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AUTHOR Wong, Eugene; Youssefi, Karel
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ABSTRACT

Multivariable queries can be processed in the data base management system INGRES. The general procedure is to decompose the query into a sequence of one-variable queries using two processes. One process is reduction which requires breaking off components of the query which are joined to it by a single variable. The other process, tuple-substitution, involves substituting for one of the variables a tuple at a time. The query processing algorithm has been developed for QUEL, the data language for INGRES. Algorithms for reduction and for choosing the variable to be substituted are given. The decision about which variable to substitute depends on estimation of costs, and some procedures for making cost estimates are outlined. (Author/CH)

DECOMPOSITION-A STRATEGY FOR QUERY PROCESSING

by

Eugene Wong and Karel Youssefi

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College of Engineering
University of California, Berkeley
94720

Decomposition-A Strategy for Query Processing

Eugene Wong and Karel Youssefi

Dept. of Electrical Engineering and Computer Sciences
and Electronics Research Laboratory,
University of California, Berkeley

Abstract

This paper deals with the strategy for processing multivariable queries in the data base management system INGRES. The general procedure is to decompose the query into a sequence of one-variable queries by alternating between (a) reduction: breaking off components of the query which are joined to it by a single variable, and (b) tuple-substitution: substituting for one of the variables a tuple at a time. Algorithms for reduction and for choosing the variable to be substituted are given. In most cases the latter decision depends on estimation of costs and heuristic procedures for making such estimates are outlined.

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1. Introduction

The structural simplicity of a relational data model encourages the use of a non-procedural data sublanguage which specifies what is to be found rather than how it is to be found. Thus, it is not surprising that nearly every one of the relational languages which have been proposed is non-procedural. As is generally true with high level languages, a price which may have to be paid is a loss of efficiency. For a relational data base of any size and for queries spanning several relations, the price can be fearsome. Results of various degrees of generality on improving search strategies for a relational data base system have been reported by Palermo [PALE72], Astrahan and Chamberlin [ASTR75], Rothnie [ROTH74,ROTH75], Pecherer [PECH75], Smith and Chang [SMIT75], and Todd [TODD75]. Nonetheless, the lack of a general approach to optimizing query processing remains a major impediment to achieving a satisfactory degree of efficiency for non-procedural relational languages.

The purpose of this paper is to describe in some detail the query processing algorithm developed for QUEL [HELD75], which is the data language for the INGRES system. Insofar as the problems encountered in QUEL are common to all non-procedural relational languages, their solution should find general application.

In section 2 a brief description of QUEL, the query language to be processed, is presented. In section 3 we sketch a skeletal outline of the decomposition algorithm emphasizing the functions of the component algorithms and the flow of information and control among them. The details of the component algorithms are presented in subsequent sections.

2. QUEL

A complete definition of QUEL is given in [HELD75]. Here, we shall confine ourselves to a brief description sufficient to make the processing strategy comprehensible. There are four commands: RETRIEVE, REPLACE, DELETE, APPEND. An update command is turned into a RETRIEVE command which is then followed by a low level tuple-by-tuple operation. We shall restrict our attention to RETRIEVE. A statement to retrieve in QUEL has the following form.

```
RANGE OF (Variable [,Variable]) IS
            (Relation Name [,Relation Name])

RETRIEVE [INTO result name] (Target List)

            WHERE  Qualification
```

Example 2.1:
Consider a data base with relations

```
Supplier (S#, Sname, City)
Parts (P#, Pname, Size)
Supply (S#, P#, Quantity)
```

and a query to find the names of all parts supplied by suppliers in New York. This can be stated in QUEL as follows:

```
RANGE OF ( S, P, Y, ) IS ( Supplier, Parts, Supply )

RETRIEVE INTO NYparts (P.Pname) WHERE (P.P#= Y.P#)
                                AND   (Y.S#=S.S#)
                                AND   (S.City=`New York')
```

From the point of view of query processing there are two principal sources of complexity. First, QUEL permits aggregation operators such as MAX and AVG, and nesting of such operators. Secondly, queries involving several variables require deft handling in order to avoid the obvious possibility of combinatorial growth. For example, if the query in Example 2.1 is processed by first forming a cartesian product, then the number of tuples to be scanned is equal to the product of the cardinalities of the three relations. In our system all aggregations are performed on single relations. If an aggregation is to be done on a subset of the product of several relations, the subset must first be assembled by processing a multivariabe query. Aggregations once evaluated are kept for possible reuse until updates render them obsolete. In the remainder of the paper we shall deal only with aggregation-free queries, and the thrust of the query-processing strategy is to cope effectively with aggregation-free but multivariable queries.

Let $X = (X_1, X_2, \ldots, X_n)$ denote the variables declared in the range statement, and let $R_1, R_2, \ldots, R_n$ be their respective ranges. Then the qualification can be considered to be a Boolean function $B(X)$ on the cartesian product $R = R_1 x R_2 x \ldots x R_n$. The target list can be considered to be a set of functions $(T_1(X), T_2(X), \ldots, T_m(X)) = T(X)$ on the product space, and the result relation of the query is constructed by evaluating $T(X)$ on the subset of R defined by $B(X) = 1$, and eliminating duplicate tuples. We note that for a query free of aggregation operators each tuple X in the product space R contains enough information to completely determine the values of $B(X)$ and $T(X)$.

The interpretation of QUEL statements suggests the following procedure for their processing:

(a) Product: A cartesian product of the range relation is formed.

(b) Restriction: Tuples X in the product which satisfy $B(X)=1$ are determined.

(c) Computation and Projection: $T(X)$ is computed on the subset determined in (b) and duplicate tuples are eliminated.

Unfortunately, this procedure is as inefficient as it is obvious. The cardinality of the product R (i.e., the number of tuples in R) is equal to the product of the cardinalities of R_i, $i=1,2,\ldots,n$. It does not take very large relations or very many of them to make this number enormous. Aside from the difficulty of having to form and store a very large relation, to determine the subset which satisfies $B(X)=1$ requires examining a number of tuples equal to the cardinality of R.

3. Decomposition

The query processing strategy that we have adopted has two overall objectives:

(a) No cartesian product - The result relation is to be constructed by assembling comparatively small pieces, rather than by paring down the cartesian product.

(b) No geometric growth - The number of tuples to be scanned is to be kept as small as possible, and for most queries this number is much less than the cardinality of R.

Our general procedure is to reduce an arbitrary multivariable query to a sequence of single-variable ones. We call this process <u>decomposition</u>. Observe that the first objective is automatically achieved by such an approach. To attain the second requires a detailed examination of the tactical moves which are available.

