEPT.all) where DEPT.UID = parameter-1

In this way procedures can be used to support the capability that a field in one relation can be a uniquely identified tuple in another relation.

2.6. Aggregation and Generalization

Procedural fields can support both generalization and aggregation as proposed in [SMIT77]. For example, consider:

PEOPLE (name, phone#)

where phone# is of type procedure and is an aggregate for the more detailed values area-code, exchange and number. As such, the following parameterized procedure can be used for the phone# field:

retrieve (area-code = parameter-1, exchange = parameter-2, number = parameter-3)

A simple append to PEOPLE might be:

append to PEOPLE (name = "Fred", phone# = "415-841-3461")

Here, "-" is the assumed separator between the values of the three parameters.

Generalization is also easy to support. If all employees have exactly one hobby, then the hobbies field in the example EMP relation from Section 2.1 will specify a simple generalization hierarchy. In fact, our example use of hobbies supports a generalization hierarchy with members which can be in several of the sub-categories at once.

2.7. Summary

In summary, data base procedures are a high leverage construct. Not only can they be used to simulate a variety of semantic data modeling ideas such as generalization and aggregation, but also they can be used to support objects that have unpredictable composition and shared subobjects. In addition, they are useful

in simplifying the design of current relational systems by allowing a more uniform treatment of compiled queries and views. Lastly, support for procedures written in an arbitrary programming language is a natural and valuable extension, and a preliminary proposal in this direction appears in [STON86]. Hence, a single construct is useful in a wide variety of circumstances.

3. THE QUERY LANGUAGE, QUEL+

In order to make procedures a useful construct, several extensions must be made to QUEL and these are indicated in the next several subsections. This language, QUEL+, contains slight modifications to the facilities proposed in [STON84], and a concise summary of its extensions to QUEL appears in Appendix 1.

3.1. Execution of the Data

A procedural field can be interpreted in two ways, namely it has a definition which is the QUEL code in the field and a value which is obtained by executing the QUEL commands. Since a user needs to gain access to both representations, we use the convention that a normal retrieval returns the definition. For example, the query:

retrieve (EMP.hobbies) where EMP.name = "Smith"

will return a collection of QUEL commands. Execution of a procedural field is accomplished by an additional QUEL+ command which allows one to execute data in the data base. For example, one can find all the hobby data for Smith by running the following command:

execute (EMP.hobbies) where EMP.name = "Smith"

This command will search for qualifying tuples and then execute the contents of the hobbies field.

Two points should be noted about the above command. First, notice that a user program must be prepared to accept the tuples returned from the above query. Since the composition of these tuples may vary from tuple to tuple, the run time system must send output to an application program using a more complex format than often used currently. In particular, each tuple must either be self-describing or a tuple descriptor must be sent to the application which describes all subsequent tuples until a new descriptor is sent. Run time support code in the application program must be prepared to accept this more complex format and deal with the more complex buffering and communication with variables in an application program that this entails. Second, a user must note which fields contain procedural data, since retrieving a procedural field does not yield the ultimate data value. We considered automatic evaluation of procedural fields, but this option requires a second operator to "unevaluate" the procedure and seemed no more user-friendly. Also, it would have required the application program to accept unnormalized relations. For example, automatic evaluation of procedural fields for the query:

retrieve (EMP.name, EMP.hobbies) where EMP.age > 35

would yield an unnormalized relation as a result.

In some applications, it is desirable to execute only one of a collection of qualifying tuples. The following command will execute the hobby description for one

employee over 70.

execute-one (EMP.hobbies) where EMP.age > 70

The intent of this command is that query processing heuristics along the lines of [SELI79] would be run on each candidate hobby description. The one with the expected least cost would be selected for execution. The use of this construct in a particular expert system application is discussed in [KUNG84].

3.2. Multiple-Dot Notation

Our second extension to QUEL allows the components of a complex object to be addressed directly. For example, one could retrieve the batting average of Smith as follows:

retrieve (EMP.hobbies.average) where EMP.name = "Smith"

This multiple-dot notation has many points in common with the data manipulation language GEM [ZANI83], and allows one to conveniently access subsets of components of complex objects. More exactly, QUEL+ allows an indirectly referenced column name of the form:

relation.column-name-1.column-name-2 ... column-name-n

wherever a normal column name:

relation.column-name

is allowed in QUEL. The only restriction is that "column-name-i" must be a procedural data type for $1 \leq i < n-1$. Moreover, column-name-(i+1) is a column in any relation specified by a RETRIEVE command contained in the field specified by column-name-i. Of course, the same construct is allowed for relation surrogates (tuple variables).

The above QUEL+ command returns the average of Smith for any hobby that has a field with name "average". Since there may be several hobbies with this field defined, one requires a notation to restrict the average only to the SOFTBALL relation. This is easily accomplished with another operator, i.e:

retrieve (EMP.hobbies.average)
where EMP.name = "Smith"
and EMP.hobbies.average in SOFTBALL

Here "in" expects an indirectly referenced column name as the left operand and a relation name as the right operand and returns true only if the column is in the indicated relation. Additional operators associated with procedural objects may be appropriate and will be added to QUEL+ as a need arises.

