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Response time minimization in distributed query optimization.

Mohan Kumar S. Bethur
University of Windsor

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Response Time Minimization in Distributed Query Optimization

by

Mohan Kumar S. Bethur

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- Genetics 0369
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Abstract

In Distributed Database Systems, the principal objective is to find an execution strategy which minimizes the cost. To find the best strategy, the query processing strategies which are commonly used include joins, semijoins and improvement algorithms. Here, in this thesis, a semijoin query processing strategy is used to find the best execution strategy.

In the AHY (Apers-Hevner-Yao) algorithms, the investigations only focus on reducing the amount of transmissions. They make the assumption that the cost to send the packets from any source to any destination is the same and they don't take into consideration the differences in delays in the links on the network. The objective of this thesis is to develop a heuristic which will take the network load along with the size of the data to be transmitted and compare it to the AHY algorithm GENERAL (Response time version).

Dedicated to my
father B.M. Siddaiah,
mother H.G. Shivalingamma,
sisters Shakuntala and Sunitha,
and brother Vijay Kumar

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

In the past, storing data in a single large and expensive centralized computer was extensively used in data processing. Due to recent developments in computer networks and workstations, distributed database management systems (DBMS) have become prominent.

The technology of distributed databases is based on two technologies : ***computer networks*** and ***database technology***. In distributed database management systems, the data is distributed and stored at different sites or nodes. These nodes are connected by a computer network. One of the principal objectives involved when retrieving the data is to get the information for a particular query very quickly. Therefore, most of the research now is being carried out in *optimizing query processing* in distributed database management systems so that the data requested by the user is made available quickly.

Computer communication technology has undergone revolutionary changes since the early 80's. Currently, optical communication (fibre optic) technology allows data transmission at very high speeds. Distributed database management systems depend critically on fast and efficient computer communications but current query optimization techniques do not take into account network parameters useful for communication.

One of the main difficulties in a distributed database system is to select an execution strategy that minimizes resource consumption, since equivalent strategies may consume differing amounts of computer resources. Therefore the primary objective is to find the

best strategy to execute a query. Popular methods for query optimization include joins [11, 34], semijoins [14, 13, 12], and improvement strategies [7, 9, 10]. In this thesis we concentrate on semijoin query processing strategies.

1.1 PROBLEM TO BE INVESTIGATED

In computer communication the main task is to send a given piece of information from any source to any destination as fast as possible and at the least cost. Whether the communication will at all take place or not is not an issue in computer communication. In distributed query optimization, in order to find the optimum sequence of semijoins, we clearly need to determine how much is the cost of the semijoin and what is the resulting benefit. Both of these parameters are determined by two factors,

- the amount of data that has to be communicated, and,
- the expected delay from the source to the destination.

The AHY (Apers-Hevner-Yao) query optimization algorithm [2] assumes that the cost to send the same amount of data from one site to another is independent of the address of the source and the destination node. They are only concerned with minimizing the amount of transmission in order to reduce the cost. The fact that the delay in the path used to transmit the relation from the source to the destination may vary widely is ignored in the AHY algorithms.

It is shown here that it is possible to improve the response time — the time elapsed from the initiation to the completion of the query, by developing a query optimization algorithm which takes into account both the *network load* and the *size of the data transmission.*

1.2 THE THESIS STATEMENT

Heuristics for minimizing the response time in distributed query processing can be improved by taking into account the network load.

1.3 OBJECTIVES AND SCOPE OF THE THESIS WORK

The objectives and the scope of this thesis are as follows :

1. To develop a query optimization heuristic to reduce the response time which takes into account both the network load and the size of the transmission.
2. To compare the new heuristic with the AHY Algorithm GENERAL (Response Time Version).
3. To carry out the simulation experiments under different network load conditions.

1.4 ORGANIZATION OF THE THESIS REPORT

Chapter 2 surveys previous work in two areas related to the thesis. First a brief introduction to distributed query optimization is presented. It also discusses the basic concepts and the benchmark AHY Algorithm GENERAL (Response time version). The second area which is discussed in this chapter is computer networks which facilitate communication in a DDBMS (Distributed Database Management System).

Chapter 3 describes the proposed query optimization heuristic. An example is given to show how the heuristic works. Chapter 4 presents the results of the investigation and the evaluation. Finally chapter 5 presents the conclusions, recommendations and suggests possible future work.

CHAPTER 2
BACKGROUND : REVIEW OF THE LITERATURE

2.1 DISTRIBUTED QUERY PROCESSING AND OPTIMIZATION

A distributed database system (DDS) is a system in which many computers are located at different locations and they are all interconnected by a network. Each of the computers contains a local database system. This collection of databases constitute the global database.

The software which manages the DDS is called the**Distributed Database Management System (DDBMS)**. There are two major components of a DDBMS. The first one is called the *user processor* and it is responsible for interpreting user input and formatting output, determining the execution strategy (query processor) and monitoring the global transaction execution. The second component is called the *data processor* and its responsibility is to optimize queries, ensure integrity control, concurrency and to provide recovery should failure occur.

In a DDBMS, the data processor contains four major components that are directly involved in the execution of a distributed query. They are the *query processing subsystem, the integrity subsystem, the scheduling subsystem and the reliability subsystem*. Efficient and reliable query processing is the result of proper interaction between these four components.

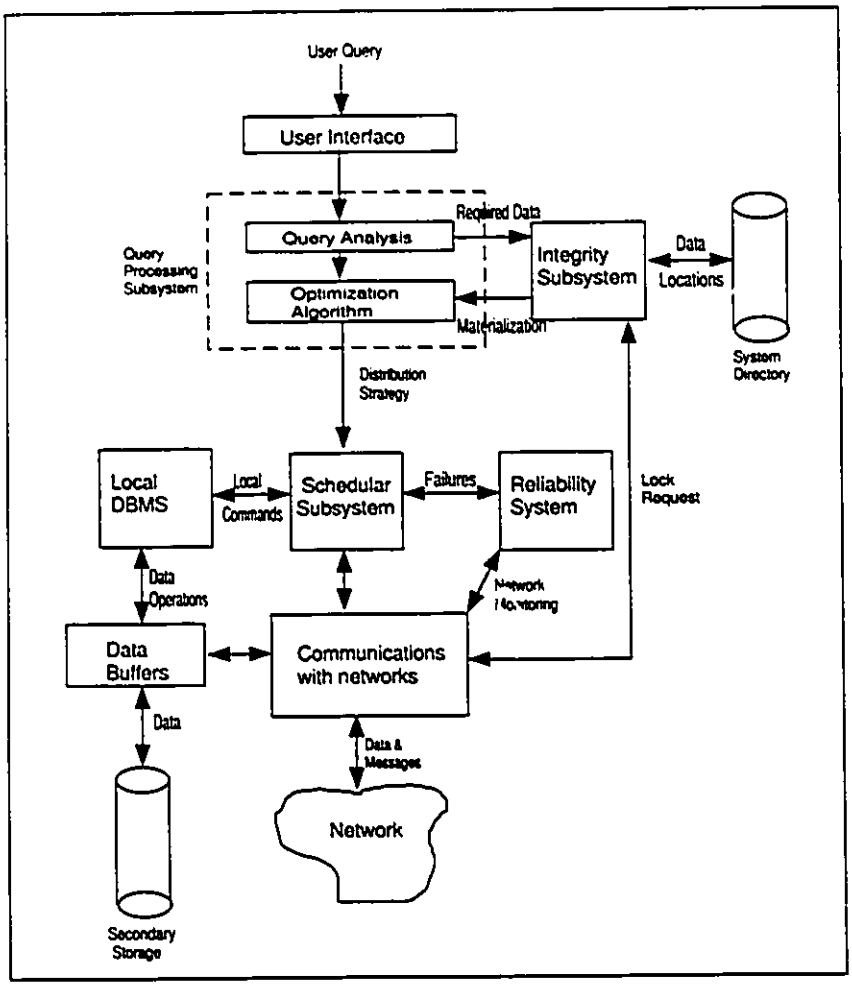


Figure 1 Query Processing System in [AHY79].

Before a query can be optimized, the *query processing subsystem* must have access to the subset of the database needed to answer the query. This materialization along with the location of the fragments and/or files is provided to the query processing subsystem by the *integrity subsystem.*

The problem of synchronizing update queries on the redundant data in the network is handled by the *integrity subsystem.* It must solve the problem of controlling concurrent

queries so that the database integrity and consistency is maintained while the communication overhead of transmitting control information among the network nodes is minimized.

Once the query processing subsystem receives a materialization for the query, the optimization algorithm (using algorithm PARALLEL, SERIAL, etc) can then produce an optimal distribution schedule. The *scheduling subsystem* coordinates the various schedules in the strategy result node. The complex distributed strategy will require considerable network coordination of transmission and local processing.

Another objective in a distributed database is to increase the reliability of data in the system. In order to achieve this objective, it is better that a number of copies of the same relation are distributed on different nodes in the network. In the case of a node failure, there is always another node where a copy of the desired data can be found. The *reliability subsystem* continuously monitors the system for failures. If a failure occurs the reliability subsystem notifies the scheduling subsystem of the event. The *scheduling subsystem* either waits for the reliability subsystem to integrate the failed component back into the system or it halts execution and requests that the query processing subsystem provide a new schedule based on the current status of the system.

Distributed Query Processing

There are a number of problems that are involved in distributed query processing. These problems are extremely complex. The reason for the complexity is that there are so many different variations on

- the kinds of networks available,
- the way in which these networks are set up, and,
- the way in which data is fragmented, replicated and distributed.

Distributed Query processing differs from centralized processing in two significant ways

1. There is a substantial amount of processing delay involved due to the communication among the sites which are involved in the query.
2. There is an opportunity for parallel processing since there are several computers involved in handling the query.

Query processing has been an active area of research ever since the beginning of the development of relational databases. Many different query processing strategies can be employed to optimize the processing of a query. The query entered by the user should be transformed into an equivalent query, so that it can be computed more efficiently. The method of generating this kind of improved strategy while processing a query is called ***query optimization***.

The primary objective involved in query optimization is to decide on a strategy for executing each query over the network in the most cost-efficient way.

Semijoin Query Processing Strategy

The simplest distributed query processing strategy is to ship all relations that are involved in a query to the point where the query originated. This strategy is expensive if large relations have to be transmitted to the originating node and if the result of the query only contains a few tuples and attributes. This strategy is referred to as the initial feasible solution (IFS) [2].

Another solution is to use the join as a query processing strategy [11, 16, 43, 34]. This involves joining selected relations before they are transmitted. The join operation is denoted as $\bowtie$. Computing the join of two relations can be expensive. Whenever possible joins should exploit concurrency. Unwanted information is eliminated before

any transmission using reducers. ***Reducers*** reduce the amount of information that has to be transmitted. It is better to execute the unary operations (selection, projection) as soon as possible.

The projection of a relation R over the set of attributes A is denoted by $\Pi_A[R]$. The result of the projection is obtained by discarding all columns of R that are not in A, and eliminating any duplicate rows if necessary.