The decision to reduce multivariable queries to one-variable ones separates the overall optimization into two levels. It has obvious advantages in structuring the optimization procedure which otherwise may well become unbearably complex. The only situation in which our approach may be undesirable is when inter-relational information such as "links" [TSIC75] is available in which case the desirable atomic units may be two-variable queries.

It is useful to distinguish two types of operations which are repeatedly invoked in decomposition.

(I) Tuple substitution: ~~An~~ n-variable query Q is replaced by a family of (n-1)-variable queries resulting from substituting for one of its variables tuple by tuple, i.e.,

$$Q(X_1,X_2,\ldots,X_n) \longrightarrow \{Q'_\alpha\ (X_2,X_3,\ldots,X_n),\ \alpha \in R_1\}$$

(II) Detachment of a subquery with a single overlapping variable : A query Q is replaced by Q′ followed by Q" such that Q′ and Q" have only a single variable in common.

Operations of these two types suffice to decompose any query completely. Indeed, a series of successive tuple substitutions is sufficient, albeit tantamount to forming the cartesian product. Tuple substitution for a single variable means that the cost of processing the remaining portion of the query is multiplied by a factor which in most cases is equal to the cardinality of the range of the substituted variable. It is important, therefore, that the ranges of the variables be reduced as much as possible before substitution takes place. The most straightforward way of doing this is through restriction and projection, which are special cases of (II). Something equivalent to such a step has been proposed in every paper on optimizing query processing.

Example 3.1

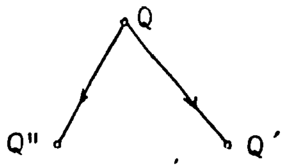
Consider a data base with three relations

```
Supplier (S#, Sname, City)
Parts (P#, Pname, Size)
Supply (S#, P#, Quantity)
```

and a query Q:

```
RANGE OF (S,P,Y) IS (Supplier, Parts, Supply)
RETRIEVE (S.Sname) WHERE (S.City = `New York')
                     AND (P.Pname = `Bolt')
                     AND (P.Size = 20)
                     AND (Y.S# = S.S#)
                     AND (Y.P# = P.P#)
                     AND (Y.Quantity ≥ 200)
```

If we represent a detachment of Q′ from Q leaving Q" by the binary tree



then the successive detachment of subqueries can be represented by

Q

Q1 : (P.P#) WHERE (P.Size=20) AND (P.Pname=`Bolt')

Q2 : (Y.P#, Y.S#) WHERE (Y.Quantity ≥ 200)

Q3 : (S.S#, S.Sname) WHERE (S.City = `New York')

Q4 : (Y.S#) WHERE (Y.P# = P.P#)

Q5 : (S.SName) WHERE (Y.S# = S.S#)

In this example operations of type II have reduced Q to three one-variable queries Q1, Q2, Q3 which can be processed in parallel or in arbitrary order, followed by a 2-variable query Q4, and then another 2-variable query Q5. Q4 and Q5 cannot be further reduced by operations of type II, and tuple-substitution must be used to complete the decomposition. We note, however, the ranges of the variables in Q4 and Q5 are likely to be very much smaller than the original relations, and tuple substitution at these stages is relatively harmless. As an example of tuple substitution, consider

Q5 : RETRIEVE (S.Sname) WHERE (Y.S#=S.S#)

Suppose that at this point the range of Y is the relation

S#
101
107
203

Then, successive substitution for Y yields

Q5(101): RETRIEVE (S.Sname) WHERE (S.S#=101)

Q5(107): RETRIEVE (S.Sname) WHERE (S.S#=107)

Q5(203): RETRIEVE (S.Sname) WHERE (S.S#=203)

We note that unlike SEQUEL [ASTR75], QUEL has no block structure and there is no a priori preferential order of variables in substitution.

The general situation covered by (II) is the following: Consider a query of the form

$$\begin{array}{ll} & \text{RANGE OF } (X_1, X_2, \ldots, X_n) \text{ IS } (R_1, R_2, \ldots, R_n) \\ Q & \text{RETRIEVE } T(X_1, X_2, \ldots, X_m) \\ & \text{WHERE } B''(X_1, X_2, \ldots, X_m) \\ & \text{AND } B'(X_m, X_{m+1}, \ldots, X_n) \end{array}$$

It is natural to break off B' to form

$$\begin{array}{ll} & \text{RANGE OF } (X_m, X_{m+1}, \ldots, X_n) \text{ IS } (R_m, R_{m+1}, \ldots, R_n) \\ Q' & \text{RETRIEVE INTO } R_m' \; (T'(X_m)) \\ & \text{WHERE } B'(X_m, X_{m+1}, \ldots, X_n) \end{array}$$

where $T'(X_m)$ contains the information on X_m needed by the remainder of the query which can now be expressed as

$$\begin{array}{ll} & \text{RANGE OF } (X_1, X_2, \ldots, X_m) \text{ IS } (R_1, R_2, \ldots, R_m') \\ Q'' & \text{RETRIEVE } T(X_1, X_2, \ldots, X_m) \\ & \text{WHERE } B''(X_1, X_2, \ldots, X_m) \end{array}$$

<u>Observations</u>: (1) Q'' is necessarily simpler than the original query Q since $m \leq n$ and R'_m is smaller than R_m. Even for the worst possible case where $R'_m = R_m$ and $m=n$, Q'' is no worse than Q. (2) The detachment of Q' does not lead to an increase in the maximum number of variables for which substitution has to be made. To see this, note that the maximum number of variables to be substituted for in an n-variable query is $n-1$. Hence, this number is $(n-m+1)-1$ for Q' and $m-1$ for Q'' so that the total is again $n-1$. (3) Q' and Q'' are strictly ordered. Q' needs no information from Q'' so that it can be processed completely before processing on Q'' begins. At any given time we only need to deal with a total of n or less variables.

Two special cases of one overlapping-variable subqueries are worthy of special note. First, it may happen that the detached subquery Q' has no variable in common with the remainder Q''. That is, B' is a function of only $(X_{m+1}, \ldots, X_n)$ and not of X_m. In such a case we shall say Q' is a <u>disjoint</u> subquery. The interpretation of this situation is that if B' is satisfied by a nonempty set then Q is equivalent to Q'', otherwise Q is itself void, i.e., its result is empty. The second special case arises when $m=n$ and B' is a one-variable query.

This is a frequent and important occurence, as the previous example illustrates. We say a query is connected if it has no disjoint subquery, one-free if it has no one-variable subquery, and irreducible if it has no one-overlapping-variable subquery. An irreducible query is obviously both connected and one-free.