3.3. Extended Scoping

To change the position of Smith from catcher to outfield, one could make a direct update to the SOFTBALL relation. However, it is sometimes cleaner to allow the update to be made through the EMP relation as follows:

replace EMP.hobbies (position = "outfield") where EMP.name = "Smith"

The desired construct is that a procedural field (in this case EMP.hobbies) can appear as the target of a DELETE, REPLACE or APPEND command. In general, this procedural field is identified by an arbitrary multiple-dot expression of the

form discussed in the previous section, and we term this expression the scope of the update.

The semantics of an extended scope command are that the RETRIEVE commands in the procedural field used as the target of the update command define conventional relational views. Once a specific instance of such a procedural field has been identified, for each view, V_i , associated with a RETRIEVE command, R_i , one need only replace the the update scope by V_i in every place it appears in the user command, and then standard query modification [STON75] using R_i should be performed on the qualification and the target list of the resulting user's command.

For example, if Smith's "EMP.hobbies" field contains the single query:

retrieve (SOFTBALL.all) where SOFTBALL.name = "Smith"

then the above command to move Smith to the outfield will have the form

replace EMP.hobbies (position = "outfield")

once the clause

where EMP.name = "Smith"

has been evaluated to identify a specific "EMP.hobbies" value. Hence, this query is turned into:

replace V1 (position = "outfield")

and then query modification converts it to:

replace SOFTBALL (position = "outfield") where SOFTBALL.name = "Smith"

Notice that this construct allows a very simple means for supporting relational views. If the definition of each view appears in the VIEW relation as suggested in the previous section, e.g:

VIEW (name, query)

then any command involving a view, V , need only be modified to replace every reference to V with VIEW.query and then the clause

VIEW.name = V

must be added to the qualification. The resulting command will be one containing multiple-dot clauses and extended scoping statements and can be executed as a conventional QUEL+ command.

3.4. Extended Scoping with Tuple Variables

In addition to allowing the above construct, QUEL+ also allows a tuple variable to be used whenever a relation name or a field of type QUEL is permissible. Hence, the example above can also be expressed as:

range of e is EMP.hobbies

replace e (position = "outfield") where EMP.name = "Smith"

3.5. Relation Level Operators

In addition, QUEL+ supports relation level operators, including union, intersection, outer join, natural join, containment and a test for emptiness. We illustrate the use of this construct with an example from the previous section where

objects were made up of lines, polygons, and text fragments. In this situation, one might want to find all pairs of objects, one of which contains all the shapes in the other. This would be formulated as:

```
range of o is OBJECT
range of ol is OBJECT
retrieve (o.Oid, ol.Oid) where o.shape >> ol.shape
```

Here, the containment operator $>>$, accepts two procedural operands and returns true if the relation specified by the procedure in the left operand includes the relation specified by the procedure in the right operand. The relation on the left is found by constructing the outer union defined by the RETRIEVE commands in o.shape. If all commands have identical target lists, then the outer union is the same as a normal union. Otherwise, it is formed by constructing a relation with all columns appearing in any command, filling each target list with nulls to be the full width of the composite relation, and then performing a normal union. This resulting relation must be compared for set inclusion with the relation to which ol.shape evaluates. Our initial collection of operators is indicated in Table 1.

4. PROCESSING QUEL+

The purpose of this section is to explain how our existing prototype executes QUEL+ commands. This prototype supports the complete language noted in the previous section with the exception of execute-one and extended scoping statements. Moreover, it only implements general QUEL procedural fields. The optimization routines to support the special case that all queries in a given column differ only by a collection of parameters have not yet been implemented.

Although more sophisticated query processing algorithms have been constructed [SELI79, KOOI82], our implementation builds on the original INGRES strategy [WONG76]. The implementation of QUEL+ has been accomplished using this code because it is readily available for experimentation. Integration of our constructs into more advanced optimizers appears straightforward, and we discuss

Operator	Function
U	union
!!	intersection
>>	containment
<<	containment
==	equality
<>	inequality
JJ	natural join on all common column names
OJ	outer (natural) join
empty	emptiness

Relation Level Operators

Table 1

this point again at the end of this section.

Detachment of one-variable queries that do not contain multiple-dot or relation level operators can proceed as in the original INGRES algorithms [WONG76]. Similarly, the reduction module of decomposition is unaffected by our extensions to QUEL. In addition, tuple substitution is performed when all other processing steps fail. A glance at the left hand column of Figure 1 indicates that a test for zero variables must be inserted into the original flow of control after the reduction module. Then, new facilities must be included to process the "yes" branch of the test. These include a test for whether there is a relation to materialize and the code to perform this step. Lastly, the one-variable query processor must be extended to process relation level operators. We explain these extensions with a detailed example. The desired task is to find the polygon descriptions with identifiers less than 5 for all objects which have the same collection of shapes as the complex object with Oid equal to 10, i.e:

```
range of o is OBJECT
range of o1 is OBJECT
retrieve (o.shape.p-desc)
where o.shape.Pid < 5
and o.shape == o1.shape
and o1.Oid = 10
```

In the initial step of the reduction process the last clause in the query is found to have a single variable, so it can be executed as:

```
retrieve into TEMP-1 (o1.shape) where o1.Oid = 10
```