The ***Semijoin*** strategy is an important strategy for query processing. Let R_1 and R_2 be two relations with common attribute A. The ***Semijoin*** operation is carried out as follows :

1. $R'_1 = \Pi_A[R_1]$
2. Transfer R'_1 to the site of R_2
3. $R_2^1 = R_1 \bowtie R_2$

The notation $R_1 - A \rightarrow R_2$ will be used to denote a semijoin operation between the relations R_1 and R_2 over the common joining attribute A.

Semijoins are important in DDS because they usually reduce the amount of data that needs to be transmitted between sites in order to evaluate a query.

In [6], semijoins are used as the principal reduction operator. The paper defines the semijoin operator, explains why semijoins are effective as a reduction operator and presents an algorithm that constructs a cost-effective program of semijoins, given an envelope and a database. An envelope is a relational calculas expression that maps a database into a sub-database[6].

Semijoins are beneficial only when an attribute has a good selectivity [11, 34], in which case the semijoin act as a powerful reducer. In [43] it is stated that although the use

of semijoins reduces the amount of data transfer and is a valuable tool, it is not always superior to the use of joins. The reasons are:

1. Additional messages may be generated when semijoins are employed.
2. For certain networks, the number of messages exchanged rather than the amount of data transferred may be a dominating factor.
3. Many tactics based on semijoin do not take into account local processing costs.

2.2 COST ESTIMATION TECHNIQUES

Cost Measures

The cost function is usually defined in terms of time units or in terms of computing resources such as disk space, disk I/O, buffer space, CPU cost, communication cost and so on. There are two very important performance variables in query optimization, *total cost* and *response time*.

Total Cost : It is a good measure of resource consumption that will be incurred when processing a query. It is the sum of all the times incurred in processing the operations of the query at various sites and in intersite communication. A general formula for determining the total cost is as follows [34, 11]:

Total Cost : C_{CPU}*#*insts* + $C_{I/O}$*#*I/Os* + C_{MSG}*#*msgs* + C_{TR}*#*bytes*

- C_{CPU} : is the time to execute one CPU instruction.
- $C_{I/O}$: is the time to execute one disk I/O.
- C_{MSG} : is the fixed time to execute the initiation & receiving of a message.
- C_{TR} : is the time to execute the transmission of a data unit from one site to another. A typical assumption is that C_{TR} is a constant.

Response Time : This is the elapsed time for query execution. Since the operations can be executed in parallel at different sites, the response time of a query may be significantly less than its total cost. A general formula for determining the response time is shown below [34, 11].

Response Time = C_{CPU}**seq.#insts* + $C_{I/O}$**seq.#I/Os* + C_{MSG}**seq.#msgs* + C_{TR}**seq.#bytes*

Example :

The example illustrates the difference between total cost and response time. In order to compute the answer to a query at site 3, data has to be communicated from site 1(2) to site 3.

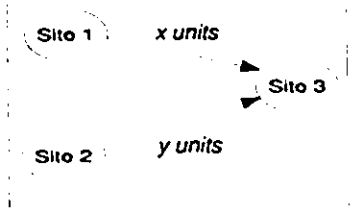


Figure 2 An example to calculate response time and total time.

Assumptions :

1. We only consider the communication costs.
2. C_{MSG} and C_{TR} are expressed in *time units.*

Total Cost = $(C_{MSG} + C_{TR} * x) + (C_{MSG} + C_{TR} * y) = 2 * C_{MSG} + C_{TR} * (x + y)$

Response Time = Max $\{ C_{MSG} + C_{TR} * x, C_{MSG} + C_{TR} * y \}$

since the transfers can be done in *parallel.*

Let x = 1000 be the number of units to transmit from site 1 to site 3 and y=2000 be

the number of units to transmit from site 2 to site 3. If the value of C_{TR} = 1, and the value of C_{MSG} = 20, then :

Total cost = 2 * 20 + 1000 * 1 + 2000 * 1 = 3040.

Response Time = max { 20 + 1000 * 1, 20 + 2000 * 1} = 2020 as the transfers are done in parallel.

Database Statistics

An important factor affecting the performance of an execution strategy is the size of the intermediate relations that are produced during execution. Therefore, it is necessary to estimate the size of the data transfers. This estimation is based on statistical information about:

1. The base relations
2. Formulae to predict the cardinalities of the results of the relational operations.

The main goal of an optimization algorithm is the production of an optimal query execution strategy. The formulation of such an optimal execution strategy can only be accomplished by an exhaustive search of all the possible strategies. The complexity of such an enumeration is shown to be NP-hard [34] resulting in an algorithm that is too computationally expensive to be of any use. Therefore heuristic algorithms are employed to formulate near-optimal strategies.

As most execution strategies are computed statically [11, 34, 7, 9, 10], they require some means of estimating the various values associated with each relation. These values include :

1. the size of the partial relations.
2. the cardinalities of attributes in reduced relations.

3. the selectivities of attributes in reduced relations.

The selectivity ρ_i [11, 34] is defined as the ratio of the number of distinct attribute values of $R_i.A_j$ to the number of possible attribute values in A_j (in R_i).

Let p_{ia} be the probability of a value in an attribute A which appears in Relation R_i, $i=1, 2$. Since the values in the relations are independently distributed, the probability that a value appears in both the relations is $p_{1a} * p_{2a}$. Thus the expected number of distinct tuples in common between the two relations is $|A| * p_{1a} * p_{2a}$ where $|A|$ is the cardinality of the domain of the attribute A. The estimated size of the reduced relation R_1 is $|A| * p_{1a} * p_{2a} * w$ where w is the size of one tuple in bytes.

In a relation which has more than one joining attribute, reducing the relation on an attribute may contribute to the reduction of the attribute values of the associated attributes. Here the computation time in evaluating the equation can be expensive if the number of tuples in the reduced relation is large. In [21], the following equation has been proposed. Let $R_i(A_1)$ and $R_j(A_1A_2)$ be two relations in the semijoin, $R_i - A_1 - R_j$ and let n=$|R_j|$, m=$|R_jA_2|$ and k=$\left|R_j^1A_2\right|$ then the factor of reduction of $\left|R_j^1A_2\right|$ is given by

$$p = \begin{cases} 1-(1-k/n)^{n/m} if n/m < k \\ 1-(1-1/m)^{k} otherwise \end{cases}$$

The above estimation can be extended to multi-attribute semijoins also. It has been shown that a satisfactory estimate can be found for the semijoins using multiple attributes based on the ball color problem [19, 15, 21, 43]. " Given n balls with m colors, find the expected number of colors if t balls are selected from n of the m balls". In this case n represents the number of tuples of R_i before the semijoin, m is the number of distinct values of R_i projected on the A attribute before the semijoin and t is the number of tuples

of R_i after the semijoin. The expected cardinality is

$$g(m,n,t) = m * \left[1 - \prod_{i=1}^{t} \left(\frac{(n((m-1)/m) - i + 1)}{n - i + 1}\right)\right]$$

While t is a given parameter in the ball color problem, the number of tuples in $R_i{}^l$must be estimated. In its given form, the application of the formula is computationally expensive and may result in overflow/underflow errors for large values of t and a reasonable approximation for the formula is given by

$$g(m,n,t) = \begin{cases} m, & t \geqslant 2m \\ t, & 2m \geqslant t \geqslant (m/2) \\ \frac{(m+t)}{3} & \left(\frac{m}{2}\right) > t \end{cases}$$

It is shown that the cardinality of the relation resulting from the join query can be found out using a theorem explained in [16].

A ***beneficial semijoin*** refers to a semijoin in which the benefit of performing the semijoin exceeds the cost of executing it. The ***benefit*** of a semijoin can be considered as the amount of data that is eliminated after the semijoin operation is performed. The benefit is computed by the following function.

$$Benefit(R_i - d_{ik} \rightarrow R_j) = s_j - s_j^1 \ \ where\ s_j^1 = s_j * \rho_{ik}$$

where s_j is the size of relation R_j and ρ_{ik} is the selectivity of attribute d_{ik}

The ***cost*** associated with a semijoin refers to the transmission of the joining attribute after projection from the reducing relation to the reduced relation. Assuming that the transmission cost is fixed between the sites, the cost of the semijoin can be computed using

$$Cost(R_i - d_{ik} \rightarrow R_j) = C_0 + C_1 * b_{ik}$$

where C_0 and C_1 represents the start-up cost for a transmission and the fixed cost per byte transmitted respectively and b_{ik} is the size of the attribute.

2.3 SEMIJOIN QUERY OPTIMIZATION STRATEGIES

The aim of query optimization is to produce an optimal strategy. In distributed query optimization, the main problem is to determine a sequence of database operations and data communications such that the cost function is minimized. Here we concentrate on the semijoin strategies for relational databases. In [22], an algorithm based on the query optimization technique of decomposition is developed. This algorithm is implemented in a distributed INGRES database system.

In [2] query optimization algorithms using semijoins to minimize the total time and the response time for simple queries are discussed. The algorithms are discussed in more detail later in this literature.

There are other distributed query optimization strategies. In [28] Kang, H and Rousopolous, N have discussed a ***two-way semijoin*** for more cost-effective distributed query processing. The two way semijoin is used to reduce the relations in a more efficient way and can be an efficient reducer like the semijoin operation. The two way semijoin is an extended operator because of the fact that it produces two semijoins from its operands.

If there are two relations, relation R_i and R_j which have a common join attribute A, the result of the two way semijoin is a set of two relations $\{ R_i', R_j' \}$ where $R_i'(R_j')$ is the projection on the attribute of $R_i(R_j)$ of the join of R_i and R_j. The two-way semijoin operation of R_i and R_j is denoted as $R_i \leftarrow A \rightarrow R_j$. We can see that two semijoin operations are performed and they can be represented as,

$$R_i \leftarrow A \rightarrow R_j = \{R_i - A \rightarrow R_j, R_j - A \rightarrow R_i\}$$

Here R_i and R_j are reduced to $R_i'$and R_j'.

Simulation results [28] have shown the performance of the two-way semijoin to be more powerful than the ordinary semijoins. A pipeline N-way join algorithm is also proposed using a two-way semijoin [36].

Another semijoin based strategy called the ***composite semijoin***, which involves multiple attributes is presented in [35]. A composite semijoin is a semijoin in which the projection and transmission involve multiple columns. In most algorithms, multiple semijoins are performed with common source and destination sites when multiple attributes are involved. Whenever there is a situation like this, it is beneficial to do the semijoins as one composite rather than multiple single column semijoins. Through simulation results, it has been shown [35] that including the possibility of composite semijoins in a query processing algorithm substantially reduces the response time.

Another semijoin strategy [20] uses the hash function, ***Hash-semijoin***. Hashing techniques are generally considered to be an efficient way of finding the matching tuples. In [31] Bloom filters are used to filter out the tuples that do not participate in the join. A bloom filter is a large vector of bits that are initially set to zero. This is called *bloom join*.