Broadly speaking, we will always break up a query into irreducible components before tuple-substitution. In effect, we will always prefer not to tuple-substitute if it can be avoided or postponed. Although examples can be constructed to show that such a choice is not always optimal, in general this is not a bad heuristic. Detaching subqueries involves an additive growth in complexity, while tuple-substitution incurs a multiplicative growth. Our decomposition algorithm is recursively applied to all the subqueries which are generated.

The Decomposition Algorithm consists of four sub-algorithms: Reduction, Subquery Sequencing, Tuple Substitution and Variable Selection and makes use of the One-Variable Processor of the system. The interaction among these component processes is indicated in Figure 3.1 below

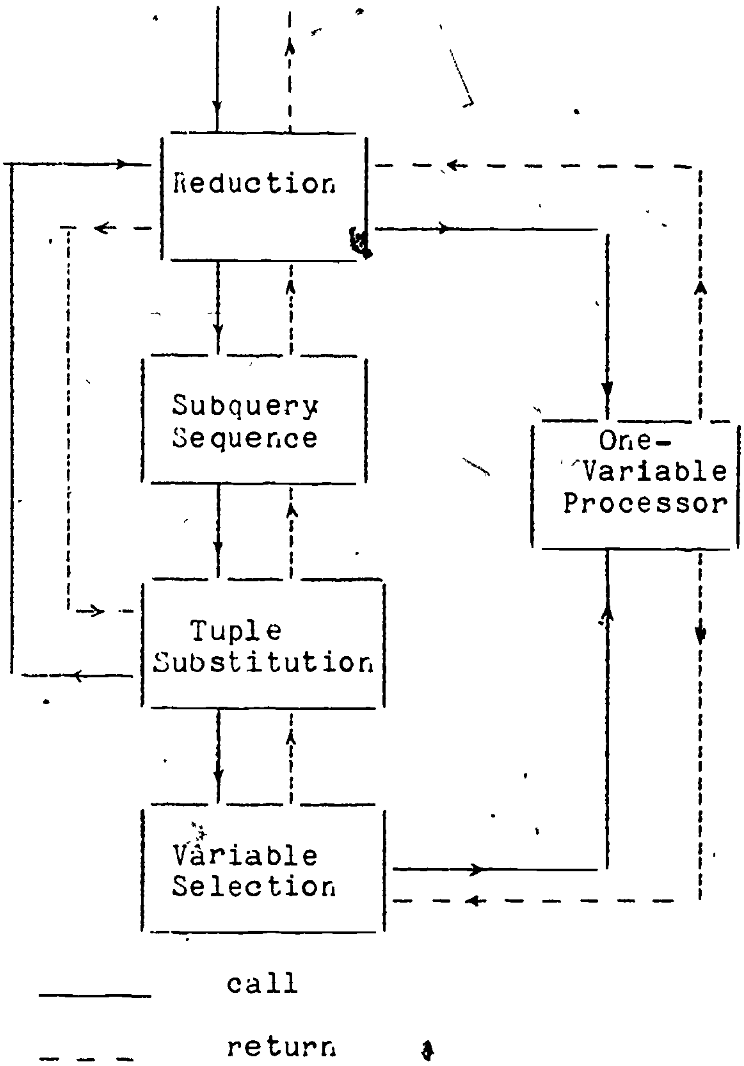


Figure 3.1 Flow of Control in Decomposition

The fact that the decomposition algorithm is recursive is made clear by the existence of a sequence of calling-paths (Reduction-Subquery Sequencing-Tuple Substitution-Reduction) which form a cycle. The basic functions of the sub-algorithms are as follows:

(a) Reduction breaks up the query into irreducible components and puts them in a certain sequential order.

(b) Subquery Sequencing uses the result of Reduction and generates in succession subqueries each of which contains a single irreducible component together with one-variable clauses. As each subquery is generated it is passed to Tuple-Substitution, and the generation of the next subquery awaits return of the result.

(c) Tuple Substitution manages the process of substituting tuple values. It calls Variable-Selection to select a single variable for substitution. After substituting each tuple for that variable, it passes the resulting reduced query to Reduction and awaits the return before substituting the next value.

(d) Variable Selection is where most of the optimization takes place. It estimates the relative cost of substituting for each variable and chooses the variable with the minimum estimated cost. In so doing, it may have to preprocess some one-variable subqueries.

The details of the sub-algorithms will be described in the next few sections.

4. Reduction Algorithm

The input consists of a multivariable query Q, and the output consists of the irreducible components of Q arranged in an appropriate sequential order. This sequence is passed to Subquery Sequencing, and the result relation for Q is returned. The basic steps of the algorithm are illustrated below.

