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INFORMATION SYSTEMS EDUCATION JOURNAL

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A Relational Algebra Query Language For Programming Relational Databases

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Abstract

In this paper, we describe a Relational Algebra Query Language (RAQL) and Relational Algebra Query (RAQ) software product we have developed that allows database instructors to teach relational algebra through programming. Instead of defining query operations using mathematical notation (the approach commonly taken in database textbooks), students write RAQL query programs as sequences of relational algebra function calls. The RAQ software allows RAQL programs to be run interactively, so that students can view the results of RA operations. Thus, students can learn relational algebra in a manner similar to learning SQL—by writing code and watching it run.

Keywords: database, query, relational algebra, programming, SQL

1. INTRODUCTION

Most commercial database systems are based on the relational data model. Recent editions of database textbooks focus primarily on the relational model. In this dual context, the relational model for data should be considered the most important concept in an introductory database course.

The heart of the relational model is a set of objects called relations or tables, plus a set of operations on these objects (Codd, 1972). Coverage of the relational model in database courses includes the structure of tables, integrity constraints, links between tables, and data manipulation operations (data entry and queries).

Classroom discussion of queries and query languages generally leads to a detailed presentation of SQL. *Relational algebra* (RA) as a query language receives less attention. In a survey of database educators, Robbert and

Ricardo (2003) found that only 70% included RA in their courses, compared to 92% for SQL.

Database textbooks provide substantially more material on SQL than on RA. An extreme case is the textbook by Hoffer, et al (2008), which provides two full chapters on SQL but does not mention RA.

Why Teach Relational Algebra?

There is almost universal agreement that SQL is an essential component of an introductory database course. But should we also teach relational algebra? There are several good reasons for doing so.

1. The main reason for teaching RA is to help students better understand the relational model. At the conceptual level, the relational model provides a flexible, adaptable way to query a database. The organization of data into tables, together with RA operations, provides the foundation for this flexibility.

Relational algebra is a *query* language, not a database design tool. However, an understanding of how RA operations can be performed on tables to extract information should help support database analysis and design decisions.

2. Knowledge of RA facilitates teaching and learning SQL as a query language. The basic syntax of the SQL SELECT statement provides an integrated framework for combining RA operations to express a query.

3. An understanding of RA can also be used to improve query performance. The query-processing component of a DBMS engine translates SQL code into a query plan that includes RA operations. The DBMS query optimizer, together with the database administer, can speed up query execution by reducing the processing time of the RA operations.

How to Teach Relational Algebra?

If an instructor decides to include relational algebra as a topic in a database course, a follow-up question is how to present this topic to students? RA coverage in leading database textbooks often takes a *mathematical* approach. For example, the texts by Connolly and Begg (2009), Elmasri and Navathe (2006), and Silberschatz, et al (2006) present RA concepts using mathematical notation. There are several problems with this form of representation.

Many database students are not comfortable with mathematical notation, such as the use of Greek letters (e.g. σ and π) in a new context. The mathematical approach often mixes *infix* notation (operator name is placed *between* two operands; e.g. table1 union table2) and *functional* notation (operator name is placed *before* the operands; e.g. project table3 cols) when performing multiple RA operations within a single expression. This makes the expressions difficult to interpret, and it disguises the procedural nature of RA.

More importantly, students cannot execute query programs written in the mathematical notation. There is no easy way to verify that the mathematical description of a query is correct.

The mathematical approach contrasts with how *programming* courses are taught. In a programming course, an important part of learning occurs when students write instructions for the computer and watch their code run. Errors in program execution provide feedback, which reduces the gap between a student's perception of the problem and how the computer interprets the proposed solution.

To demonstrate how computer implementations differ from mathematical models, students need software to experiment with. Students learn mathematical and computational concepts more effectively when they can work with actual computer representations. As with other programming languages, this principle applies when we teach students how to query using relational algebra.