Consider a join between the relations R_i and R_j with the join attribute A. The hash semijoin relation from R_i and R_j, denoted by$R_i - A \stackrel{hsj}{\rightarrow} R_j$ is defined as

$$\{t_j \in R_j | \exists t_i \in R_i \ni h_{ij}(t_j.a) = h_{ij}(t_i.a)\}$$

where h_{ij} is the hash function associated with the hash semijoin $R_i - A \stackrel{hsj}{\rightarrow} R_j$. The implementation of the hash semijoin is done in the following steps,

1. The projection of R_i on the join attribute is done.
2. The join attribute is hashed by h_{ij} and the bit array B_{ij}(i.e. B_{ij}[k] is set to 1 if there exists a join attribute value v in relation R_i, such that h_{ij}=k).

3. Send B_{ij} to the site of R_j, and finally select the tuples of R_j, whose join attribute value is u and $B_{ij}[h_{ij}(u)] = 1$, as the result of hash semijoin.

Semijoins with multiple hash functions has been suggested by [40]. Here after step (1), the join attribute is hashed with multiple hash functions and it uses the results as the addresses into the bit arrays respectively. That is, a set of hashing functions h_1, h_2, ... h_m are used, each associated with the bit array B_1, B_2, ... , B_m, respectively. For each value v of the join attribute, all of the corresponding bit in each B_i must be set (i.e. $B[h_1(v)]=1$, $B[h_2(v)]=1$, ... , $B[h_m(v)]=1$.) (It is shown in [3] that as we increase m, the probability of collisions approach *0*) Then these bit-arrays are sent to the site of R_j. Each tuple of relation R_j, whose join attribute value is u, belongs to the semijoin if $B[h_1(u)]=1$, $B[h_2(u)]=1$, ... , $B[h_m(u)]=1$. Semijoin with multiple hash functions is very complex since many hash functions have to be used to reduce the collisions. Collisions can cause some problems but still hash semijoins are considered useful for the following reasons :

1. *Flexibility* : The cost and benefit of an hash semijoin are affected by the probability of the collisions of the hash function used in this hash semijoin. Since the hash function used in the hash semijoin may be any randomizing function, there may be many hash functions which can be chosen and their probabilities of collisions are all different. Therefore hash semijoins are flexible.
2. *Simplicity* : Since there is only one hash function used in each hash semijoin, there is only one-bit array used in each hash semijoin. The processing overhead and transmission cost of hash semijoins are therefore smaller than that of semijoin with multiple hash functions.

The semijoin query processing strategy has also been extended to fragmented databases. In [14], ***Domain specific semijoins*** are proposed for distributed query processing in horizontal partitioned database systems. A complete description is given in [14].

2.4 AHY ALGORITHM

In [2] a family of distributed query optimization algorithms using semijoins to minimize the response time and total time for simple queries (algorithm PARALLEL and algorithm SERIAL) is discussed. *Simple queries* are defined such that at initial local processing, each relation in the query contains only one common join attribute, which is also the only output of the query. A general query that contains multiple join queries is decomposed into simple queries and then the algorithm can be applied to each of them.

It is claimed that algorithm PARALLEL derives minimal response time distribution strategies by searching for cost beneficial data transmissions in the current system state given by s_i, *selectivity* p_i and schedule response time r_i of each relation R_i. The *selectivity* ρ_i of an attribute is defined as the number of different values occurring in the attribute, divided by the number of all possible values of the attribute. Thus $0 < \rho_i \leq 1$.

A complete description of the AHY Algorithms is given in [2].

Algorithm PARALLEL

The basic strategy of algorithm PARALLEL is to search for cost beneficial data transmissions by trying to join small relations to large relations. First an Initial Feasible solution (IFS) is chosen, where all relations are transmitted in parallel to the query site. The algorithm then tries to improve on the solution by considering alternative schedules where some relations are sent to an intermediate site. The algorithm does not consider all schedules that could be generated for a given relation R_i. Relations larger than R_i

cannot improve the original schedule of R_i and thus are discarded after first ordering the relations by increasing sizes after projections on the join attributes. The algorithm PARALLEL is given below:

1. Order the relations R_i such that $s_1 \leq s_2 \leq .... \leq s_m$ where s_i is the size of relation R_i.
2. Consider each relation R_i in ascending order of size.
3. For each relation R_j $(j<i)$, construct a schedule to R_i that consists of the parallel transmission of the relation R_j and all schedules of relation R_k $(k<j)$. Select the schedule with minimum response time.

Algorithm SERIAL

To minimize the total time a serial strategy is discussed in [2]. Given an ordering on the required relations of the simple query, the SERIAL strategy consists of transmitting each relation, starting with R_1, to the next relation in a serial order. The strategy is represented by $R_1 \rightarrow R_2 \rightarrow .... \rightarrow R_n \rightarrow R_r$, where R_r is the relation at the result node. There are two cases of the SERIAL strategy. In case 1, R_r is included in its proper order in the transmission pattern, $R_1 \rightarrow R_2 \rightarrow .... \rightarrow R_r \rightarrow ... \rightarrow R_n \rightarrow ... \rightarrow R_r$. In case 2, R_r is not included in its proper order, $R_1 \rightarrow R_2 \rightarrow .... \rightarrow R_n \rightarrow R_r$. It is claimed that the SERIAL strategy has minimal total time when the relations are ordered so that $s_1 \leq s_2 \leq .... \leq s_m$.

The algorithm SERIAL is given below:

1. Order relations R_i such that $s_1 \leq s_2 \leq .... \leq s_m$.
2. If no relations are at the result node, then select strategy:

   $R_1 \rightarrow R_2 \rightarrow .... \rightarrow R_n \rightarrow resultnode$

Or else if R_r is a relation at the result node, then there are two strategies:

$R_1 \rightarrow R_2 \rightarrow .... \rightarrow R_r \rightarrow .... \rightarrow R_n \rightarrow R_r$ or

$R_1 \rightarrow R_2 \rightarrow .... \rightarrow R_{r-1} \rightarrow R_{r+1} \rightarrow .... \rightarrow R_n \rightarrow R_r$.

3. Select the one with minimum total time.

Owing to the fact that algorithms PARALLEL and SERIAL only work in specialized situations, the algorithm can be extended to work in general query environments. Algorithm GENERAL (discussed in the next section) is a general heuristic that uses an improved exhaustive search to find efficient distribution strategies for general queries.

Algorithm GENERAL

Apers and Hevner developed an improved algorithm called GENERAL to process general queries[1]. A general query is characterized by $\alpha_i > \beta_i > 1$ for i = 1, 2, ... , m where m is the number of relations, α_i is the number of attributes in relation R_i and β_i is the number of intermodal joining attributes in relation R_i. Let σ represents the number of joining attributes in a query.The tactic used in the algorithm is to reduce the size of a relation with semijoins on different joining attributes.

Each relation R_i is examined in a small to larger order (i.e., the index of the relation indicates its relative size after projection on the join attribute): $size(R_1) \leq size(R_2) \leq ...size(R_m)$ to find a schedule that has minimum response time or minimum total time, depending upon the declared cost objective.

Algorithm GENERAL makes the following assumptions

1. The cost of processing a query is determined by the transmission cost only.
2. All relations are located at different sites.

[1] A general query means that a relation can contain more than one joining attribute.

3. Local processing cost is not taken into account.
4. The query processing strategy is run on a dedicated system.
5. Communication line and subsequent queueing delays are not considered in the algorithm.
6. All initial local processing has been performed.

The Algorithm GENERAL (Response time version) is given below :

1. Do all *initial local processing*
2. *Generate candidate schedules.* Isolate each of the σ joining attributes, and consider each to define a simple query with an undefined result node.
    - Since response time is being reduced, apply algorithm PARALLEL to each simple query. Save all candidate schedules for integration in step (3).
3. *Integrate the candidate schedules.* For each relation R_i, the candidate schedules are integrated to form a processing schedule for R_i. To minimize the response time, procedure RESPONSE is used to integrate the schedules.
4. *Remove schedule redundancies.* Eliminate relation schedules for relations which have been transmitted in the schedule for another relation.

Procedure RESPONSE is carried out as shown here :

1. *Candidate schedule ordering* : For each relation R_i order the candidate schedules on the joining attributes d_{ij}, j = 1, 2, ...σ in ascending order of arrival time. Let ART_l denote the arrival time of candidate schedule $CSCH_l$. (For the joining attributes not in R_i, disregard the corresponding candidate schedules)

2. *Schedule Integration* For each candidate schedule $CSCH_l$ in ascending order, construct an integrated schedule for R_i that consists of the parallel transmission of $CSCH_l$ and all $CSCH_k$ with $k<l$. Select the integrated schedules with minimum response time.

2.5 COMPUTER NETWORKS

The connection of a number of autonomous computers that are capable of exchanging information among themselves is called a computer network. The computers should be autonomous because they should be capable of executing programs on their own. The computers in the network are called nodes, sites or hosts. A computer network is a special case of a Distributed Computing Environment (DCE).

Network Topology

Based on the interconnection structure of the computers, we can classify computer networks. There are different topologies which are used. Either point-to-point topology or multi-point topology can be used in the construction of the Wide Area Network. In point-to-point network, every site is connected by an IMP (Interface Message Processors). An IMP is a dedicated processor connected by a communication channel. In a point-to-point network, the IMP's have the responsibility of choosing the path along which a message is transmitted in the presence of alternatives. In a multi-point topology the fundamental medium of transmission is a broadcasting channel such as a radio or satellite link. Another popular form of data communication is Microwave transmission. In a broadcast network, everybody can listen and therefore it is not as secure as a point-to-point network. Most of the wide area networks are implemented according to point-to-point topology.

The different computer architectures used are star, tree and mesh. In a star topology, all the computers are connected to a central computer that coordinates the transmission on the network. Therefore if any two computers want to communicate they have to go through the central computer. One disadvantage is their unreliability. Since the communication between any two computers depends on the availability of the central computer, a failure

at this node will cause the transmission over the network to stop completely. Another disadvantage is the excessive load on the central computer.

In a hierarchy or tree network, all the nodes are connected in the structure of a tree. The transmission among the nodes at the same level has to proceed upward until a common node can be found, and then it proceeds down to the other node. In a meshed interconnection scheme, each node is interconnected to every other node. Even though it provides reliability and better performance, the implementation is very expensive.

The Physical Transmission of Data

Due to the fact that the sites in Wide Area Networks are distributed physically over a large geographical area, the communication links are likely to be relatively slow and less reliable as compared with Local Area Networks (LANs). Typical WAN links are telephone lines, microwave links and satellite channels. In LANs all sites are close together, so the communications are of higher speed and have lower error rates than their counterparts in WANs. The most common links are twisted pair, baseband coaxial, broadband coaxial, and fiber optics.

The sites in the computer communication system can be connected physically in a variety of ways. The various topologies are represented as graphs whose nodes correspond to sites. An edge from node A to node B corresponds to a direct physical connection between two sites. In most cases it is just not feasible to connect all sites together. The network topologies like ring or bus network provide for the sharing of transmission facilities among many sites. Therefore the cost incurred by any pair of sites is reduced.

The best known ways to transmit digital information are Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM). In WDM, the frequency spec-

trum is divided into logical channels, with each user having exclusive possession of this frequency band (frequency sharing). In TDM, each user takes turns accessing the entire bandwidth for short periods of time. The advantage of multiplexing schemes is that a large number of voice and data transmissions can occur simultaneously, thus making better use of the existing communication facilities.