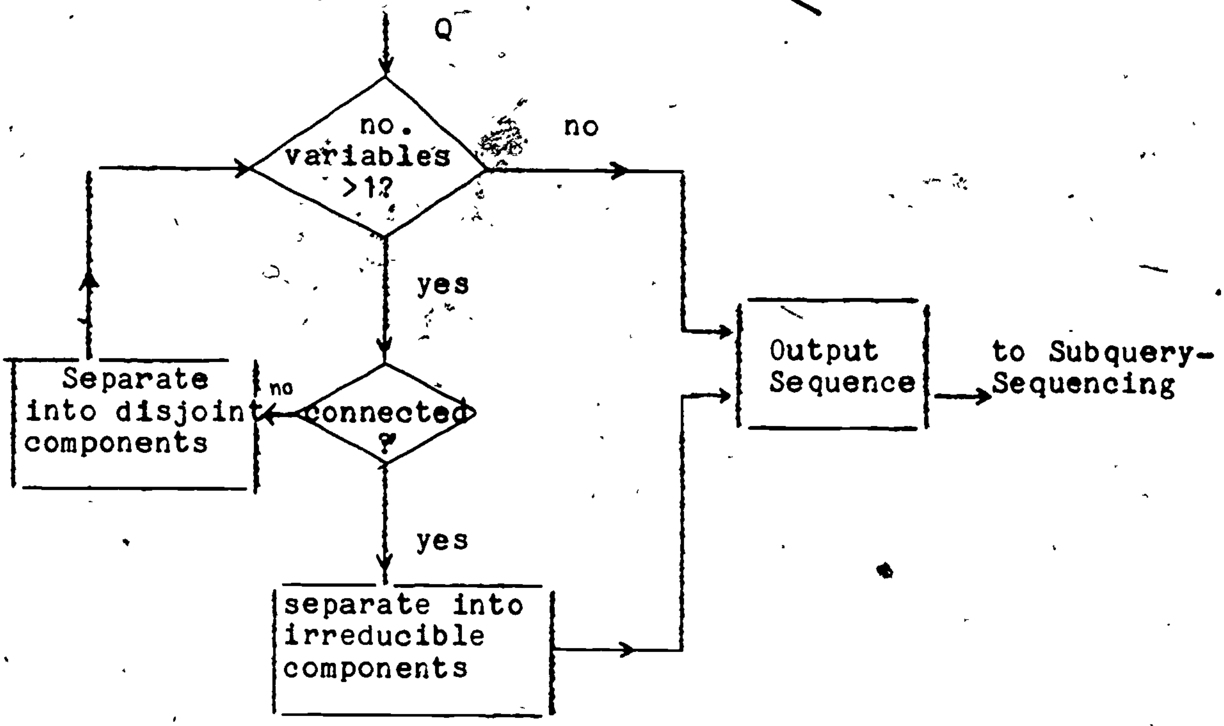


Figure 4.1 Reduction Algorithm

Let $X = (X_1, X_2, \ldots, X_n)$ denote the variables of Q and let $T(X)$ and $B(X)$ denote its target list and qualification respectively. We assume that $B(X)$ is expressed in conjunctive normal form

$$B(X) = \bigwedge_i C_i(X)$$

where each clause $C_i(X)$ contains only disjunctions. Now consider a binary (0 or 1) matrix with p+1 rows corresponding to T(X) and the p clauses, and with n columns corresponding to the variables $X_1, \ldots, X_n$. An entry of 1 will denote the presence of a variable in a clause (or target list), and 0 will denote its absence. We shall call this the incidence matrix. For example 3.1 this matrix is given by

	S	P	Y
T: S.Sname	1	0	0
C1: S.City=`New York'	1	0	0
C2: P.Pname=`Bolt'	0	1	0
C3: P.Size=20	0	1	0
C4: Y.S#=S.S#	1	0	1
C5: Y.P#=P.P#	0	1	1
C6: Y.Quantity≥ 200	0	0	1

We note that in Figure 4.1 there are two steps for which detailed algorithms remain to be provided. First, we need a test for connectedness, and to separate Q into disjoint components if it is not connected. Second, we need an algorithm to separate a connected query into irreducible components and to put them in a suitable sequential order.

(a) Connectivity Algorithm

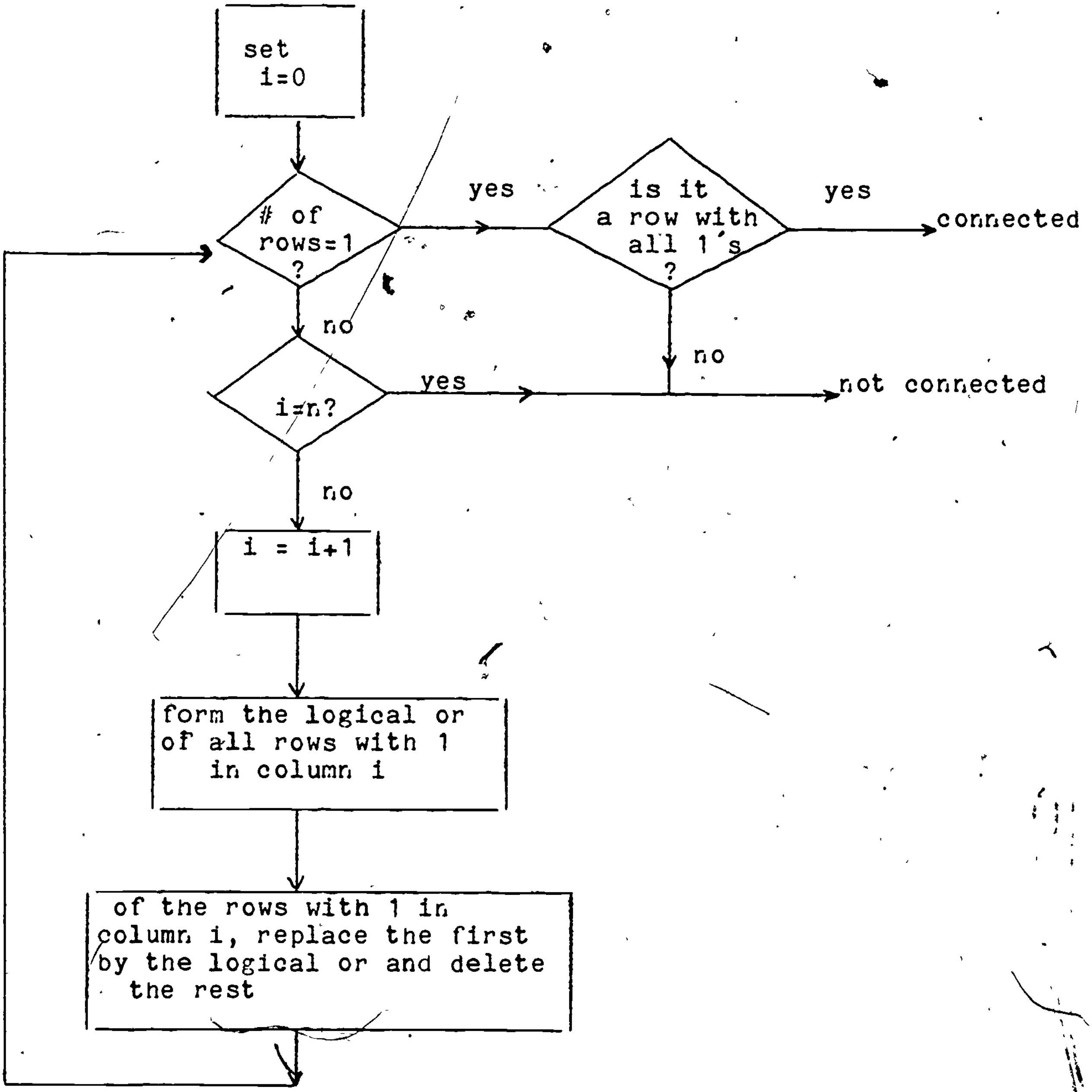


Figure 4.2 Connectivity

If the connectivity algorithm results in a matrix with a single row which is not all 1's then the variables corresponding to the zero-entries are superfluous and can be eliminated. If the final matrix has more than one row, then the sets of variables corresponding to different rows must be disjoint. If we keep track of the original rows which are combined to make up each of the rows of the final matrix, then the connected components of the query can be separated.