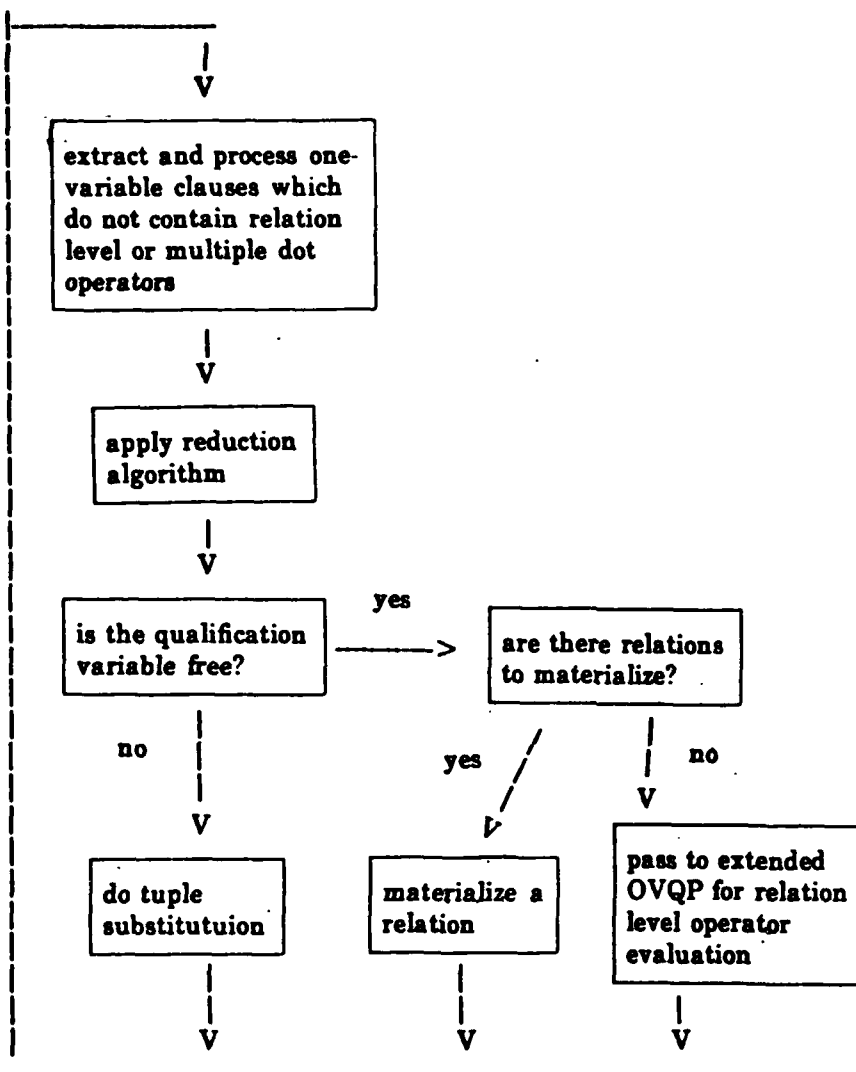
The original query is now:

```
retrieve (o.shape.p-desc) where o.shape.Pid < 5 and o.shape == TEMP-1.shape
```

The first clause above contains a multiple-dot attribute and should not be processed until later. At this point reduction fails and the query still has two variables in it, so processing falls through to the tuple substitution module. If TEMP-1 is selected for substitution, the resulting query is:

```
retrieve (o.shape.p-desc)
where o.shape.Pid < 5
and o.shape == "QUEL-constant-1"
```

Figure 1 shows a diagram of the extended decomposition process.



Extended Decomposition

Figure 1

Notice that the variable "TEMP-1.shape" has been replaced by a constant "QUEL-constant-1" which is a collection of QUEL commands. Processing now returns to the top of the loop where the query still does not have any one-variable clauses. Processing again returns to tuple substitution where the variable o might be chosen. This results in the query:

```
retrieve ("QUEL-constant-2".p-desc)
where "QUEL-constant-2".Pid < 5
and "QUEL-constant-3" == "QUEL-constant-1"
```

Notice that o.shape has been replaced by two constants "QUEL-constant-2" and "QUEL-constant-3" which are identical. When o.shape is materialized, there will be a one-relation clause (o.shape.Pid < 5) that can be used to restrict and project the relation. Moreover, it is desirable to check this clause as early as possible because the current query will have no answer if this clause is false. On the other hand, o.shape must be retained as a complete object so that the relation level comparison with QUEL-constant-1 can be performed if necessary. In order to avoid forcing the relation level operator to be executed first, we have duplicated the QUEL constant and thereby retained the option of performing the one-variable restriction first. Even though QUEL-constant-2 and QUEL-constant-3 define the same object, the caching discussed in Section 6 should avoid materializing this object more than once.

Now the command has zero variables and is passed to the materialize module. This processing step chooses one of the QUEL constants and materializes the outer-union of the RETRIEVE commands into a relation TEMP-2. If "QUEL-constant-2" is chosen, then the resulting query will be:

```
retrieve (TEMP-2.p-desc) where
TEMP-2.Pid < 5
and "QUEL-constant-3" == "QUEL-constant-1"
```

This query now has a one-variable clause which can be detached and processed creating another temporary relation TEMP-3. If TEMP-3 is empty then the query is false and can be terminated. Alternately, processing must continue on the following command:

```
retrieve (TEMP-3.p-desc) where "QUEL-constant-3" == "QUEL-constant-1"
```

The qualification is again free from variables, so another relation must be materialized. If "QUEL-constant-1" is chosen, we obtain:

```
retrieve (TEMP-3.p-desc) where "QUEL-constant-3" == TEMP-4
```

The qualification is still free from variables, so the final relation must be materialized as follows:

```
retrieve (TEMP-3.p-desc) where TEMP-5 == TEMP-4
```

After another trip around the processing loop, no further materialization is possible. Hence, the query must now be passed to the one-variable query processor. This module will process the operator == for the two relations involved.