All major relational database products offer SQL as the primary query language. On the other hand, very few computer environments are available for developing and running RA programs. One database system to offer RA as a query language is LEAP (Leyton, 2010). The Rel DBMS (Voorhis, 2010) uses a form of RA called Tutorial D (Date and Darwen, 2007). A third choice is WinRDBI (Dietrich, 2001), which supports queries using RA and other query languages.

Each of the above systems enables RA queries within a specific database system. None allow you to use RA to query desktop databases. In this paper, we introduce a Relational Algebra Query Language (RAQL) and a custom Relational Algebra Query (RAQ) software product that can be used to query relational databases.

We first present a function-based syntax for writing RAQL query programs as sequences of RA operations. We outline the main features of the RAQ software. Next, we demonstrate how to use the software to execute RAQL programs. Finally, we give examples of RA concepts that can be taught using this approach.

2. RELATIONAL ALGEBRA PROGRAMMING

A RAQL query program consists of a set of statements that specify operations to perform on database tables. The statements are executed in a particular sequence to yield a result table that satisfies a query. Each statement might consist of a single relational algebra operation, or several operations can be combined into one "algebraic" expression. Rather than use complex expressions in query programs, we prefer to have each line of code perform a single RA operation. Our coding style reflects 2GL (assembly language) thinking more than 3GL thinking (e.g. Fortran, C).

We provide a library function for each RA operation. A RAQL program is written as a sequence of RA function calls. Each function has one or two input parameters that are tables, plus other input parameters as necessary. The output of each function is another table. Using functions to implement RA operations provides database students with a comfortable programming environment for creating RAQL query programs.

Functions are provided for the following relational algebra operations:

Table 1: Relational Algebra Functions

Operation	Function
selection	TSelect(Table1,RowCondition)
projection	TProject(Table1,ColumnList)
join	TJoin(Table1,Table2,JoinCondition)
union	TUnion(Table1,Table2)
intersection	TIntersect(Table1,Table2)
difference	TMinus(Table1,Table2)
product	TProduct(Table1,Table2)
division	TDivide(Table1,Table2)
rename	TRename(Table1,OldColumnName, NewColumnName)

To illustrate programming using RA functions, we require a sample database. The structure of a simple inventory database is described in the next section.

Relational Database Example

Suppose an INVENTORY database for a manufacturing environment consists of two tables, STOCK and STKTYPE. The diagram in Figure 1 describes the relational model for this database.

This data model assumes that inventory items are divided into categories, or types. Attributes that apply to individual items are recorded in the STOCK table. Attributes that apply to all items of the same type are included in the STKTYPE table. The two tables are linked by a common type code (SType and TType).

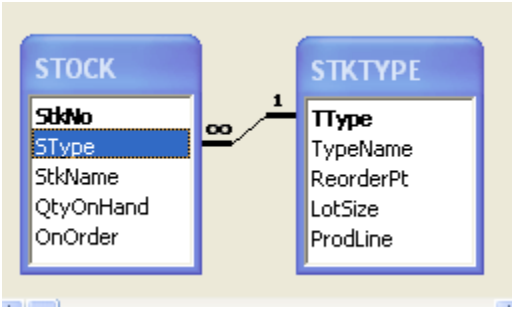

Figure 1: Inventory Database
Primary keys are shown in **bold**

In this basic system, when the quantity-on-hand for an item drops below its reorder point, a production run of a predetermined lot-size is scheduled on a specific production line. It is assumed that reorder point, lot-size, and production line depend on the stock type rather than on the individual item. Whenever a production run is scheduled, the OnOrder field for the item is set to 'Y'. This field is reset to 'N' after the order is filled.

RA Query1 Program

Consider the following query for the INVENTORY database.

Query1: List the stock number, name, and quantity-on-hand for all items that are manufactured on production line 3.