Consider example 3.1, modified by the deletion of C4. The incidence matrix now has the form

	S	P	Y
T	1	0	0
C1	1	0	0
C2	0	1	0
C3	0	1	0
C5	0	1	1
C6	0	0	1

Applying the connectivity algorithm, we get successively

	S	P	Y
T,C1	1	0	0
C2	0	1	0
C3	0	1	0
C5	0	1	1
C6	0	0	1

	S	P	Y
T,C1	1	0	0
C2,C3,C5	0	1	1
C6	0	0	1

	S	P	Y
T,C1	1	0	0
C2,C3,C5,C6	0	1	1

Hence, the query is not connected and the connected components are (T,C1) and (C2,C3,C5,C6).

(b) <u>Reduction into Irreducible Components</u>

Let Q be a connected multivariable query. We observe that it is reducible if the elimination of any one variable results in Q being disconnected. Let a variable with this property be called a *joining-variable*. Thus, Q is irreducible if and only if none of its variables is a *joining-variable*. Joining-variables have some important properties which greatly facilitate the reduction algorithm, and these are summarized as follows:

Proposition 4.1 Suppose that X is a joining-variable of Q such that its removal disconnects Q into k connected components. Then any joining-variable of one of the components is a joining-variable of Q, and every joining-variable of Q is a joining-variable of one of the components. Further, successive elimination of two joining variables in either order results in reducing Q to the same disjoint components.

proof: Each joining-variable joins a number of components which can overlap only on the joining-variable. Let X be a joining-variable of Q which joins components $Q_1, Q_2, \ldots, Q_k$. Let Y be a joining variable of one of these components, say Q_1. Then, Y joins components $Q_{11}, Q_{12}, \ldots, Q_{1j}$ of Q_1, only one of which can contain X, say Q_{11}. Therefore, $(Q_{12}, \ldots, Q_{1j})$ overlaps the remainder of Q only on Y and Y is a joining-variable of Q. Conversely, let Y be a joining-variable of Q, and join components Q_1', $Q_2', \ldots, Q_j'$. Only one of the set $\{Q_1', Q_2', \ldots, Q_j'\}$ can contain X, say Q_1', and only one of the set $\{Q_1, Q_2, \ldots, Q_k\}$ can contain Y, say Q_1. Then $\{Q_2', \ldots, Q_j'\}$ and $\{Q_2, \ldots, Q_k\}$ must be disjoint since each Q_i, $i \geq 2$, can overlap its remainder in Q only on X and none of $\{Q_2', \ldots, Q_j'\}$ contains X. Hence, $Q_2', \ldots, Q_j'$ are subsets of Q_1 joined to it only by Y, so that Y is a joining-variable of Q_1. It is clear that Q has components $\{Q_2, Q_3, \ldots, Q_k\}$ each joined by only X, $\{Q_2', Q_3', \ldots, Q_j'\}$ each joined by only Y, and a component Q_{xy} joined by both X and Y. Elimination of X and Y in either order results in disjoint components $\{\bar{Q}_2, \bar{Q}_3, \dots, \bar{Q}_k, \bar{Q}_2', \dots, \bar{Q}_j', \bar{Q}_{xy}\}$ where $\bar{Q}_i$ denotes Q_i with X removed, $\bar{Q}_i'$ denotes Q_i' with Y removed and $\bar{Q}_{xy}$ denotes Q_{xy} with both X and Y removed.

The substance of Proposition 4.1 is illustrated by Figure 4.3.

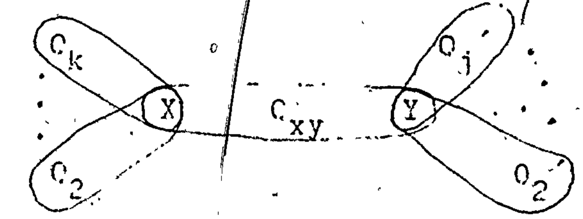


Figure 4.3 Joining-Variables

The results of Proposition 4.1 mean that we can find the irreducible components of Q by successively checking each variable for the possibility of being a joining variable. Each variable only needs to be examined once, and the order they are tested is immaterial. Further, since a variable is joining if and only if its elimination disconnects Q, we can use the connectivity algorithm for the test.

Take the incidence matrix of Q and eliminate from it all rows with only a single "1". Beginning with the first, eliminate each column in turn and test for connectedness. Suppose that when column m is eliminated Q breaks up into k connected components with $n_1, n_2, \dots, n_k$ variables respectively. Then, these correspond to components of Q with $n_1+1, n_2+1, \dots, n_k+1$ variables respectively, any pair of which overlap only on X_m. We can now proceed to test columns $m+1, \dots, n$. We note that each of the variables $X_{m+1}, \dots, X_n$ occur in only one of the components so that after the mth column (i.e. the first joining-variable) the tests are performed on matrices of reduced size.

Each irreducible component of Q corresponds to one or more row of the incidence matrix, and can be represented by the "logical or" of the corresponding rows. Hence, Q can be represented in terms of its irreducible components by a matrix with variables as columns and components as rows. We shall call this the <u>reduced-incidence-matrix</u>. It is convenient to arrange the rows as follows:

(1) One-variable rows except the target list./
(2) Components which are one-overlapping after deletion of one-variable clauses and which do not contain the target list. These should be grouped according to the joining variable.
(3) Other components which do not contain the target list.
(4) The component which contains the target list.

For example 3.1 the resulting reduced incidence matrix is given by:

	S	P	Y
C1	1	0	0
C2	0	1	0
C3	0	1	0
C6	0	0	1
C5	0	1	1
T,C4	1	0	1

8. Estimate of Result Parameters

In order to use (7.5) in (7.4), we must know the number of pages occupied by the range relations for every q_α in the sequence S_i. We note that S_i is a sequence and not a set, so that the range relation of a query may involve the result relations of queries which precede it. Therefore, knowing the sizes of the range relations of Q is not sufficient to determine (7.5) for the q_α's. Since we don't want to execute the sequence S_i except for the optimal i, we must rely on a procedure to estimate the sizes and other parameters of the result relation for a query.

Consider a query Q with range relations $R_1, R_2, \ldots, R_n$, a target list T(X) and a qualification B(X). Let the domains of R_i be denoted by D_{ij}, $j=1,2,\ldots,d_i$. Each R_i is by definition a subset of $\prod_{j \le d_i} D_{ij}$.

Hence, the product $\prod R_i$ is a subset of

$$D = \prod_{i \le n} \prod_{j \le d_i} D_{ij} \tag{8.1}$$

To determine what subset of $\prod R_i$ satisfies $B(X)=1$ requires accesses to the actual relations, but to determine what subset of D satisfies $B(X)=1$ requires only knowing the domains $\{D_{ij}\}$. The storage required to represent $\{D_{ij}\}$ is in general far less than that required for $\{R_i\}$.