Recent advancements in the area of light wave technology, have made it possible to transmit the data on an optical fiber using light pulses to represent bits (a light pulse represents a 1 bit, no light pulse represents a 0 bit). Some reasons why fiber optic technology is so important are that a fiber has high bandwidth, is thin and lightweight, is not affected by electromagnetic interference, and has excellent security because it is nearly impossible to wiretap without detection.

Architecture and Importance of Computer Networks

The Local Area Network (LAN) is defined as a communication network that provides interconnection of a variety of data communicating devices within a small area. LANs support minis, mainframes, terminals and other peripherals. In many cases, these networks can carry not only data but voice, video, and graphics.

The most common type of LAN is the bus or tree using coaxial cable. Rings using twisted pair, coaxial, or even fiber are alternative media. The data transfer rates on LANs are high enough to satisfy most requirements and provide sufficient capacity to permit large numbers of devices to share the network.

The usual length of LANs is less than 3 miles. This restriction is a result of propagation delays in the network.

Metropolitan Area Networks (MANs) are defined as networks that support two way communication over a shared medium, such as optical-fiber cable, span a distance of approximately 50 miles, and may offer point-to-point high speed circuits or packet switched communication. MANs are expected to transmit data at rates of 150 MBits/s. They do not, however have the huge traffic handling capability of a switched exchange network. Essentially a MAN is a very large LAN, using access protocols less sensitive to network size than those used in LANs.

Most early networks were WANs designed for voice communication. Because of the proliferation of computers within individual sites, LANs were developed to interconnect these local computers in order to share data and resources. WANs usually span greater distances and are based on the store-and-forward switching mechanism, and require the routing of packets. LANs on the other hand, span distance of up to 3 miles, are based on the ring topology which constitute a single data link, and are usually error prone.

The characteristics of LANs and WANs [39] are given in the table below

Local Area Networks (LAN)	**Wide Area Networks (WAN)**
Within site up to 3 miles	Distances up to thousands of miles
High Bandwidth (> 1M. bits/s)	Typical data rates up to 100 K. bits/s
Simpler protocols	Complex protocols
Interconnect cooperating computers in distributed processing applications	Interconnect autonomous computer systems

Table 1 Characteristics of LAN and WAN. (Continued) . . .

Local Area Networks (LAN)	Wide Area Networks (WAN)
Usually operated by the same organization which operates the computer it connects	May be managed by organizations independent of users.
Generally digital signalling over private cables	Often use analogue circuits from the telephone system
Lower error rates (1 in 10^9)	Higher error rates (1 in 10^5)
Can broadcast a single message to multiple destinations	Generally use point-to-point links
Common topologies - bus or ring	Common topologies - mesh or star

Table 1 Characteristics of LAN and WAN.

FTP and PING

In this thesis the following UNIX network commands have been used :

1. The ftp command is the user interface to the Internet Standard File Transfer Protocol (FTP). It is used to transfer files to and from a remote network site. It is described in detail in [1].
2. PING is a command [1] which is used to find the round trip delay time for a given pair of sites. It also gives the packet loss statistics for a particular host and can also be used to check if a particular host is active or not. There are a number of options which are available when the PING is used. It is described in detail in [1].

CHAPTER 3
HEURISTIC FOR QUERY OPTIMIZATION

The cost model, the description and an example of the heuristic is discussed in this chapter. Section 3.1 discusses how the cost is measured in this heuristic. Section 3.2 discusses the heuristic in detail and Section 3.3 illustrates an example of this heuristic.

3.1 COST MODEL OF THE HEURISTIC

In this thesis an attempt has been made to minimize the delay involved in communicating all data relevant for the query. In order to do this, a model is needed to determine the delay. The model used here takes into account the fact that there is some time to set up the network before any communication can start. This is the start up (or set-up) time. After that the number of packets containing the data is transmitted from the source node to the destination node. Depending on the delays on each edge of the path from the source to the destination, each packet will take a certain amount of time for communication from the source to the destination. A simple cost model that is used to calculate the delay τ in all the query processing algorithms is given below:

$$\tau = \sum_{i=0}^{\phi-1} Cost^{i}_{(s-d)} + Cost_{set-up}$$

where $Cost^{i}_{(s \rightarrow d)}$ is the delay to send the *ith* packet from source s to destination d and $Cost_{set\text{-}up}$ is the set-up time and ϕ is the number of packets to be transmitted from a given source to a destination.

In the AHY algorithm, it is assumed that the time to send a given amount of information from a source to a destination is determined only by the amount of data to be transmitted and that the actual path does not play a role. In other words, they assume that the delay between any source and destination is 1. (i.e., $Cost^{i}_{(s \rightarrow d)} = 1$, for all i and for all source-destination pairs).

The PING results were used to find out the delays between a source-destination pair and also for finding the initial set-up times.

The results obtained from the experiments carried out using the PING / FTP (given in Chapter 4) shows that :

- the initial set-up time for any source-destination pair is very small
- the time required to send the packets between sites does not change very much from packet to packet.
- the delay between one source-destination pair on the network is not necessary the same as the delay on another source-destination pair.

As a result of these experiments, the set up time $Cost_{set\text{-}up}$ is ignored in the heuristic and the following simple cost-model for calculating the delay to send each packet from a given source to a destination has been used :

$$\tau = Cost_{(s-d)} * \phi$$

Since a static strategy is used, the contents of the global delay table maintained by the routing manager [39] are used to estimate the $Cost_{(s \rightarrow d)}$ which is the expected delay/packet from any source node to any destination node. In this approach, when the semijoin optimization strategy is being formulated, the value of $Cost_{(s \rightarrow d)}$ is determined from the network parameters [39].

The FTP results (given in Chapter 4) give the delays between a source-destination pair to transfer a file of a particular size. Based on the results, the delays used in the heuristic were changed suitably at regular intervals of time.

3.2 ASSUMPTIONS, DEFINITIONS AND NOTATIONS

In this section the assumptions, definitions and the notations used are explained.

The following assumptions are made in the heuristic :

1. Point-to-point communication is used
2. The relations and the query site QS are at distinct sites in the network.
3. SPJ (Select-Project-Join) queries are considered.
4. Local processing costs are ignored.

The assumption that the relations are stored at distinct sites is made because if any two relations exist at the same site then the processing of these relations can be done locally.

In a WAN the sites may be thousands of miles apart and the local processing cost may safely be ignored since it is negligible when compared to the actual communication time. In SPJ queries, the selection and projection operations are done locally before the actual join operations. Therefore in SPJ queries, only the join attributes which participate in the query are considered.

For the query $Q = R_1 \bowtie R_2 \bowtie ..... \bowtie R_n$ (n is the number of relations involved in the query) to be processed the following information is necessary :

- the Relations R_1, R_2, ... , R_n
- the delays on the different edges of the network

The above information is available in two tables — **Relation table** and **Delay table** as described below.

The following metadata about the relations R_1, R_2, ... , R_n is stored in the Relation table :

1. For each relation R_i, $i = 1,2,....n$

    a. the number of attributes (m_i)

    b. the size of each relation s_i.

    c. the site where the relation resides, $site_i$

2. For each attribute d_{ij}, $j = 1, 2, ...m_i$ of relation R_i,

    a. the selectivity of d_{ij}, ρ_{ij}

    b. the size (in tuples) of attribute b_{ij}.

The Delay table stores the delay to send the packet from a source s to a destination d. Examples of the Relation table and Delay Table are given in Table 12 and Table 13.

Definition

If the time to generate and ship the reducer to the site of Relation R_j is less than the reduction in time to send the reduced relation Relation R_j to the query site QS then the semijoin reducer is called ***beneficial*** for relation R_j.

Example 3.1

For the Relation table in Table 5, consider using the attribute d_{12} to reduce relation R_2. Since there are 100 tuples in attribute d_{12}, the time to send d_{12} to R_2 is 100 units and the time to send the reduced R_2 to Query site QS is 2000*0.2 where 0.2 is the selectivity of attribute d_{12}. The total time of carrying out the operation is 500 units, which is less than

the time required to ship the unreduced relation R_2 to QS. The reducer d_{12} is ***beneficial*** for relation R_1.

Definition

If relation R_i (R_j) has attribute $r_i(r_j)$ defined on the same domain, then $r_i(r_j)$ is a ***potential reducer*** for relation $R_j(R_i)$.

Example 3.2

For the Relation table in Table 5, the ***potential reducers*** of relation R_2 are attributes d_{11}, d_{12} of relation R_1 and attribute d_{31} of relation R_3

Definition

If two attributes r_i and r_j are defined on the same domain, then $r_i(r_j)$ is a ***potential reducer*** for attribute $r_j(r_i)$.

Example 3.3

For the Relation table in Table 5, the ***potential reducers*** of attribute d_{11} are attributes d_{21} and d_{31} because they all lie in the same domain.

3.3 DESCRIPTION OF THE HEURISTIC

The heuristic is explained in detail here. The objective of our heuristic is to minimize the response time by taking into account

- the amount of data that is being transmitted
- the delay from a source to a destination as given in the Delay Table.

First the time to send the relations from the site where these relations exist to the query site, taking into account the delays on each edge in a path, is calculated. Since the heuristic considered is a greedy heuristic, the relation which gives the worst

communication time is chosen and an attempt is made to minimize this communication time. A greedy heuristic selects the most beneficial reducer. In this way, the best execution schedule for each of the relations is generated. The main program is explained below.

```
Worst_Time = 0
L -> List of all relations Ri, 0≤i≤n
While L is not empty
{
        Choose the relation Rj which requires the largest communication time Tj to send the
        relation to the Query Site QS.
        If Tj < W, exit from the loop
        Topt = find_best_schedule(Q, Rj, W)
        If Topt > W, W = Topt
        Remove the relation Rj from List of relations L
}
Print the schedules of all relations
```

Table 2 Algorithm of Main Program

First the communication time for each of the relations R_i, $1 \leq i \leq n$ to the query site QS is computed. The relation R_j which has got a communication time more than the communication time of any other relation to the QS is chosen. Since this communication time degrades the response time the most, we attempt to reduce this as much as possible using the cost (communication time to send the reducer) and benefit analysis (reduction in delay in communicating needed tuples of R_j to query site). After the relation R_j is chosen, we find out the potential reducers r_i $1 \leq i \leq m$, (where m is the number of potential reducers) for relation R_j. The communication time of sending the potential reducers r_i to the relation to be reduced and the communication time of sending the

reduced relation to the query site is calculated. The potential reducer r_i for relation R_j which gives the least total communication time is considered.