A RAQL program for this query takes the form of a sequence of Table 1 function calls. Each function receives one or two tables as arguments and returns a temporary table. The temporary table can be used in later RA

operations. Sample code for this query is shown below:

```
-- RA Query1: Inventory Query - Line 3
T1 = TJoin('STOCK', 'STKTYPE', "SType=TType")
T2 = TSelect(T1, "ProdLine=3")
T3 = TProject(T2, "StkNo,StkName,QtyOnHand")
```

An explanation of each line of code for this program follows:

Line 1: This is a comment (--)

Line 2: The STOCK and STKTYPE tables are *joined*. The join condition states that the SType field in the STOCK table must match the TType field in the STKTYPE table. Actual table names are placed in matching single (or double) quotes, since they are fixed string values. The join condition is also placed in quotes. The output of the TJoin function is a *cursor* (a temporary table in memory). The cursor name is randomly generated and is assigned to variable T1. The name of the cursor is unknown to the programmer, but the cursor can be referred to in later program statements using the variable name.

Line 3: Rows of cursor T1 are then *selected* if they satisfy the condition that the ProdLine (production line) field in T1 equals 3. Quotes are not needed for the number 3. If quotes are needed inside a row condition, then single and double quotes should be nested in pairs (e.g. "OnOrder='N'"). The output cursor name is assigned to variable T2. The T1 argument is not placed in quotes, since T1 is a variable.

Line 4: The three columns of cursor T2 specified in the column list are *projected* as cursor T3, which is the final result table for the query.

3. RAQ COMPUTER SOFTWARE

The RAQ software allows us to execute queries written in the format of Query1. Our explanation of how to use RAQ to perform queries is organized according to the controls (textboxes and command buttons) on the RAQ main screen (see Figure 2).

1. *Database File* textbox: Choose a database file. The database must be in a Microsoft Access MDB file. The file can be selected with the file-chooser dialog box, which includes the ability to search in subdirectories. No other actions can be performed in the RAQ software until a valid database file is opened. Once a database is open, it cannot be changed without exiting and then rerunning the RAQ software.

2. *Query Program* textbox: Choose a RAQL query program. The program must be in a text file having a TXT extension. A new query program can be selected at any time during the execution of the RAQ software, but the actions that follow must be repeated.

3. *Display* button: Display the RAQL program code in a window. This command can be selected whenever the Display button is enabled. Press the Escape key to close the window. The display window is read-only. Any changes or corrections to the RAQL program must be made in a separate text editor.

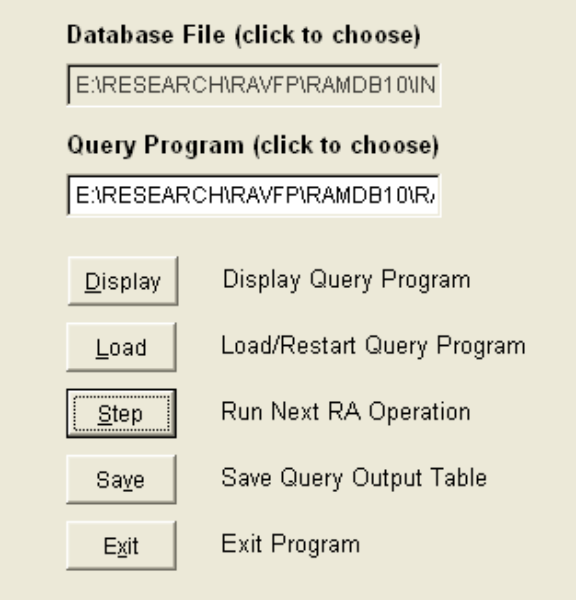

Figure 2: RAQ Program Main Screen

4. *Load* button: Before a RAQL program can be run, it must be loaded. This action can be repeated when you want to restart the program from the beginning.

5. *Step* button: Each click of this button executes one RAQL instruction. This will normally be a single relational algebra operation. Comments in the program code are skipped. For each successful RA operation, the resulting query output cursor is shown on the screen. Hit the escape key to close this view.

If an error occurs while trying to execute an instruction, an error message is displayed in the top right-hand corner of the screen. The error message shows the code for the line that was

just attempted. Clicking the Display button allows the user to see the error in the context of the full RAQL program.