Let R(Q) denote the result relation of Q. We can estimate the cardinality of R(Q) as

$$|R(Q)| = \left| \prod_{i \le n} R_i \right| \cdot \{\text{fraction of D satisfying } B(X)=1\} \tag{8.2}$$

The domains of R(Q) can be estimated by evaluating T(X) on the subset of D which satisfied $B(X)=1$. That is, the kth domain of R(Q) is estimated to be

$$\{T_k(X) \; ; \; X \in D, \; B(X) = 1\} \tag{8.3}$$

In most cases D_{ij} has sufficient regularity to permit it to be represented by just a few parameters. For example, D_{ij} might be simply all integers between a and b. Thus, the storage requirement for keeping track of the domains for the result relations of the sequence S_i can be expected to be reasonable.

6. Tuple Substitution

The input to tuple substitution is a query Q consisting of a single irreducible component in variables $X_1, X_2, \ldots, X_n$, zero or more one-variable clauses in each of the variables, and the range relations $R_1, R_2, \ldots, R_n$ of the variables. It returns the result relation to the calling process.

The first thing that Tuple Substitution does is to call Variable Selection which takes Q and the range relations and chooses a variable to be substituted for. In order to make this choice it may have to process some or all of the one-variable clauses to restrict the ranges. Thus, in general, it returns $\{Q', R_1', R_2', \ldots, R_n'\}$ and the variable to be substituted for (say X_n). For each tuple in R_n', Q' becomes a (n-1)-variable query $Q'(\alpha)$ in the variables $X_1, X_2, \ldots, X_{n-1}$. For each α, $Q'(\alpha)$ is passed to Reduction which returns the result. The results to $Q'(\alpha)$ for all α in R_n' are accumulated and returned to the calling process.

7. Variable Selection

This is the heart of optimization. The input is a multivariable query which is irreducible except for one-variable clauses. As its name suggests, the task of this portion of the decomposition algorithm is to select a variable for substitution, although to do so it may also have to process some of the one-variable clauses.

Consider a query Q with variables X_1, $X_2,\ldots,X_r$ and ranges $R_1, R_2,\ldots,R_r$. Suppose that X_i is substituted tuple-by-tuple. For each tuple, Q becomes an (r-1)-variable query $Q_i(\alpha)$. It is likely that $Q_i(\alpha)$ takes the same amount of time to process for every α, and in most instances every α in R_i has to be used. Hence,

(7:1) Cost of processing Q if X_i is substituted

$$= (\text{cardinality of } R_i) \times \text{Cost of processing } Q_i$$

The first thought, therefore, is to choose X_i with the smallest range. However, this is not optimal for several reasons.

First, it may be possible to reduce some or all of the relations $R_1, R_2,\ldots,R_r$ by preprocessing one variable clauses. Should this be done for all, for some, or for none of the variables? If all of the R_i's can be reduced, this decision alone involves 2^n choices. The situation is further complicated by the fact that for a given variable the decision as to whether to preprocess the one-variable clauses depends on whether the variable is chosen for substitution. If it will be chosen for substitution then its range should be reduced as much as possible. If not, preprocessing may be a waste of time. On the other hand which variable should be chosen depends not so much on R_i as on the reduced R_i. Let $\tilde{Q}(X_i)$ denote the one-variable subquery of Q in X_i, and let R_i' be the reduced range after $\tilde{Q}(X_i)$ is processed. The following policies seem to be reasonable alternatives:

(a) Preprocess every $\tilde{Q}(X_i)$, basing the policy on the argument that the cost of processing one-variable queries is relatively small and it is important to choose the variable for substitution well.

(b) On the basis of $\tilde{Q}(X_i)$, a decision is made for each variable whether to preprocess or not. Variable selection takes place after preprocessing.

The version of INGRES completed in January, 1976, opts for policy (a). In part, it is because in this version the variable selection is then based solely on the cardinalities of the reduced ranges and no other information. It is important, therefore, for these cardinalities to be accurate.

For (b) a workable policy is to use $\tilde{Q}(X_i)$ to estimate the size of R_i' for each i, and preprocess only if X_i is likely to be a contender for selection. For example, we might choose the top three contenders for preprocessing, or preprocess every variable for which the estimated size of R_i' is less than min $|R_i|$. One good feature of (b) is that except for very unusual situations, the actual variable selected will be among those which have been preprocessed, and no further processing is necessary before substitution.

A second and more important objection to the strategy of choosing X_i with the smallest range is that the complexity of Q_i can vary greatly with i and this must be taken into account in any strategy which lays claim to being even near-optimal. What must be determined is the extent to which Q can be reduced as a consequence of substituting for X_i.

Assume that we choose either (a) or (b) for the policy on preprocessing one-variable clauses so that that decision is decoupled from the selection of variable. We can assume that the query at this point consists of a single irreducible component with some one-variable clauses. The crux of the matter is how the irreducible component is affected by the substitution. Assume that whatever preprocessing is to be done has been done. Let the query be denoted by Q. Let $X_1, X_2, \ldots, X_n$, be the variables, and let $R_1, R_2, \ldots, R_n$ be their ranges. Let $Q_i(\alpha)$ denote the resulting query from substituting α for X_i in Q. Let C(Q) denote the <u>minimum cost</u> of processing Q. Then

$$(7.2) \qquad C(Q) = \min_i \{ \sum_{\bar{R}_i} C(Q_i(\alpha)) \}$$

where $\bar{R}_i$ denotes the set of tuple-values which have to be substituted for X_i. In most instances this is simply R_i, although as we indicated earlier there are exceptions.

Equation (7.2) is a dynamic programming

equation for the optimization problem at hand. As it stands, it is not too useful, since how $C(Q)$ depends on Q is not known. However, (7.2) is a suitable starting point for optimization. The variable selected will correspond to the value of i which minimizes an <u>estimated value</u> for

$$(7.3) \qquad C_i = \sum_{\alpha \in \bar{R}_i} C(Q_i(\alpha))$$

Although we have in effect transferred the optimization problem to one of estimating cost, the latter is amenable to a variety of heuristic approaches. Consider some of these:

(i) Suppose we take the estimate of $C(Q_i(\alpha))$ to be independent of α and i. Then, the minimum C_i corresponds to the smallest R_i. This somewhat simplistic policy is what has been implemented in the version of INGRES operational as of January, 1976.