Several comments are appropriate at this time. First, this algorithm delays materializing a relation until there is no conventional processing to do. In addition, it delays evaluating relation level operators until there is nothing else to do. This reflects our belief that expensive operations should never be done until

absolutely necessary. The current prototype only materializes a procedural field if the desired columns actually appear in the result. This tactic avoids obviously unnecessary materializations. However, no attempt has been made to materialize only a subset of a procedural object by using qualification in the user command to advantage. For example, only the tuples where $Pid < 5$ could have been materialized from the query in "QUEL-constant-2" by modifying the qualification. Such restricted materializations would not allow the caching that we have in mind, and we did not consider them. A more sophisticated query planner would try to optimize the decision of whether to materialize the value of the whole procedural object or a qualified subset.

Second, most current optimizers build a complete query plan in advance of executing the command. Such optimizers (e.g. [SELI79, KOOI82]) can construct a plan for the portion of the query without nested dot constructs. However, run-time planning will be required on remaining portions of commands. For example, the following query must be processed by tuple substitution for o or ol.

retrieve (o.shape.p-desc, ol.shape.p-desc) where o.shape.l-desc = ol.shape.l-desc

After substitution twice, the remaining query is:

retrieve (TEMP-1.p-desc, TEMP-2.p-desc) where TEMP-1.l-desc = TEMP-2.l-desc

The characteristics of TEMP-1 and TEMP-2 are not known until run time, so further query planning must be deferred to this time.

The only exception to run time planning would occur if all values in a procedural column contain the same query as discussed in Section 2. In this situation, a view translation algorithm can be run on the initial user command instead of applying the algorithm of this section. The algorithm is similar to the one presented in [STON75] and would translate a multiple-dot query into a conventional query which can be optimized in the conventional fashion. This "flattening" of a query will allow a compile time plan to be built and additionally will support a wide range of query processing alternatives to be explored, rather than just the "outside-to-inside" strategy discussed in this section. The details of this algorithm are straight-forward and are omitted for the sake of brevity.

Lastly, in our prototype the module that materializes a relation passes the RETRIEVE commands to another process which also runs the INGRES+ code. This second INGRES+ executes the command, stores the resulting relation in the data base, and then passes control back to the first INGRES+. A second process is required because the INGRES code will not allow a command to suspend in the middle of the decomposition process so that a new command can be executed. The ability to "stack" the execution state of a query would be a very desirable addition to the system.

5. BENCHMARK RESULTS

It would be clearly desirable to compare the performance of INGRES+ against various other approaches to object management. These could include using a conventional relational system as well as prototypes with other capabilities (e.g. [COPE84, LORI83]). Only a conventional relational system was easily available in our environment as a test case. Hence, a more detailed performance study is left as a future exercise and would require the acquisition of appropriate hardware to

run other prototypes.

In this section we describe a collection of benchmarks which we performed on our prototype. We modeled three different tasks using QUEL+ and then compared them to a conventional relational system, namely INGRES [STON76]. In all cases we chose tasks which would result in different queries in the two systems. Running the same command in both systems would clearly result in equal performance. In all tests recovery and concurrency control has been turned off, and CPU time and total elapsed time in a single user environment were tabulated. For convenience, INGRES numbers are normalized to 1 while INGRES+ numbers are given as a multiple of the corresponding INGRES result. All tests are run on a single-user VAX 11/780.

Both systems contain substantial inefficiencies (e.g. run-time optimization, generation of an excessive number of temporary relations). However, it appears that such problems penalize both systems about equally. Only three issues excessively penalize INGRES+. First, the unnecessary communication with a second INGRES+ task adds unnecessary overhead that could be eliminated in a commercial implementation. Second, in many cases INGRES will be seen to execute a single two-variable query while INGRES+ runs a larger number of one-variable commands. Run time query planning of a larger number of commands imposes an excessive penalty on INGRES+. Lastly, the flattening of parameterized procedural fields has not yet been implemented in INGRES+. Consequently, execution of multiple-dot queries is constrained by the structure of the query, and an inefficient plan may be executed as a result. Hence, a compiled query implementation of QUEL+ which included parameterized procedural fields should yield results similar to or more favorable toward INGRES+ than those we present.

The three experiments are discussed in the following subsections.

5.1. Simulation of Simple Complex Objects

This experiment involves accessing simple variant records corresponding to hobbies in the EMP relation of Section 2. Each of 7000 employees has a collection of hobbies. From a total of 50 possible hobbies, each employee practices between one and eight.

Both an INGRES and an INGRES+ data base must store records on each of the 50 hobbies in relations:

SOFTBALL (emp-name, other data)
SAILING (emp-name, other data)
JOGGING (emp-name, other data)

.

A normal DBMS would store in addition the relations:

EMP(name, age, salary)
HOBBIES(emp-name, hobby-name)

while an INGRES+ data base would only require a single relation:

EMP(name, age, salary, hobbies)

The field "hobbies" has a collection of queries, one per hobby as noted in Section 2.