6. *Save* button: When an operation has completed, the current output cursor can be saved to disk. The format of the saved file is an Excel XLS file. The name of the output file is the name of the RAQL program file, followed by the step number. The contents of the XLS file can be easily transferred to a word processing document or other data file.

7. *Exit* button: Click this button to exit the program. You will be prompted to confirm this request before the program ends.

The availability of most RAQ menu choices depends on which actions have already occurred during program execution. Textboxes and command buttons are disabled when their selection would be inappropriate. For example, a result table cannot be saved if the current command fails to execute correctly.

Running the RA Query1 Program

The previous discussion of RAQ controls and features was fairly general. To provide a more concrete demonstration, we list below one possible sequence of RAQ actions that could be taken to execute the Query1 program.

1. Load the INVENTORY database file. Sample data for this database is listed in Appendix A.

2. Load the text file that contains Query1. Assume this file is named RA*Query1.txt*.

3. Click the Display button to view the query program code (optional).

4. Click the Load button to initialize the program.

5. Click the Step button. The comment line will be skipped, and the TJoin operation will be performed. The joined cursor T1 will appear in a window.

6. Click the Step button again, and the TSelect operation will produce cursor T2.

7. Click Step a third time, and TProject will produce and display cursor T3. The final result for Query1 is shown in Figure 3.

8. To save a result cursor, click the Save button after closing the window showing the cursor. If the final result in this example is saved, the output file name will be RA*Query1-3.xls*.

Query Output 3: PROJECT

Stkno	Stkname	Qtyonhand
301	Mint-Truffles	116
303	Almond-Truffles	44
304	Mocha-Truffles	72
306	Mixed-Truffles	93
401	Chocolate-Fudge	145
404	Marble-Fudge	103

Figure 3: RA Query1 Final Result

9. Click Exit when you are finished; then confirm when prompted. If you prefer, you can Load and rerun the same RAQL program, or choose a new query program.

Appendix B contains a sample Relational Algebra Project to give students experience writing and running RAQL programs.

4. USING RAQ TO TEACH RELATIONAL ALGEBRA CONCEPTS

The RAQ software can be used to teach relational algebra concepts interactively that are usually explained intuitively. The advantage of using RAQ is that students can visualize the concepts when they are implemented as RAQL programs. Some examples of RA concepts that can benefit from this approach are described next.

Select Before Join

When *select* is used before *join*, the size of the joined table will usually be much smaller than if the join operation is performed first. This will reduce the memory resources required for a query and should decrease processing time. The Query2 RAQL program shown below achieves the Query1 result, but starts with a select operation.

```
-- RA Query2: Select before Join
T1 = TSelect('STKTYPE', "ProdLine=3")
T2 = TJoin('STOCK', T1, "SType=TType")
T3 = TProject(T2, "StkNo,StkName,QtyOnHand")
```

This program can be compared to the Query1 program, where the join operation is performed first. The relative size of the two joined cursors (T1 in Query1 and T2 in Query2) highlights the advantage of joining tables "later."

Set Union and Intersection

The *union* of sets A and B consists of all distinct members of A and B. In RA, the union of two tables does not include duplicate rows. This

concept can be illustrated with the following Query3 program.

```
-- RA Query3: Union and Intersection
TA = TSelect('STOCK', "QtyOnHand<50")
TB = TSelect('STOCK', "SType='C'")
T1 = TUnion(TA, TB)
T2 = TIntersect(TA, TB)
```

In this program, cursors TA and TB have identical attribute domains (*union-compatible*). The union cursor T1 does not contain duplicates of rows that satisfy both conditions. The intersection cursor T2 identifies the rows that are in both TA and TB.