(ii) We observe that unlike Q, $Q_i(\alpha)$ is not irreducible. One should therefore call Reduction-Subquery-Sequencing to reduce $Q_i(\alpha)$ to a sequence S_i of subqueries, each of which is irreducible except for one-variable clauses. Now, α enters the subqueries only as a parameter, and the sequence S_i is really independent of α. Thus, we have

$$(7.4) \qquad C(Q_i(\alpha)) = \sum_{q_\alpha \in S_i} C(q_\alpha)$$

Since the structure of $Q_i(\alpha)$ has now been represented, we can accept a relatively crude estimate for $C(q_\alpha)$. For example, we might take the estimate of $C(q_\alpha)$ to be

$$(7.5) \qquad C(q_\alpha) = \prod_j P(R_j)$$

where R_j are the ranges of q and $P(R)$ is the number of pages occupied by R.

(iii) We might try to obtain an estimate for cost by sampling. Consider the equation obtained from using (7.4) in (7.2)

$$(7.6) \qquad C(Q) = \min_i \left[\sum_{\alpha \in \bar{R}_i} \sum_{q \in S_i} C(q_\alpha) \right]$$

This is truly recursive, since Q and q_α are queries of the same restricted type (viz, irreducible except for one-variable clauses). If the number of variables in Q is not enormous (in practice, very few queries contain more than 4 or 5 variables) one might try to push the recursion (7.6) all the way down to one-variable queries, but using small samples for the range relations of Q. It is very likely that the costs of different paths in the decision tree vary widely, and only a few are contenders for the optimal path. With efficient management, this approach need not be prohibitively expensive.

These are but three possible approaches to estimating C(Q). Other approaches including some variants and combinations of these are under consideration. We expect to implement at least the three outlined above for experimental evaluation. Indeed, (i) has been implemented, and (ii) is in the process of being implemented.

8. Estimate of Result Parameters

In order to use (7.5) in (7.4), we must know the number of pages occupied by the range relations for every q_α in the sequence S_i. We note that S_i is a sequence and not a set, so that the range relation of a query may involve the result relations of queries which precede it. Therefore, knowing the sizes of the range relations of Q is not sufficient to determine (7.5) for the q_α's. Since we don't want to execute the sequence S_i except for the optimal i, we must rely on a procedure to estimate the sizes and other parameters of the result relation for a query.

Consider a query Q with range relations $R_1, R_2, \ldots, R_n$, a target list T(X) and a qualification B(X). Let the domains of R_i be denoted by D_{ij}, $j=1,2,\ldots,d_i$. Each R_i is by definition a subset of

$$\prod_{j \leq d_i} D_{ij}.$$

Hence, the product $\prod R_i$ is a subset of

$$(8.1) \qquad D = \prod_{i \leq n} \prod_{j \leq d_i} D_{ij}.$$

To determine what subset of $\prod R_i$ satisfies $B(X)=1$ requires accesses to the actual relations, but to determine what subset of D satisfies $B(X)=1$ requires only knowing the domains $\{D_{ij}\}$. The storage required to represent $\{D_{ij}\}$ is in general far less than that required for $\{R_i\}$.

Let R(Q) denote the result relation of Q. We can estimate the cardinality of R(Q) as

$$(8.2) \qquad |R(Q)| = |\prod_{i \leq n} R_i| \cdot \{\text{fraction of D satisfying } B(X)=1\}$$

The domains of R(Q) can be estimated by evaluating T(X) on the subset of D which satisfied $B(X)=1$. That is, the kth domain of R(Q) is estimated to be

$$(8.3) \qquad \{T_k(X) \; ; \; X \in D, \; B(X) = 1\}$$

In most cases D_{ij} has sufficient regularity to permit it to be represented by just a few parameters. For example, D_{ij} might be simply all integers between a and b. Thus, the storage requirement for keeping track of the domains for the result relations of the sequence S_i can be expected to be reasonable.

Since the sizes of the tuples are always known, the number of pages required for each of the result relations for the sequence can be computed from the estimated (8.2), which in turn is computed from the estimated domains using (8.3).

9. Summary

In this paper we have presented a detailed account of how multivariable queries are decomposed in system INGRES. The basic ingredients of the decomposition are two in number:

(a) To discover pieces of a query which are joined to the remainder by a single joining-variable.

(b) To substitute for a variable.

The overall strategy is to break up a query at the joining-variables whenever this is possible, and to select a variable for substitution which incurs a "minimum cost" whenever substitution can no longer be postponed. A detailed algorithm for reducing a query into irreducible components has been given. Alternative approaches to estimating costs have also been discussed.

Optimization itself incurs a cost which has not been taken into consideration. For simple queries, elaborate optimization may well do more harm than good. The approach to resolving this difficulty that we have opted is one suggested by M.R. Stonebraker. Suppose that we have two or more strategies $st_0, st_1, \ldots, st_n$, each one being better than the previous one but also requiring a greater overhead. Suppose we begin a query on st_0, and run it for an amount of time equal to a fraction of the estimated overhead of st_1. At the end of that time, by simply counting the number of tuples of the first substitution variables which have already been processed, we can get an estimate for the total processing time using st_0. If this is significantly greater than the overhead of st_1, then we switch to st_1. Otherwise we stay and complete processing the query using st_0. Obviously, the procedure can be repeated on st_1, to call st_2 if necessary, and so forth. st_n may correspond, for example, to progressively more levels in the decision tree, or to progressively more elaborate estimates of result parameters, or better sampling.

We have not addressed the question of optimizing the processing of one-variable queries. Some optimization is currently being done in INGRES, and this is described elsewhere [STON76].

In the appendix we have given a brief description of how INGRES is implemented. The original design of the implementation was primarily the work of M.R. Stonebraker and G.D. Held. Redesign of process 3, and in particular the design of the query tree and the implementation of the decomposition algorithm in the current version (as of January, 1976) have been largely the work of Peter Kreps. We have also included in the appendix specifications of the principal data structures needed for our decomposition algorithm.

One of us (E.W.) is responsible for introducing the conceptual framework in which the decomposition algorithm rests, viz. the policy of transforming a multivariable query to one dimensional ones, and the strategy of alternating between reduction and tuple substitution. We have collaborated on the reduction algorithm, and on the heuristics for variable selection. The implementation of the full algorithm as well as monitoring subsystems for the performance evaluation is being designed and executed by K.A.Y. The decomposition algorithm, being at the heart of INGRES, has enjoyed the attention of many participants of the project. It is difficult to remember who suggested what, but the three aforementioned colleagues have all made important contributions. In particular, as in every aspect of INGRES, the influence of M.R.S. is discernible throughout our algorithm.

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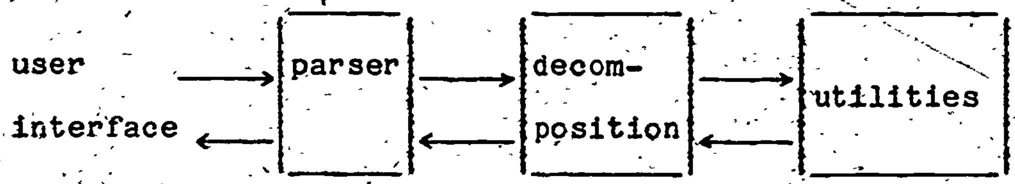
APPENDIX A.