The task is to find the information on all hobbies for a given employee and is expressed in INGRES+ as follows:

```
execute (EMP.hobbies) where EMP.name = "unique-emp"
```

A normal DBMS query language cannot express this task, and the most reasonable option is to execute the following algorithm:

```
retrieve (HOBBIES.hobby-name) where HOBBIES.emp-name = "unique-emp"
for each such hobby-name do
  retrieve (hobby-name.all) where hobby-name.emp-name = "unique-emp"
end-do
```

Table 2 indicates a performance comparison for various numbers of hobbies per employee. The INGRES+ numbers result from running the above execute command while the INGRES numbers were obtained using the terminal monitor to retrieve the hobbies for a given employee and then executing the appropriate number of retrieve commands to obtain hobby data. This would simulate a user who ran a query to obtain the collection of hobbies and then ran the correct collection of queries on the various hobbies relations. Notice that the INGRES+ option is superior except when there is a single hobby per employee. This performance difference results from the fact that a large number of queries are passed through the INGRES terminal monitor, which has noticeable overhead. The INGRES+ solution runs the same collection of queries, but the hobby queries are generated internally by the system and do not go through a terminal monitor.

5.2. Simulation of More Complex Objects With Shared Subobjects

Consider the example from Section 2 where complex objects are composed of lines, text and polygons. Moreover, assume that these subobjects must be shared among various complex objects. Consequently, both schemas have relations for the subobjects as follows:

```
LINE (Lid, l-desc)
TEXT (Tid, t-desc)
```

Query	INGRES-CPU	INGRES+-CPU	INGRES-total	INGRES+-total
one-hobby	1	1.23	1	1.28
four-hobby	1	.73	1	.61
eight-hobby	1	.59	1	.61

A Benchmark of Simple Complex Objects

Table 2

POLYGON (Pid, p-desc)

Then, a normal schema must have three additional relations indicating which subobjects are in which complex objects:

T-obj (Tid, Oid)

P-obj (Pid, Oid)

L-obj (Lid, Oid)

However, an INGRES+ schema needs only the single additional relation from Section 2, namely:

OBJECT (Oid, trim, shape)

The trim field in OBJECT is a collection of queries of the form:

retrieve (TEXT.all) where TEXT.Tid = value

while the shape field has a collection of queries of the form:

retrieve (LINE.all) where LINE.Lid = value

retrieve (POLYGON.all) where POLYGON.Pid = value

The benchmark query is to find the shapes of a particular complex object, e.g:

retrieve (POLYGON.all)

where POLYGON.Pid = P-obj.Pid

and P-obj.Oid = "unique-value"

retrieve (LINE.all)

where LINE.Lid = L-obj.Lid

and L-obj.Oid = "unique-value"

The QUEL+ query is simply:

execute (OBJECT.shapes) where OBJECT.Oid = "unique-value"

The INGRES+ prototype limits the length of procedural fields to 255 bytes (about 9 queries); hence, multiple rows are required to express an object with a larger number of subobjects. This limitation affects INGRES+ performance marginally. The costs of the two systems for objects having respectively 1, 4, 8, 16 and 32 subobjects is shown in Table 3. INGRES must run 2 two-variable queries while INGRES+ runs a single query on the OBJECT relation followed by a one-relation query per subobject. If there is only one subobject, it is clear that INGRES+ will run 2 one-variable queries and have better performance than INGRES. This performance advantage deteriorates until there are 16 subobjects at which point 17 one-variable queries take more time than 2 two-variable queries. In a commercial implementation, two-variables queries would be better optimized and the crossover point might occur at a lower number of subobjects. On the other hand, run-time optimization of 17 commands in INGRES+ is a serious source of overhead which would not be present in a commercial system. Hence, it is not clear how Table 3 would look in a commercial environment.

Query	INGRES-CPU	INGRES+ -CPU	INGRES-total	INGRES+ -total
Q1	1	.54	1	.67
Q4	1	.75	1	.78
Q8	1	.99	1	1.0
Q16	1	1.35	1	1.44
Q32	1	2.17	1	2.94

Benchmarks of Complex Objects

Table 3

5.3. Simulation of Unnormalized Relations

Although QUEL+ is most useful when applied to applications with complex structure, it is also possible to provide multiple-dot addressing on conventional data. This will allow a more natural query formulation compared to conventional techniques; however, much of the same effect can be alternately achieved using relational views. This section is included to demonstrate that QUEL+ provides reasonable performance even in ordinary situations.

The normal way to store data for the standard EMP, DEPT and JOB data base is:

```
EMP (name, age, salary, dept, jid)
DEPT(dname, floor)
JOB (jid, jname, benefits)
```

Here, employees have a name, an age, a salary, are in a department, and have a job identifier. The other two relations are self-evident. We assume that there are 7000 employees, 500 departments and 50 job descriptions. Moreover, EMP tuples are 32 bytes wide, DEPT tuples are 14, and JOB tuples are 24.

On the other hand, in INGRES+ one can use an alternate schema as follows:

```
EMP (name, age, salary, dept, j-emp)
DEPT(dname, floor, d-emp)
JOB (jid, jname, benefits)
```

Here, j-emp is a procedural field of the form:

```
retrieve (JOB.all) where JOB.jid = "value-for-this-employee"
```

In addition, d-emp is a procedural field of the form:

```
retrieve (EMP.all) where EMP.dept = "this-dept"
```

Consequently, all the employees in a specific department are accessible through the d-emp field while the job description of a particular employee can be obtained through the j-emp field.