Next, the potential reducers for the attribute r_i are determined. For each of the potential reducers r_t, the cost of sending r_t to r_i is computed. Using a greedy heuristic the reducer r_i is further reduced. The sequence of semijoins which reduces the time of sending r_i to R_j and the relation R_j to the query site QS to the minimum is chosen. This process is repeated for all the potential attributes of relation R_j

```
Reducer_List -> List of all reducers ri, of relation Rj
For each reducer ri in the list of reducers, reduce relation Rj and estimate the time to
communicate relation Rj to QS.
While Reducer_List is not empty
{
        Choose the reducer ri which gives the best reduced time.
        Tmin = find_best_reducer_schedule(Q, Rj, ri)
        If (Tmin < Time(Rj->Q) * delay(Rj, QS)) then insert this reducer to schedule.
        Remove the reducer ri from the list of reducers Reducer_List
}
```

Table 3 Algorithm of function find_best_schedule

In the function ***find_best_schedule*** (Table 3), first the list of potential reducers for the relation R_j is computed. The communication time for each of the potential reducers is calculated. The way the communication time is calculated is given below.

$$C_{time} = time_{r_i \rightarrow R_j} + sel_{r_i} * size(R_j) * Delay(R_j, QS)$$

Here *time* $(r_i \rightarrow R_j)$ is the total number of tuples to transmit to relation R_j, *sel*(r_i) is the selectivity of the reducer r_i. The reducer r_k which gives the best C_{time} is picked. After

choosing the best reducer r_k, the next question is whether the time to communicate r_k can be further reduced by semijoin operations on reducer r_k. This is done by function ***find_best_reducer_schedule***. If the particular reducer gives the best improvement in time then this semijoin schedule is appended to the main schedule. The process is carried until all the reducers have been examined. The algorithm for the function ***find_best_reducer_schedule*** is shown in Table 4.

Reduced_reducer_list = List of all potential reducers for reducer r_i. Find the communication time for each of the potential reducers r_k, which is used to reduce the reducer r_i. Choose the reducer r_k which gives the best improvement in time and pass this to the function **find_best_schedule**

Table 4 Algorithm of function find_best_reducer_schedule

The process is repeated for the relation having the next largest communication time. The process stops when there does not exist a relation which

- has not been examined so far and
- has a communication cost more than the reduced relation having the worst communication time.

A detailed description of the heuristic is given in Appendix C. To illustrate how the algorithm works, an example is considered and explained in the next section.

3.4 EXAMPLE OF THE HEURISTIC

The important characteristics of the three relations of query $Q = R_1 \bowtie R_2 \bowtie R_3$, are given in Table 5. The example used is taken from [2].

Relation	Size	d_{i1}		d_{i2}	
R_i	S_i	b_{i1}	p_{i1}	b_{i2}	p_{i2}
R_1	1000	400	0.4	100	0.2
R_2	2000	400	0.4	450	0.9
R_2	3000	900	0.9	-	-

Table 5 Relation Table

In the table the notation S_i represents the size of the relation R_i, in terms of the number of packets needed to communicate R_i. The relation R_1 (R_2) consists of two join attributes d_{11} (d_{21}) and d_{12} (d_{22}). Relation R_3 has one join attribute d_{31}. Here b_{ij} and p_{ij} stands for the size and the selectivity of the attribute j of relation i. The attributes d_{11}, d_{21}, and d_{31} are defined on the same domain. Similarly the attribute d_{12} and d_{22} are defined on the same domain. Since the proposed heuristic requires the delay information from the network, the following delay table is used.

		Destination			
		R_1	R_2	R_3	QS
Source	R_1		2	5	3
	R_2	1		7	2
	R_3	5	6		4

Table 6 Delay Table

The steps involved in generating the schedule using the heuristic is explained. Initially the worst time is set to 0.

Step I

In the first phase, the communication delays for sending the relations R_1, R_2, and R_3 to the query site QS are shown in Figure 3.

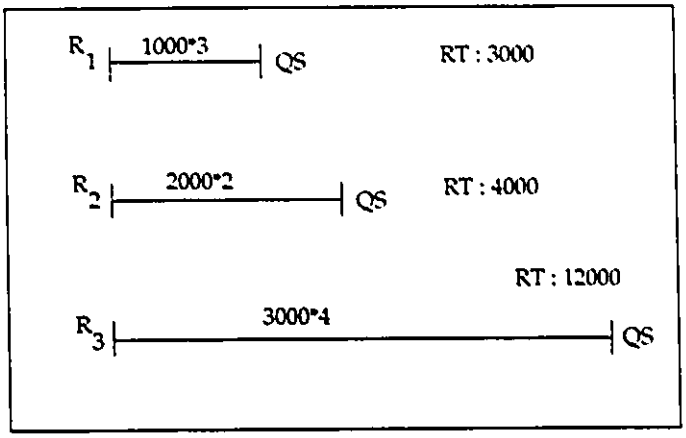


Figure 3 Relations transmitted to QS without reduction

The relation which has the largest communication time is chosen for minimization. Here relation R_3 has the largest communication time.

Step II

In this step the potential reducers for the relation R_3 are determined. The potential reducers for R_3, are the attributes d_{11} from R_1 and d_{21} from R_2. The total time required to transmit the potential reducers to reduce the relation R_3 and to transmit the reduced relation R_3 to the query site QS are then determined. Since the delay for communicating d_{21} from its site S_2 to Site S_3 is greater than that for d_{11}, the schedule involving d_{21} will have parallel transmission of d_{11} to S_3. (Schedule (3) in Figure 4). The communication time to send d_{11} to reduce the relation R_3 is less than transmitting the tuples of attribute d_{21} because of the high delay when sending it from S_2 to S_3.

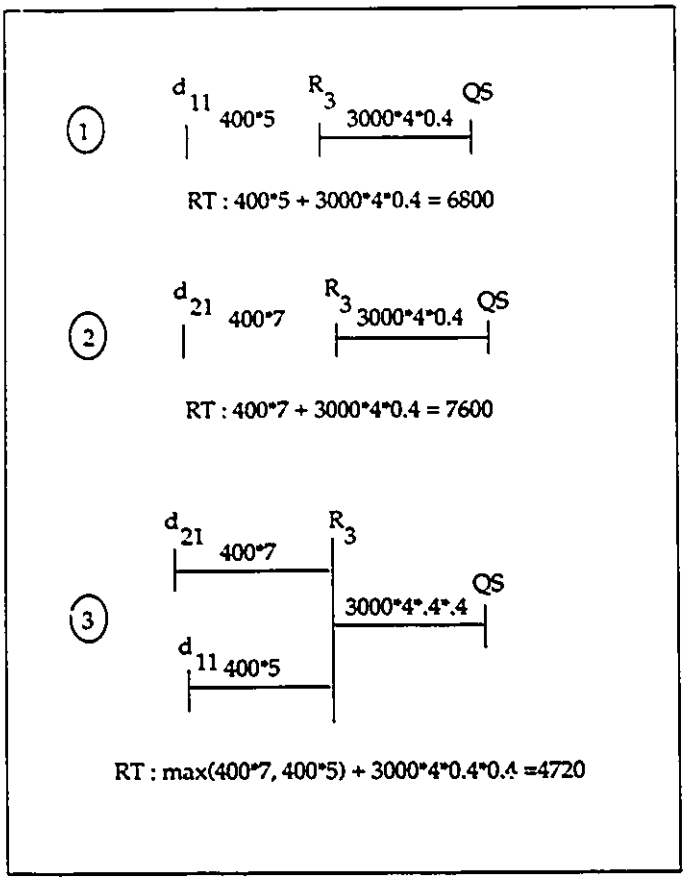


Figure 4 Selection of the best reducers to reduce a Relation

Step III

The possibility of reducing the reducer d_{11} is considered. The attributes d_{11}, d_{21} and d_{31} are all defined on the same domain and therefore they can be used to reduce one another. When considering the possibility of using d_{21} to reduce d_{11}, the cost is the time to communicate d_{21} to *Site* S_1. The size of d_{21} is 400 packets and the delay from S_2 to S_1 is 1 so the cost is 400 units of time. The total communication time is calculated.

- the size of the attribute d_{11} is reduced to 400*0.4 = 160 due to the selectivity of attribute d_{21} which is 0.4. The benefit due to the semijoin $d_{21} \ltimes d_{11}$ is 400 * (1-0.4)

= 240 packets. The delay in communicating $d_{21} \bowtie d_{11}$ is reduced by 240 * 5 = 1200 units of time

- to reduce the relation R_3, the selectivity of d_{21} and d_{11} which is 0.4 * 0.4 = 0.16 is used, instead of 0.4 of attribute d_{11} alone. The benefit for communicating the number of tuples of relation R_3 to the query site is 3000 * 0.4 * (1–0.4). The delay in communicating the reduced relation R_3 to QS is 720 * 4 = 2880.

Here the cost is less than the benefit and $d_{21} \bowtie d_{11}$ is a better reducer than d_{11}.

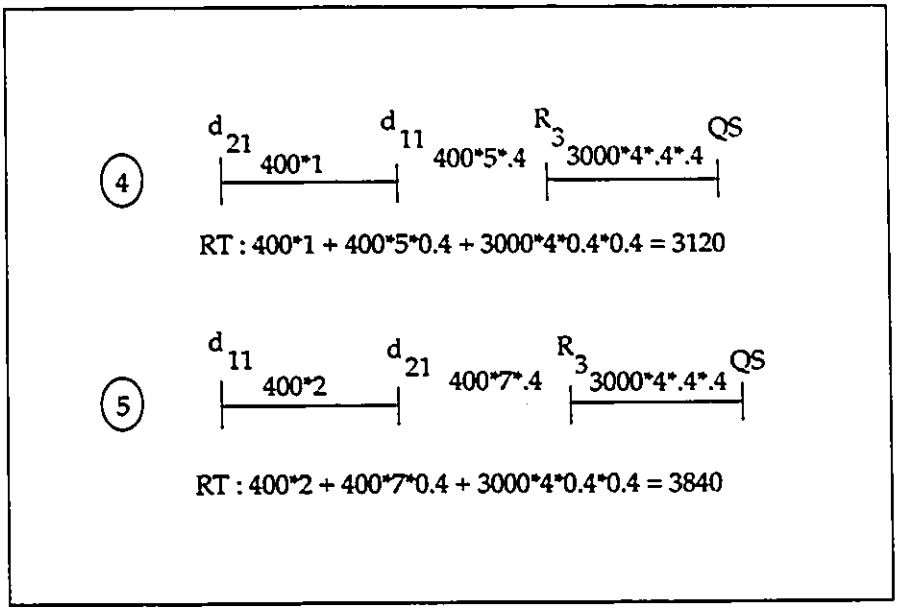


Figure 5 Selection of the best potential reducer

Step IV

The reducer d_{21} is considered next. The potential reducers for d_{21} are d_{11} and d_{31} since they are defined on the same domain. If attribute d_{11} is used to reduce d_{21} the time to communicate d_{11} to S_2 is 400 packets (size of attribute d_{11}) * 2 (the delay to from S_1 to S_2) The total cost is 3840. Therefore, $d_{21} \bowtie d_{11}$ is the best reducer for the

relation R_3 and the schedule as shown in Figure 5 is obtained. Therefore the value of Worst_time W is now 3120.

Step V

The next relation which gives the largest communication time is R_2, since the communication time of sending the relation R_2 to the QS is greater than the new Worst time. Therefore, it is important to reduce the relation R_2 further. The *potential reducers* of relation R_2 are found. Attributes d_{11}, d_{12} of relation R_1 and d_{31} of relation R_3 are the potential reducers. Then the communication time for each of the potential reducers is calculated. Then similar to relation R_3, the best schedule for the relation R_2 is constructed. The communication time for the relation R_2 is less than the communication time of the worst time ($1000 < 3120$), so the worst time is not changed.