System Organization

INGRES, Interactive Graphics and Retrieval System, runs on a PDP 11/45 under the UNIX operating system[RITC73]. The entire system is written in the programming language "C" [RITC74]. It has four major components which are organized as shown below.



These four components are set up as processes under UNIX and communicate through the use of pipes. The user interface can be one of several forms: an interactive text editor, a graphics interface [MCDO74], an interactive English-like language [CODD74], or part of a host programming language [ALLM75]. The parser accepts the user's query and processes it into a tree in conjunctive normal form. This query tree and a table of relations declared in the RANGE statements are passed to decomposition. The decomposition process contains not only the decomposition algorithm but also the one-variable query processor. The utilities process contains many functions which can be used by the system or the user.

APPENDIX B.

Data Structures

There are three main data structures which are used during decomposition of a query.

Range Table:

Some of the information for this structure is gathered during parsing and passed to decomposition as an ordered matrix. It is then put into a matrix, each entry of which has the following form:

```
struct  rangev
{       char   relid  [MAXNAME];
        struct descriptor *desp;
        int    setup;
}
```

The parser sends a table of relation names which have been declared in RANGE statements; the order of these names indicate the variable associated with each. These are relid. The second entry is a pointer to an in-core copy of the system catalogue description for that relation. The third entry is a flag which is set when the corresponding variable has been selected for substitition.

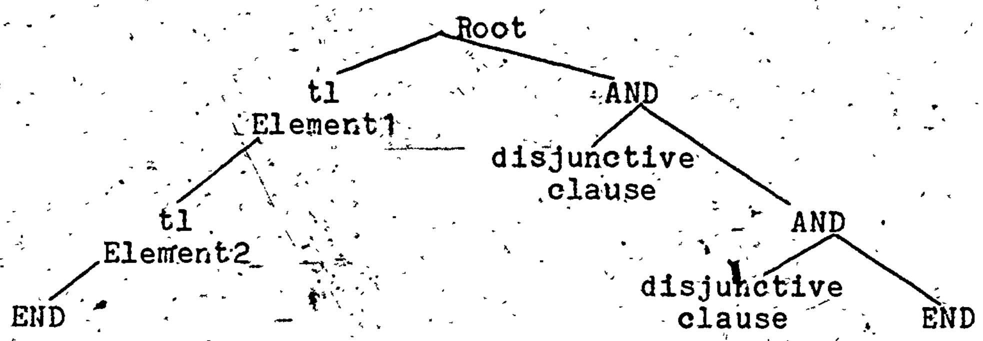
The use of this table will aid decomposition in the use of temporary relations. When a new range is created for a variable by execution of a one-variable query, the entry in the range table for that entry is the same except for the pointer to the catalogue description. The relid is always the original relation name for that variable and the descriptor is for the current subrelation it is ranging over. In this way, if a temporary relation must be created several times during the process of substitution, the same temporary relation name and descriptor can be reused by simply deleting the old tuples from the previous iteration. This saves much overhead in the creation of temporary relations.

Incidence Matrix:

This is a binary matrix of clauses (or subqueries) vs. variables which is used within decomposition to represent the current query under consideration. It is used during reduction to determine all irreducible subqueries and can be used during selection to represent the component subqueries in a compact form. This matrix will also contain an entry for each clause which points to the actual clause so that it may be easily obtained when it is necessary to build a query tree for execution of a subquery.

Query Tree:

The parser sends a list representing the query tree to decomposition which then rebuilds the query tree adding useful information as it is recognized. The general form of this tree is a root node with the target list of the query as the left branch and the qualification as the right branch. Since the query is in conjunctive normal form, all the intermediate nodes along the right side will be AND (conjunction) nodes.



More specifically, nodes of the tree are defined as:

```
struct querytree
{       struct querytree *left, *right;
        struct symbol sym;
}
```

where left and right are the pointers to the respective branches. The second entry defines the structure within the node and this varies depending on the type of node.

For nodes representing arithmetic operators, disjunctions (OR), result domains and constants, the structure is:

```
struct symbol
{       char type;
        char len;
        int value[];
}
```

where type is a code representing the type of the node (i.e., plus, minus, OR, etc.) and len is the length in bytes of value. value is a variable length field (0-255 bytes) and contains the appropriate value for that type of node. For example, if the node is representing a constant then the value contains the actual constant.

For nodes representing variable.attribute (i.e., E.SALARY) the structure is:

```
struct symbol
{       char type;
        char len;
        char varno, attno;
        char frmt, frml;
        char *valptr;
}
```

where type is the same as above and len is fixed. varno is an index into the range table for the correct variable; attno is the domain number (from the system catalogue) of the correct domain referenced. frmt and frml give the format of the attribute (i.e., A6, I2, etc.). This is used to determine new domain types and for calculations. The last entry is used during tuple substitution. If a particular variable is selected for substitution, all variable.attribute nodes involving that variable will become nodes representing constants. But the tree itself need not be changed. This field, valptr, is simply set to point to the constant value that should be used. This position remains fixed so when a new tuple value is substituted, the pointer does not change, only the value it is pointing to changes. In this way, a new tree is not needed for each level of substitution or for each iteration of substitution values. If the pointer is zero, the variable information is used; if it is nonzero, it is a constant node.

For nodes representing the root or conjunctions (AND), the structure is:

```
struct symbol
{       char type;
        char len;
        char tvarc;
        char lvarc;
        int lvarm;
        int rvarm;
}
```

where type is the same and len is fixed. tvarc and lvarc are both counts of the variables used. tvarc is the number of variables in the sub-tree below this node and lvarc is the number of variables in the left branch. So for the root node, tvarc is the total number of variables in the query and lvarc is the number of variables in the target list. For an AND node, tvarc is the number of variables in the remaining clauses and lvarc is the number of variables in the single clause of its left branch. lvarm and rvarm are bit maps of the variables used in the left and right branches of the node respectively.

This structure is not as costly as it might appear. It is true that during decomposition many subqueries are created and executed many times, but it should be noted that all of these subqueries use clauses which appear in the original query. The target lists may change, but no new clauses are ever created except through substitution. Since this is true, when a subquery is to be executed, a query tree can be constructed using nodes from the original tree. A new root node must be created for each subquery and for some target list nodes, but all the AND nodes can simply be detached from the original query tree and added to the new query tree.