We ran the following three queries in both INGRES and INGRES+:

Query 1: a normal join returning a few tuples

The queries to run in the two systems are respectively:

```
retrieve (EMP.name, DEPT.floor)
where EMP.dept = DEPT.dname
and DEPT.dname = "unique-name"
```

```
retrieve (DEPT.d-emp.name, DEPT.floor)
where DEPT.dname = "unique-name"
```

In this case, we are comparing the processing speed of normal INGRES running a two variable query with that of INGRES+ which must execute a one-variable query and then a second one-variable subquery.

Query 2: the full join

The two queries are respectively:

```
retrieve (EMP.name, DEPT.floor)
where EMP.dept = DEPT.dname
```

```
retrieve (DEPT.d-emp.name, DEPT.floor)
```

In this case, we are computing the full join between EMP and DEPT. The comparison is between a single two variable query and a single one-variable query to scan the DEPT relation along with 500 one-variable queries to find appropriate information in EMP. This should be a poor query for INGRES+ because of the run-time optimization of 500 queries. Moreover, because of the structure of the query, INGRES+ will iterate over DEPT tuples and then access the EMP relation for each one. This may (or may not) correspond to the plan which would be selected by a conventional optimizer using a flat representation of the query. If iterative substitution for DEPT tuples is not a wise plan, then INGRES+ will have poor performance because of the structure of the query.

Query 3: a three way join to find the job of a particular employee in a particular department

The queries are:

```
retrieve (JOB.jname, EMP.name)
where DEPT.dname = "value-1"
and EMP.dept = dept.dname
and EMP.job = JOB.jid
and EMP.name = "value-2"
```

```
retrieve (DEPT.d-emp.j-emp.jname, DEPT.d-emp.name)
where DEPT.dname = "value-1"
and DEPT.d-emp.name = "value-2"
```

Here, INGRES is running a single three variable query while INGRES+ will

execute three one-variable queries. The extended system should be especially attractive in this case, because of the extra complexity required to process multivariable queries in a conventional system.

Table 4 presents the results for these three queries.

Query	INGRES-CPU	INGRES+-CPU	INGRES-total	INGRES+-total
Query 1	1	1.37	1	1.15
Query 2	1	15.1	1	17.2
Query 3	1	.29	1	.36

Benchmarks of Unnormalized Relations

Table 4

As can be seen, Query 1 performs at about the same speed in both systems. In this case two one-variable queries are comparable to a single two variable query. The full join was a factor 15-17 worse in INGRES+ because the overhead of running 500 queries to retrieve EMP tuples is overwhelming. Finally, Query 3 shows that three one-variable commands are faster by a factor of 3-4 than a single three-variable command. Although one would expect superior performance from INGRES+, the magnitude is surprising and reflects the fact that the normal INGRES optimizer is not especially good at three way joins.

The conclusion to be drawn is that INGRES+ is competitive except when it utilizes a poor query plan or is forced to run a large number of commands. Bad performance in the latter situation should be eliminated by compile time query planning. Bad performance in the former case can be alleviated by flattening out multiple-dot commands when an entire column has the same query structure.

The next section turns to a suggestion to dramatically improve the performance of procedural fields.

6. CACHING PROCEDURAL FIELDS

The performance of INGRES+ may be dramatically improved by caching frequently used objects so they will not have to be repeatedly rematerialized. This section explores the use of this tactic.

6.1. The Cache Model

Caching QUEL procedures should be thought of as a two step process:

- 1) compile a query plan for the command(s) (plan caching)
- 2) execute the plan (result caching)

The first step (plan caching) is often done at compile time in current systems; however, in our model it should be thought of as computing an intermediate representation of the object. This representation can be saved for later reuse.

Moreover, in current systems a query plan is usually invalidated at execution time if the schema has changed in a way that compromises the validity of the plan. In our model query plans are cached until a compromising update forces invalidation. One can optionally support a "demon" which utilizes any idle CPU resources recompiling invalidated plans. Alternatively, one can simply recompile when the plan is executed, as in [ASTR76].

The size of a compiled plan depends on the target language of the compiler. If access plans are generated, then the size will be modest (e.g. hundreds of bytes). If machine code is generated, then the size will be thousands of bytes. If plans are of moderate size, they can be cached directly in the field that defines them. Larger plan representations can be cached in a separate relation, i.e:

CACHE (identifier, compiled-plan)

and only the identifier is stored in the defining field.

The second step (result caching) involves materializing the object from the compiled plan. Again, this step can be performed on demand and saved for reuse or even computed in advance. The size of a materialized object depends, of course, on the command(s) which are executed. Small objects can be cached directly in the defining field. Larger objects should probably be cached as individual relations, and the name of the relation(s) inserted in the defining field. When objects are hierarchically composed of other objects, the above constructs can be applied recursively; hence, small objects which are composed of small objects will be cached together in the field describing the enclosing object.

It is straightforward for the data base system to allow result caching for N1 "big objects" and execute a least recently used (LRU) algorithm to select big objects to be discarded. Of course this requires N1 relations to hold these objects and the corresponding extra entries in the system catalogs. Alternately, a data manager could reserve N2 blocks of storage for objects and select a victim based on a function of size and time-since-last-reference. Of course, N1 and N2 would be carefully chosen system-specific parameters. Objects must also be discarded upon an update to one or more tuples from which they are composed. We discuss a mechanism to accomplish this task presently. Alternately, it should be possible to incrementally update the cached object when a subobject is modified. Recent work on supporting materialized views (e.g. [BLAK86]) can be applied to this task. Moreover, if the object is an QUEL aggregate, it is straightforward to update the cached value. Additional effort in this direction is currently in progress.