For the relation R_1 the communication time of sending R_1 to QS is already less than the worst_time. Therefore it is not necessary to reduce the relation R_1 further. The final schedules for the relations R_1, R_2, and R_3 are shown in the figure below.

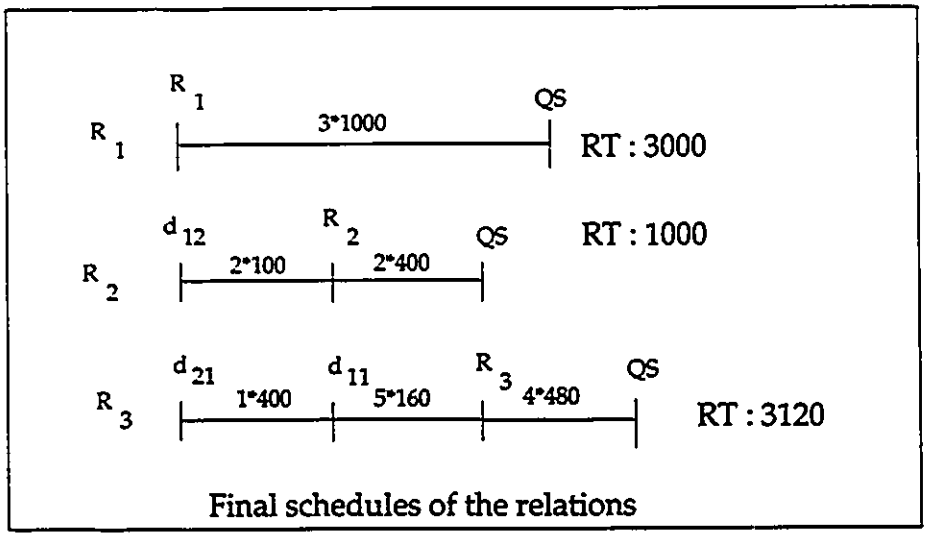


Figure 6 Final schedules for the relations

CHAPTER 4
EXPERIMENTAL RESULTS

4.1 FTP AND PING RESULTS

In order to reflect the changes in the network load, the delays had to be changed at regular intervals. The experiments carried out using the File Transfer Protocol (FTP), gave the time to transfer the files between a source-destination pair and also the delays in the networks during different times of the day. PING was used to find the delays between the source-destination pair and also for finding the initial set-up time. It was also used to check if a particular host was active before the FTP was done. Also in order to use the actual network delays, experiments were carried out for about two months using the File Transfer Protocol (FTP) and PING to check if the results of FTP correlated with the results of PING. The experimental results of using the FTP and PING are given in this section.

PING

In the example shown below, the network host is ***amazon.eng.fau.edu***; *200* represents the number of data bytes that are transferred, *10* represents the count. For the example shown below, we see that it gives the statistics of sending each datagrams (200 bytes); it gives the round trip times for each of the datagrams. Finally it gives the statistics of how many packets were transmitted, the packets that were received and information about packet loss. It also gives the minimum, average and the maximum round trip times for the number of packets specified.

ping -s amazon.eng.fau.edu 200 10
PING amazon.eng.fau.edu: 200 data bytes
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=0 time=3. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=1. time=2. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=2. time=2. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=3. time=3. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=4. time=1. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=5. time=2. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=6. time=1. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=7. time=3. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=8. time=1. ms
208 bytes from internet.uwindsor.ca (137.207.92.2): icmp_seq=9. time=4. ms
----amazon.eng.fau.edu PING Statistics----
10 packets transmitted, 10 packets received, 0% packet loss
round-trip (ms) min/avg/max = 1/2/4

Table 7 The output obtained when using the PING.

For the experiments, five different sites situated across North America were chosen at random. The sites chosen for the experiments are given below:

1. amazon.eng.fau.edu
2. ftp.ipl.rpi.edu
3. sunee.uwaterloo.ca
4. labrea.stanford.edu
5. ftp.cs.uwm.edu

An experiment to find out the time taken by each of the different sites to FTP files of similar sizes was carried out for about two months. Also on the same sites the PING experiments were carried out concurrently. In the PING and FTP results shown below,

eight experiments were randomly selected from the total of 69 experiments. Some PING results are shown below:

amazon.eng.fau.edu (200 bytes)					
Number	Time	Day	Date	Initial Set-up Time	(min/avg max) ms
1	3:30 PM	Monday	Aug 28,'95	3	1/1/3
2	00:02 AM	Wednesday	Aug 30,'95	7	1/2/10
3	11:10PM	Saturday	Sept 2,'95	3	1/1/3
4	11:15 AM	Wednesday	Sept 6,'95	3	1/2/3
5	12:15 PM	Sunday	Sept 10,'95	3	1/1/3
6	2:10 PM	Tuesday	Sept 19,'95	13	1/4/18
7	1:20 PM	Thursday	Sept 21,'95	8	1/3/9
8	4:15PM	Tuesday	Oct 17,'95	5	1/4/6

Table 8 PING results for the site *amazon.eng.fau.edu*

ftp.ipl.rpi.edu (200 bytes)					
Number	Time	Day	Date	Initial Set-up Time	(min/avg/max) ms
1	3:30 PM	Monday	Aug 28,'95	4	1/2/4
2	00:02 AM	Wednesday	Aug 30,'95	3	1/1/3
3	11:10PM	Saturday	Sept 2,'95	4	1/1/4
4	11:15 AM	Wednesday	Sept 6,'95	3	1/2/3
5	12:15 PM	Sunday	Sept 10,'95	3	1/1/3
6	2:10 PM	Tuesday	Sept 19,'95	4	1/2/4
7	1:20 PM	Thursday	Sept 21,'95	3	1/1/3
8	4:15PM	Tuesday	Oct 17,'95	6	1/2/8

Table 9 PING results for the site *ftp.ipl.rpi.edu*

sunee.uwaterloo.ca (200 bytes)					
Number	Time	Day	Date	Initial Set-up Time	(min/avg/max) ms
1	3:30 PM	Monday	Aug 28,'95	4	1/2/4
2	00:02 AM	Wednesday	Aug 30,'95	3	1/1/3
3	11:10PM	Saturday	Sept 2,'95	3	1/1/3
4	11:15 AM	Wednesday	Sept 6,'95	3	2/2/3
5	12:15 PM	Sunday	Sept 10,'95	18	1/4/21
6	2:10 PM	Tuesday	Sept 19,'95	3	1/1/3
7	1:20 PM	Thursday	Sept 21,'95	3	1/2/3
8	4:15PM	Tuesday	Oct 17,'95	11	1/2/11

Table 10 PING results for the site *sunee.uwaterloo.ca*

labrea.stanford.edu (200 bytes)					
Number	Time	Day	Date	Initial Set-up Time	(min/avg/max) ms
1	3:30 PM	Monday	Aug 28,'95	3	1/1/3
2	00:02 AM	Wednesday	Aug 30,'95	3	1/2/3
3	11:10PM	Saturday	Sept 2,'95	14	1/3/14
4	11:15 AM	Wednesday	Sept 6,'95	3	1/2/3
5	12:15 PM	Sunday	Sept 10,'95	2	1/1/2
6	2:10 PM	Tuesday	Sept 19,'95	3	1/2/3
7	1:20 PM	Thursday	Sept 21,'95	9	1/2/9
8	4:15PM	Tuesday	Oct 17,'95	3	1/2/3

Table 11 PING results for the site *labrea.stanford.edu*

ftp.cs.uwm.edu (200 bytes)					
Number	Time	Day	Date	Initial Set-up Time	(min/avg/max) ms
1	3:30 PM	Monday	Aug 28,'95	6	1/2/6
2	00:02 AM	Wednesday	Aug 30,'95	3	1/2/3
3	11:10PM	Saturday	Sept 2,'95	3	1/1/3
4	11:15 AM	Wednesday	Sept 6,'95	2	1/1/2
5	12:15 PM	Sunday	Sept 10,'95	9	1/3/9
6	2:10 PM	Tuesday	Sept 19,'95	3	1/2/3
7	1:20 PM	Thursday	Sept 21,'95	3	1/2/3
8	4:15PM	Tuesday	Oct 17,'95	8	1/3/8

Table 12 PING results for the site *ftp.cs.uwm.edu*

From the PING experiments, we found out that

- the initial set-up time is very small.
- the delay when sending packets does not change very abruptly over a period of time.

FTP (FILE TRANSFER PROTOCOL)

The ftp command is the user interface to the Internet Standard File Transfer Protocol (FTP). FTP transfers files to and from a remote network site.

For the sites chosen to carry out the experiments, the size of the files in bytes is given below:

1. ftp://amazon.eng.fau.edu – 42106 bytes
2. ftp://ftp.ipl.rpi.edu – 47050 bytes
3. ftp://sunee.uwaterloo.ca – 45407 bytes
4. ftp://labrea.stanford.edu – 49834 bytes
5. ftp://ftp.cs.uwm.edu – 44009 bytes

Some ftp results are shown below:

amazon.eng.fau.edu					
Number	Time	Day	Date	FTP (42106 bytes)	
				(secs)	(kb/ sec)
1	3:30 PM	Monday	Aug 28,'95	35	1.1
2	00:02 AM	Wednesday	Aug 30,'95	5	9.3
3	11:10PM	Saturday	Sept 2,'95	10	4.2
4	11:15 AM	Wednesday	Sept 6,'95	51	0.82
5	12:15 PM	Sunday	Sept 10,'95	11	4.1
6	2:10 PM	Tuesday	Sept 19,'95	43	0.9
7	1:20 PM	Thursday	Sept 21,'95	6	7
8	4:15PM	Tuesday	Oct 17,'95	53	0.7

Table 13 FTP results for the site *amazon.eng.fau.edu*

ftp.ipl.rpi.edu					
Number	Time	Day	Date	FTP (47050 bytes)	
				(secs)	(kb/ sec)
1	3:30 PM	Monday	Aug 28,'95	18	2.6
2	00:02 AM	Wednesday	Aug 30,'95	4	9.5
3	11:10PM	Saturday	Sept 2,'95	5	9.3
4	11:15 AM	Wednesday	Sept 6,'95	16	2.9
5	12:15 PM	Sunday	Sept 10,'95	10	4.4
6	2:10 PM	Tuesday	Sept 19,'95	17	2.7
7	1:20 PM	Thursday	Sept 21,'95	18	2.6
8	4:15PM	Tuesday	Oct 17,'95	36	1.3

Table 14 FTP results for the site *ftp.ipl.rpi.edu*

sunee.uwaterloo.ca					
Number	Time	Day	Date	FTP (45407 bytes)	
				(secs)	(kb/ sec)
1	3:30 PM	Monday	Aug 28,'95	16	2.8
2	00:02 AM	Wednesday	Aug 30,'95	3.6	12.7
3	11:10PM	Saturday	Sept 2,'95	4	11.3
4	11:15 AM	Wednesday	Sept 6,'95	9.4	4.8
5	12:15 PM	Sunday	Sept 10,'95	10.4	4.2
6	2:10 PM	Tuesday	Sept 19,'95	13.4	3.3
7	1:20 PM	Thursday	Sept 21,'95	14	3.2
8	4:15PM	Tuesday	Oct 17,'95	11.4	3.9