Set Intersection and Difference

In set theory, it is known that the relationship between *intersection* and *difference* satisfies the equation

$$A \cap B = A - (A - B)$$

The Query4 program listed below verifies this relationship.

```
-- RA Query4: Intersection and Difference
TA = TSelect('STOCK', "OnOrder='N'")
TB = TSelect('STOCK', "SType='T'")
T1 = TMinus(TA, TB)
T2 = TMinus(TA, T1)
T3 = TIntersect(TA, TB)
```

Here, cursor T1 is A - B, T2 is A - (A - B), and T3 is $A \cap B$. Students can observe that T2 and T3 are identical.

Product vs. Divide

The RA *divide* operation is sometimes described as the "inverse" of the *product* operation, in the sense that for tables A and B,

$$(A \times B) \div B = A$$

The following Query5 program illustrates the nature of this relationship.

```
-- RA Query5: Product and Divide
TA = TSelect('STOCK')
TB = TSelect('STKTYPE')
T1 = TProduct(TA, TB)
T2 = TDivide(T1, TB)
```

In this code, T1 is A x B and T2 is $(A \times B) \div B$. Students can note that cursor T2 is the same as cursor TA.

5. SPECIAL CONSIDERATIONS

The RAQ software is not a feature-rich, industrial-strength software product. It was designed for academic use to provide a simple way to teach relational algebra concepts through programming. Users of this software should be aware of certain limitations and special considerations.

1. There is a 100-line maximum for RAQL query programs (not including comments). Each instruction must be on a single line.

2. RAQ provides modest error checking. Error messages are displayed in the upper-right corner of the screen. Messages state the type of error or show the offending line of code.

3. RAQ has limited input options for data. The database must be in an Access MDB (not ACCDB) file. If necessary, convert the ACCDB file to MDB format. More generally, if the database is an ODBC data source (e.g. Oracle, SQL Server, MySQL), then the table structures and data can be *imported* into an Access file before using RAQ.

4. RAQL query programs must be in a text file with a TXT extension. Programs have to be created and modified with a separate text editor, since RAQ does not provide editing capabilities.

5. RAQ output for query results are shown on the screen. The display of intermediate cursors cannot be skipped, but RAQL programs are usually short. Query output can be saved in XLS files, and the Windows operating system provides various print-screen options.

6. For convenience in expressing RA queries, duplicate field names should be avoided in databases. If you prefer to have duplicate field names in separate tables (e.g. the same name for primary key and foreign key), use the TRename function in RAQL programs. This is a constraint inherent in relational algebra (Date, 2004) and not just in our RAQ software.

The SQL SELECT statement allows a field to be specified by including the name of the relevant table (e.g. STOCK.SType). The SELECT statement can do this because intermediate cursors generated in the processing of the statement are invisible and are not referenced. We do not have this luxury in RAQL. Each RAQL statement generates a temporary cursor with an unknown name. If a cursor has a duplicate field name, we cannot "hard-code" the unknown cursor name to identify the field.

7. Nesting of RA function calls within a single statement is permitted but not

recommended. Nested function calls defeat the opportunity to see intermediate result cursors while RA operations are performed. Nesting also disguises the procedural nature of relational algebra.

8. The RAQ software has been tested in Windows XP, Windows Vista, and Windows 7. Administrative privileges may be required for Vista or Windows 7, since RAQ writes some temporary files to the disk.

6. SUMMARY AND CONCLUSIONS

In this paper, we presented arguments for including coverage of relational algebra (RA) along with SQL in database courses. We argued that, in teaching relational algebra to database students, a programming approach is preferable to a mathematical approach. Our recommended programming style is to write query programs in a special Relational Algebra Query Language (RAQL). In this language, query programs are expressed as sequences of function calls, where each call performs one RA operation. Following this format, students gain experience using a procedural query language while learning relational algebra.

Writing query programs improves the educational experience for students, but learning is enhanced if students can execute their query programs. We have developed a custom Relational Algebra Query (RAQ) software environment in which RAQL programs can be run.

The RAQ software allows students to see the intermediate results during the sequence of relational algebra operations. With this capability, students can visualize RA concepts and explore performance issues. Thus, they can learn RA in a manner similar to how they learn SQL—by writing code and watching it run. As Knuth might say, students can better understand a problem by teaching a computer how to solve it (Shustek, 2008).