For cached big objects, it is desirable to store their name and the query(s) which compose them in a main memory data structure. Then, if the same or another user materializes an object with the same description, the one already materialized can be used instead. An example of this situation occurred in Section 4 where our algorithm materialized the object represented by o.shape twice.

The prototype discussed in Section 4 caches big objects as discussed above, but small object caching as well as invalidation on update has yet to be implemented. We turn now to the efficient invalidation of objects.

6.2. Object Invalidation

Consider a new kind of lock mode called I mode. Hence, objects can be locked in R, W or I mode. A lock set in I mode has an associated identifier indicating the object which has been precomputed using the locked object. The compatibility of the various modes is indicated in Table 5. The * in that table indicates that a W requestor for an object locked in I mode will be allowed to proceed and set a W lock on the object. First, however, the object with which the I lock is associated will be invalidated.

When INGRES+ materializes any object, it simply sets I locks on all objects read by the query(s) which materialize the object. These I locks are held until the object is deleted or invalidated through an update to a subobject.

6.3. Implementation of I Locks

A straight-forward approach would be to place I locks in the same lock table holding R and W locks. In this case, one must cope with a lock table of widely varying size since the number of I locks can change dramatically. Moreover, when a failure occurs, either all precomputed objects must be invalidated (which may be a costly alternative if the facility is extensively used) or I locks must be made recoverable. Lastly, phantoms must be correctly handled. Hence, if a new tuple is added which satisfies the qualification of some precomputed object, then this object must be invalidated.

The first objective can be satisfied by using extendible hashing [FAGI79] for the lock table instead of conventional hashing. The second objective requires setting I locks as part of a transaction and writing them into the log. If a failure occurs during this transaction, then recovery code must be extended slightly to back out the I locks which were set. Moreover, I locks must be periodically checkpointed to allow recovery from media failures. Hence, when recovery code is rolling forward from a checkpoint, I locks can be suitably updated. In summary, making I locks recoverable simply involves treating them as ordinary data and presents only modest implementation difficulties.

	R	W	I
R	ok	no	ok
W	no	no	*
I	ok	no	ok

Compatibility Modes for I Locks

Table 5

The phantom problem poses more serious issues. Systems which perform page level locking (e.g. [RTI86, CHEN84]) have few difficulties supporting correct semantics in the presence of phantoms. Hence, one can include I locks in such systems without concern. However, finer granularity locking is required to avoid an excessive number of unnecessary invalidations. Systems which perform record level locking (e.g. System R [ASTR76]) can allow detection of phantoms by holding locks on index intervals in the leaf nodes of secondary indexes as well as on data records. Hence, a transaction which inserts a tuple will hold a write lock on the tuple and on the appropriate index interval for any field for which a secondary index exists. If I locks are also held on data records and index intervals, then all conflicts caused by phantoms will be detected by a collision in some index.

When access paths other than B-trees are present, a slight generalization to the above scheme will support phantom detection. Tuple level locks are held on index and data records which use a hashed or B-tree organization. Then, a precomputed object must be invalidated if an I lock which is held on its behalf falls adjacent to a tuple on which a W lock is held. Adjacency means "logically adjacent in tuple identifier order" for B-tree data records and indexes; adjacency means "in the same hash bucket" for hashed records and indexes.

The only problem with the adjacency approach is that a B-tree page split will cause a write lock to be set on the page to be split, and thereby will cause an invalidation of all objects holding I locks on that page. Unless tuple identifiers are constructed so that they do not change when a tuple moves to a different page, this invalidation is required. Otherwise I locks will be held on the previous identifier for the moved tuple, and incorrect operation will result.

The phantom problem and the logging problem appear easier to solve if an alternate strategy is employed. Consider storing I locks in the data and index records themselves. Systems which support variable length records can simply add as many I locks to each record as necessary. Such locks are recoverable using conventional techniques which are automatically applied to data records. The phantom problem requires the above adjacency algorithm; however, structure modifications (e.g. B-tree page splits) do not cause unnecessary invalidations. Moreover, since the extra locks are stored separately from R and W locks, extendible hashing is not a prerequisite for the lock table. Lastly, this approach is easily extended to field-level locks, which may offer superior performance to record level I locks.

The drawbacks of this second alternative is that a second implementation of a lock manager must be coded for I locks. Moreover, setting an I lock on an object requires rewriting the object instead of just reading it. Hence, setting I locks will be expensive.

6.4. Performance of Cached Objects

The purpose of this section is to present a model which can be used to suggest when caching should be applied to a procedural object. Consider a "small" object which can be constructed in N_1 page accesses and inspection of N_2 records. Assume that this object occupies $R_1 = 1$ page of space, consists of R_2 tuples and is cached in the data record itself. In addition, consider a query pattern in which P percent of the accesses are reads of the complex object and $1-P$ are updates to

subobjects from which the complex object is composed. Moreover, each update is applied to a randomly chosen subobject from the N2 candidates. Lastly, the record in which the description of the complex object is stored must be read during retrieval whether or not caching is employed. Hence, that access is not counted in the following analysis.