Table 15 FTP results for the site *sunee.uwaterloo.ca*

labrea.stanford.edu					
Number	Time	Day	Date	FTP (49834 bytes)	
				(secs)	(kb/ sec)
1	3:30 PM	Monday	Aug 28,'95	13	3.8
2	00:02 AM	Wednesday	Aug 30,'95	3	16.8
3	11:10PM	Saturday	Sept 2,'95	9	5.5
4	11:15 AM	Wednesday	Sept 6,'95	14	3.6
5	12:15 PM	Sunday	Sept 10,'95	5	9.9
6	2:10 PM	Tuesday	Sept 19,'95	13	3.8
7	1:20 PM	Thursday	Sept 21,'95	9	5.7
8	4:15PM	Tuesday	Oct 17,'95	18	2.7

Table 16 FTP results for the site *labrea.stanford.edu*

ftp.cs.uwm.edu					
Number	Time	Day	Date	FTP (44007 bytes)	
				(secs)	(kb/ sec)
1	3:30 PM	Monday	Aug 28,'95	5.9	7.4
2	00:02 AM	Wednesday	Aug 30,'95	2.4	18
3	11:10PM	Saturday	Sept 2,'95	4.4	10
4	11:15 AM	Wednesday	Sept 6,'95	11	4
5	12:15 PM	Sunday	Sept 10,'95	9	4.8
6	2:10 PM	Tuesday	Sept 19,'95	13	3.8
7	1:20 PM	Thursday	Sept 21,'95	25	1.7
8	4:15PM	Tuesday	Oct 17,'95	23	1.9

Table 17 FTP results for the site *ftp.cs.uwm.edu*

From the tables, it can be seen that the time to transfer a file of a given size varies enormously, depending on

1. source and destination address
2. time of the day.

	FTP	
PING	site	Correlation factor
	amazon.eng.fau.edu	-0.11204
	ftp.ipl.rpi.edu	-0.03159
	sunee.uwaterloo.ca	0.06414
	labrea.stanford.edu	-0.04851
	ftp.cs.uwm.edu	0.11491

Table 18 Table showing the correlation factor between PING and FTP

From table 18, it was found that the FTP results do not correlate with the PING results. Since the FTP results did not correlate with the PING results, it was not possible to find out the actual delays in the network to formulate the semijoin execution strategy for the heuristic. In the cost model considered in the heuristic, the initial set-up time is ignored, from the experiments carried out using PING, it was found that the initial set-up time is very negligible for any source-destination pair. Also the time taken to send the packets between any source-destination pair does not change abruptly. When the semijoin execution strategy is being formulated using the heuristic, the delays which are present at the time of formulation are considered.

4.2 HEURISTIC RESULTS

In this chapter the results and the comparisons between the AHY algorithm and the Heuristic are given.

Objectives

The aims of the evaluation were :

- To test the heuristic on a wide variety of select-project-join queries.

- To compare the heuristic with the AHY (Apers-Hevner-Yao) algorithm GENERAL (Response Time version).

Types of Queries used

For the tests, the database statistics of the relations and the attributes which are only involved in the query after all the local processing is over are considered [4]. Each query had the following characteristics.

1. The query was made up of 3 to 6 relations and the number of join attributes varied from 2 to 4.
2. The domain cardinalities varied between 500 and 1500.
3. The number of tuples for each relation varied from 500–6000.
4. The number of join attributes for in each query ranged from 1 to the maximum number of join attributes, so that the query was "connected" in order to join all the relations to answer a query. The levels of connectivity used for the experiments are 50% and 75%. For the heuristic presented in this thesis, the following conditions had to be satisfied for the different levels of connectivity used:
   a. At least two relations must have an occurence of the same join attribute
   b. It must be possible to join every relation to form a single conjunctive normal form query.

To run the schedules generated by the AHY algorithm and the heuristic, the simulator is used. A detailed description of the simulator can be found in Appendix A. When formulating the semijoin optimization strategy, the values in the delay table at the time of query optimization are considered. The delays consist of the following characteristics.

1. The delays between the different nodes consisted of values from 0–10. If the delay between any two nodes is zero, this means that there is no direct link between the nodes. To find the shortest path between any source and the destination, the shortest path algorithm is used.
2. In order to reflect the changes in the network load, the delays on the different edges of the network are changed every 100 units of time. The delays considered are changed by 10% and 25%.

Experimental results

The heuristics were run on six different test cases. Each run consisted of 1200 queries. For each query, 100 semijoin schedules are constructed using the heuristics and the schedules were run on the simulator. A total of 7200 queries were used to evaluate the performance of the algorithms. The different types of cases run are described below:

- Unit delays are considered and run on the simulator with a 10% delay change and under 50% connectivity.
- Delays from the delay table at the time of query optimization are used and run on the simulator with 10% delay change and under 50% connectivity.
- Delays from the delay table at the time of query optimization are used and run on the simulator with 25% delay change and under 50% connectivity.
- Unit delays are considered and run on the simulator with 10% delay change and under 75% connectivity.
- Delays from the delay table at the time of query optimization are used and run on the simulator with 10% delay change and under 75% connectivity.

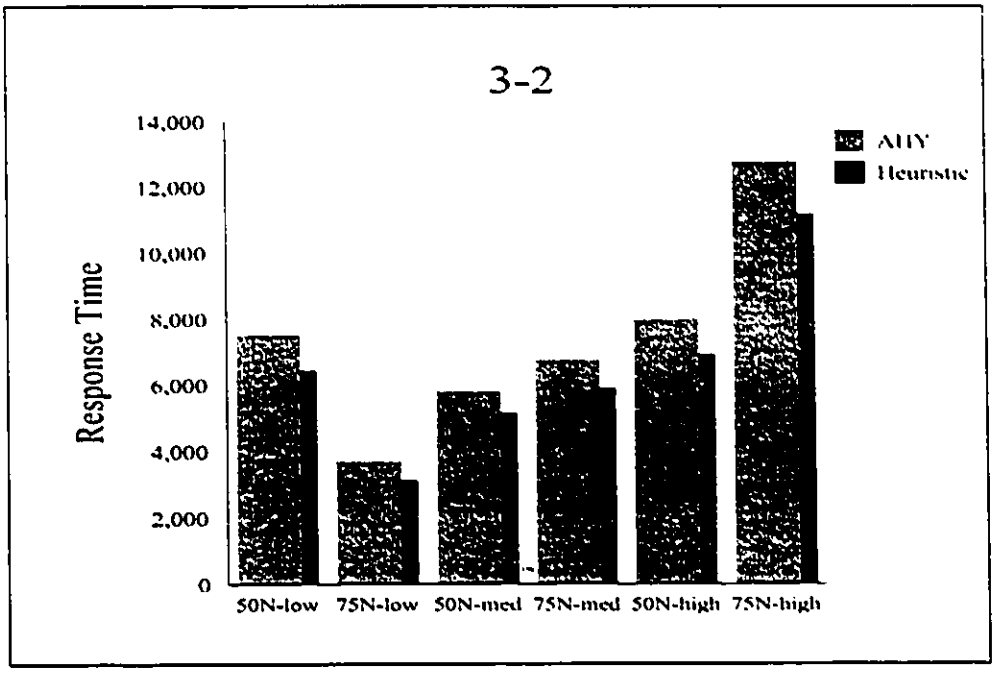
- Delays from the delay table at the time of query optimization are used and run on the simulator with 25% delay change and under 75% connectivity.

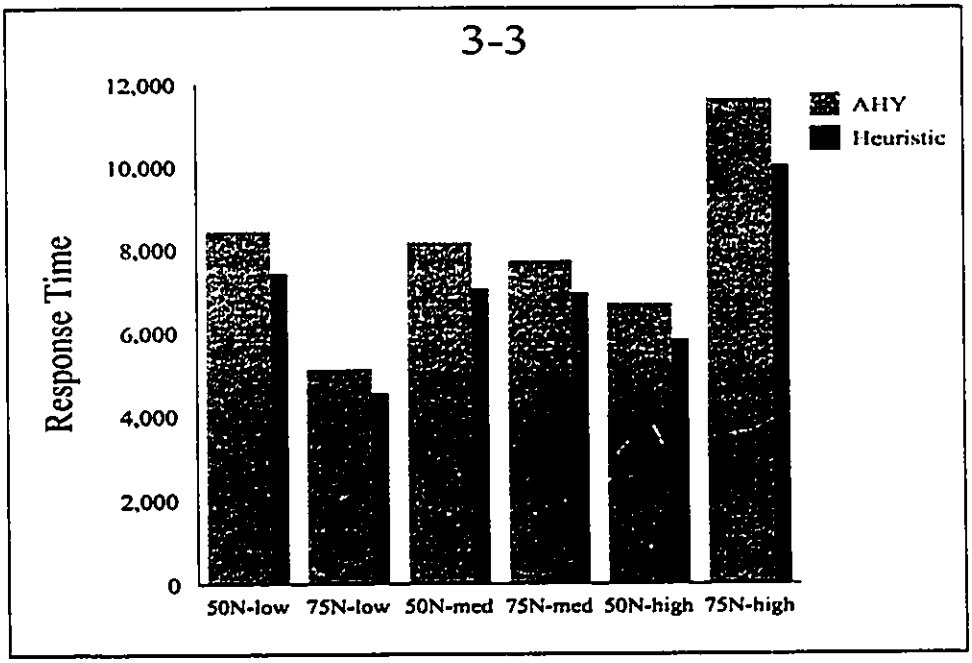
The complete data summaries for each run are given in Appendix D.