Note: An executable version of the RAQ program, along with runtime files and the database examples in this paper, can be obtained from the lead author.

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APPENDIX A: INVENTORY Database – Sample Data

STOCK Table

StkNo	SType	StkName	QtyOnHand	OnOrder
101	B	Prune Basket	65	N
105	B	Pear Basket	48	N
107	B	Peach Basket	21	Y
202	W	Deluxe Tower	54	N
204	W	Special Tower	29	N
301	T	Mint Truffles	116	N
303	T	Almond Truffles	44	Y
304	T	Mocha Truffles	72	N
306	T	Mixed Truffles	93	N
401	F	Chocolate Fudge	145	N
404	F	Marble Fudge	103	N
502	C	Berry CheeseCake	73	N
505	C	Apple CheeseCake	46	N
506	C	Lemon CheeseCake	18	Y
508	C	Plain CheeseCake	65	N

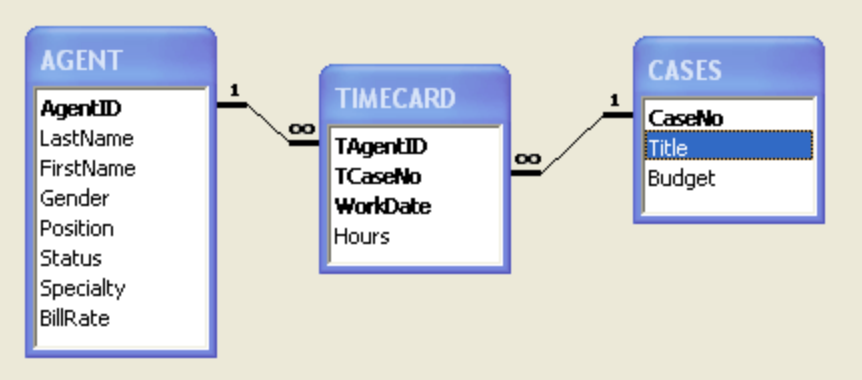
STKTYPE Table

TType	TypeName	ReorderPt	LotSize	ProdLine
B	Basket	60	90	1
C	CheeseCake	50	75	2
F	Fudge	120	180	3
T	Truffles	90	120	3
W	Tower	40	60	1

APPENDIX B: Relational Algebra Project

This project uses a Microsoft Access file that contains a Time-and-Billing database for the XFiles group in the FBI. The file is called XFILES.mdb. The database is used to track the number of hours spent by agents on cases. Each agent fills out her/his time card each day, charging up to 8 hours per day on cases.

The database consists of three tables: AGENT, CASES, and TIMECARD. The relational model for this database is shown in the following diagram.



1. Write a *Relational Algebra Query Language* (RAQL) program for each of the following queries:

   Query 1: List the agent ID, last name, position, and bill rate of all Special Agents that have a bill rate greater than $75 per hour.

   Query 2: List the case number, case title, and budget of all cases that have been worked on by a female agent.

   Query 3: List the agent ID, last name, specialty, and bill rate of all agents that have worked on the Fat-Sucking Vampire case.

   Query 4: List the work date, case title, agent ID, and hours for all time card records where less than 4 hours were charged.

   Query 5: List the last name, first name, and gender of all agents that are female *or* have worked on the Bermuda Triangle case.

   Query 6: List the last name, first name, and gender of all agents that are female *and* have worked on the Bermuda Triangle case.

   Query 7: List the agent ID, last name, and specialty of all agents that have *not* worked on the Dark Matter case.

   Query 8: List the agent ID, last name, and first name of all agents that have worked on every case that Scully has worked on.

2. Use the RAQ software to run your query programs. For each query, save the final output table in an Excel file.

3. Combine your query results in a Word document, grouping together for each query:
   a. The *word definition* of the query.
   b. The *source code* for your RAQL program.
   c. The final *output table* from the query.