Consider the sequence of accesses to be a collection of intervals, each consisting of one or more consecutive writes followed by one or more consecutive reads. In a given interval, the expected length ER of the run of reads and the length EW of the run of writes is:

$$ER = 1 / (1 - P)$$

$$EW = 1 / P$$

Consider first the no-cache alternative. With the parameter K discussed in [SELI79] which weighs the CPU time used in evaluating a query plan relative to the number of I/O's, the cost, M to materialize the object after its definition has been obtained is:

$$M = N1 + N2 * K$$

Without caching, this cost must be paid on each read access, and the cost, C1 of these accesses is:

$$C1 = (ER) * (M)$$

We now turn to the corresponding costs for cached objects. The cost to invalidate the complex object on the initial write is:

$$IN = 1$$

This assumes that I locks are stored in the records of the subobjects and that only the data record containing the object description must be rewritten to perform invalidation. All I locks are simply left in place. Subsequent writes prior to the first read also require the same cost even though the complex object has already been invalidated.

The first read to the complex object requires a materialization at cost, M. In addition, the cost, C to cache the object is:

$$C = 1$$

The materialized object must be written into the field occupied by the description of the complex object requiring a single record to be rewritten. Since I locks were never reset from prior materializations, no extra cost is required to ensure that they are set. Subsequent reads only require accessing the object in the cache. Since the access to the object description is not being counted, there is no additional I/O because the cached object is stored in this record. Hence, only the CPU cost to access the R2 records in the cached object must be paid, i.e:

$$A = R2 * K$$

Therefore, the expected cost of an interval using caching is:

$$C2 = EW * IN \quad /*cache invalidation on each write*/$$

$$+ M + C \quad /*materialize plus cache on first read*/$$

$$+ (ER - 1) * (A)$$

/*subsequent reads access the cache*/

Define $Z = M - A$ to be the caching factor, i.e. the difference between the cost to materialize the object and the cost to access the object from the cache. This cost is in weighted CPU and page costs and is typically in the range of 10 - 1000. Algebraic manipulation now yields that caching will be preferred if:

$$Z > (1 / P ** 2) - 1$$

The consequence of this analysis is that caching will generally win unless P is very small. If P is $1/2$, then Z must be greater than 3 for caching to be beneficial. If P is $1/10$, then Z must exceed 99.

6.5. Indexing Cached Fields

An extension of this caching tactic may be attractive when the queries in a field have certain compositions. Consider a situation, such as salaries in an EMP relation for which most of the fields are specified as constants while a few are specified procedurally. For example, Joe might make \$10,000 and Bill is specified as having the same wages as Joe. In this case salary can be a procedural field and most rows have a value of the form:

retrieve (wages = constant)

while Bill would have a value of:

retrieve (EMP.salary.wages) where EMP.name = "Joe"

In this case, one would desire a salary index on salaries for efficient processing of queries of the form:

retrieve (EMP.name) where EMP.salary.wages = value

This section indicates how to construct such indexes on procedural fields.

Instead of caching values as they are computed, consider caching all values in advance. If this is done, then it is straightforward to build an index on a field appearing in the cached objects using the conventional indexing utility. One can use this index to answer queries of the above form rapidly. On updates to subobjects, one must invalidate cached objects as discussed in the previous subsection. However, as part of the transaction which updates a subobject, the invalidated object must be rebuilt and the index updated. Conventional locking must be employed to guarantee consistency, and aborting a transaction must cause a backout of all updates or an invalidation of the new cached value.

In the case that most values are simply constants, such indexes should be beneficial, and be only marginally more expensive to maintain than conventional ones.

7. CONCLUSIONS

This paper has suggested that data base procedures are a natural way to model complex objects and to allow data base oriented algorithms and precompiled queries in the data base. Moreover, they appear to be easily generalizable to arbitrary programming language procedures which may be useful in certain applications. Lastly, they can be used to model aggregation, generalization and most other environments addressed by semantic data models. The advantage of data

base procedures is that a user does not need to learn additional concepts to design his application. Since he must know the query language anyway, there is little extra complexity. Hence, this proposal is in the same spirit of the "spartan simplicity" stressed by the original advocates of the relational model.

A prototype implementation was described and initial performance studies explored. They indicated comparable performance between the extended and the non-extended prototypes except when many one-variable commands were processed by INGRES+ or when a bad query plan was indicated by the structure of the query. Bad plans can be avoided if procedural fields are restricted to parameterized queries, and compile time optimization should alleviate the overhead of one-relation commands. Moreover, a caching strategy was described which should accelerate performance of the prototype especially when objects are of moderate size. Our caching scheme should offer superior performance to pointer oriented implementations of complex objects when update frequency is low or moderate.

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APPENDIX 1

The syntax of QUEL has been described elsewhere [HELD75]. Here, we report only the extensions to the original language, QUEL, which define QUEL+. Let F be the construct "QUEL-col-1,...,QUEL-col-n.field".

- 1) F can appear wherever a field of a relation can appear in QUEL.
- 2) The construct "tuple-variable F" can appear whenever a tuple variable or a relation name can appear in QUEL.
- 3) Clauses of the form:
 G1 newop G2
are allowable if G1 and G2 are tuple variables or the construct "tuple-variable.F" and newop is in the set:
 { U , !! , >> , << , == , <> , JJ , OJ , empty }
- 4) EXECUTE and EXECUTE-ONE are added as commands
- 5) An operator "in" is added accepting an indirectly referenced column as a left operand and a relation name as a right operand.
- 6) A keyword "with" is added which is usable with the EXECUTE command to indicate the presence of a parameter list.

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