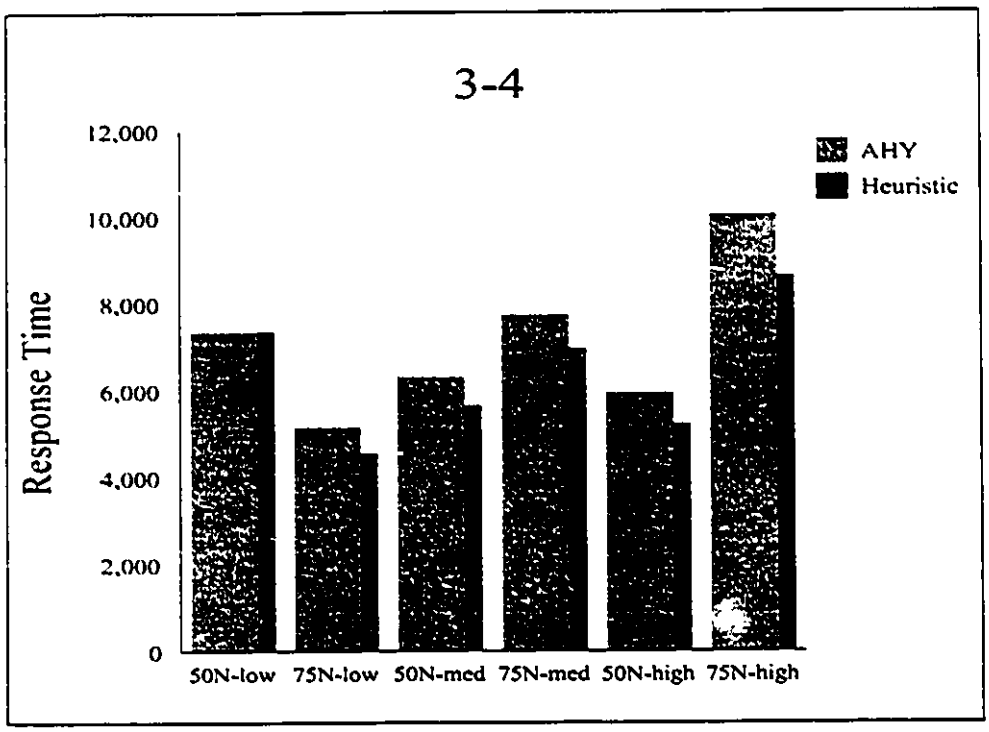
The observations of the results are given below :

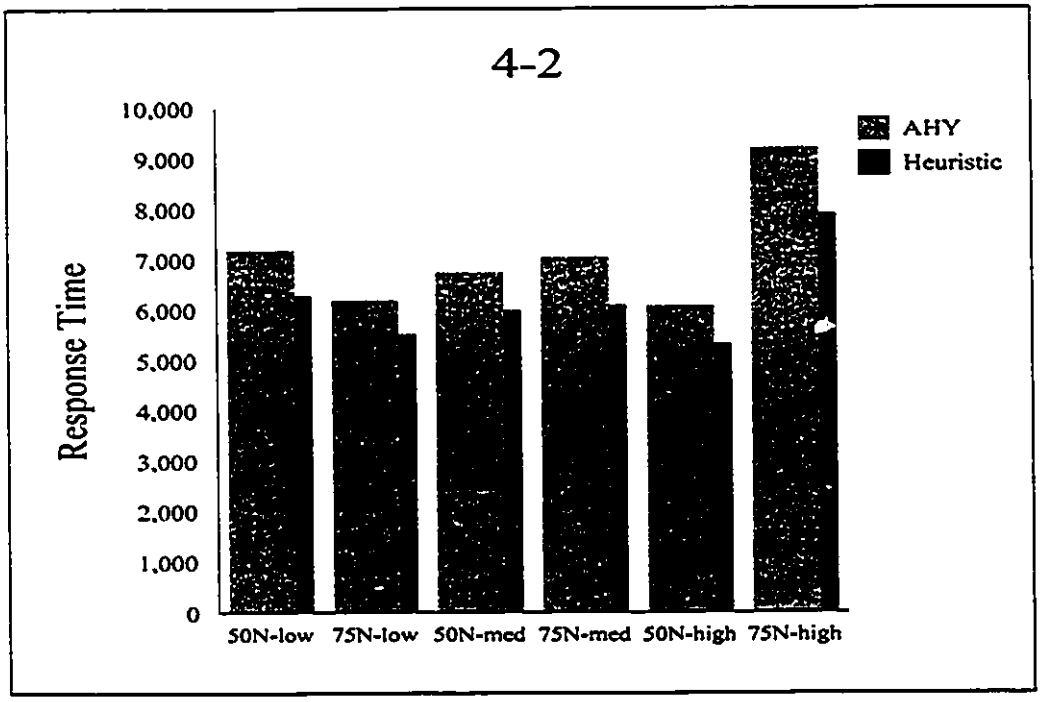
1. When unit delays were considered, the heuristic performed well compared to the heuristic AHY algorithm for about 55%-75% of the queries irrespective of the query type.
2. When the delays from the delay table at the time of query optimization are used, the heuristic performed well compared to the AHY algorithm for about 70%-80% of the queries irrespective of the query type.
3. In all the cases, for about 10%-25% of the queries, the heuristic and the AHY algorithm were equal.
4. Irrespective of the query type, the average improvement of the heuristic compared to the AHY algorithm is between 10%-15% [Appendix D].

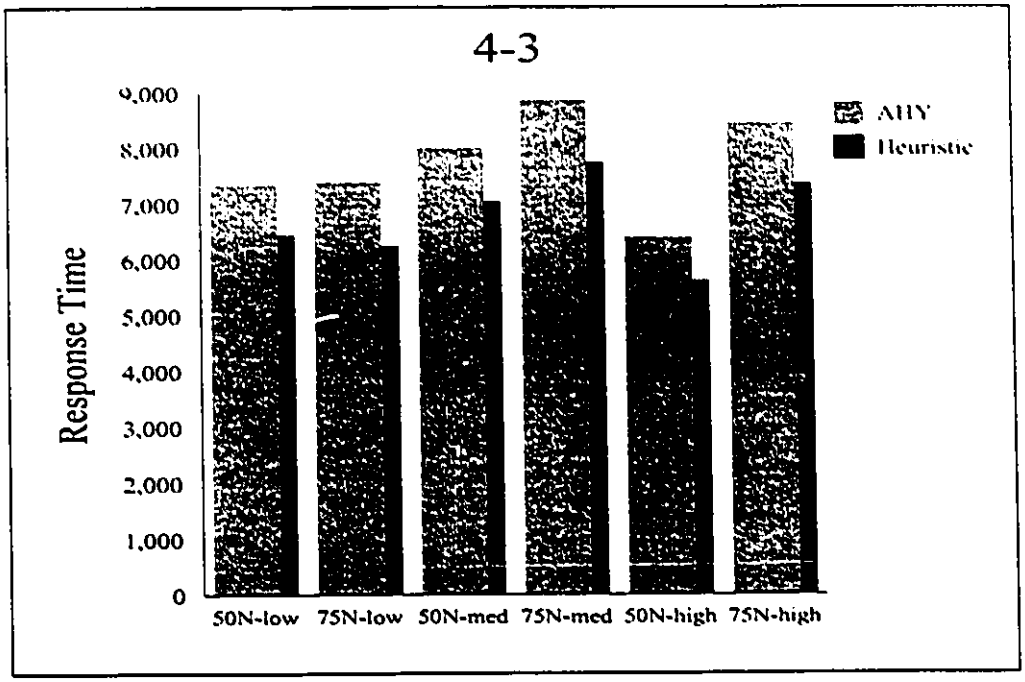
The tables shown below show the average response times of AHY algorithm (Response time version) and the Heuristic for each query type for the different cases. Here *low* indicates that unit delays are considered, *med (medium)* indicates that the differences in delays are changed by 10%, and *high* indicates that the differences in delays are changed by 25%.

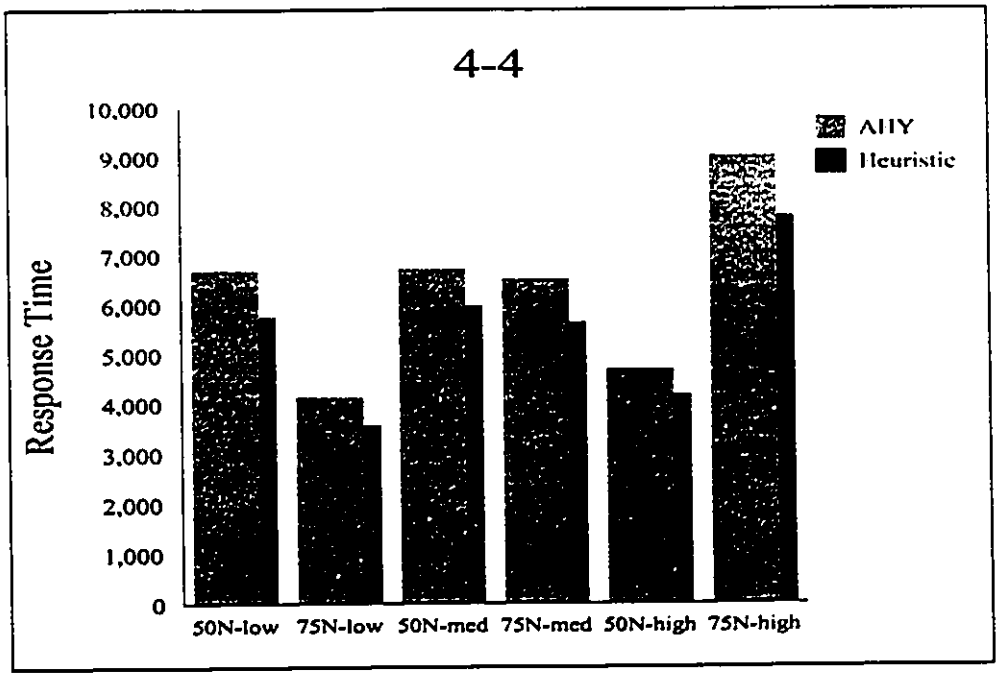

3-2
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Response Time
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high

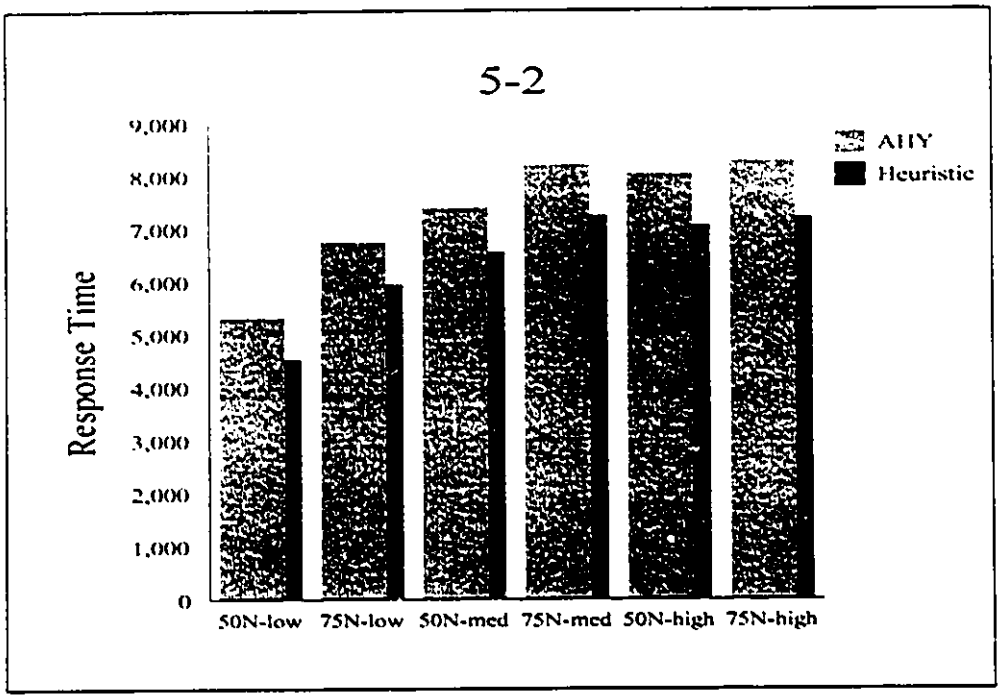

3-3
12,000
10,000
8,000
6,000
4,000
2,000
0
Response Time
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high

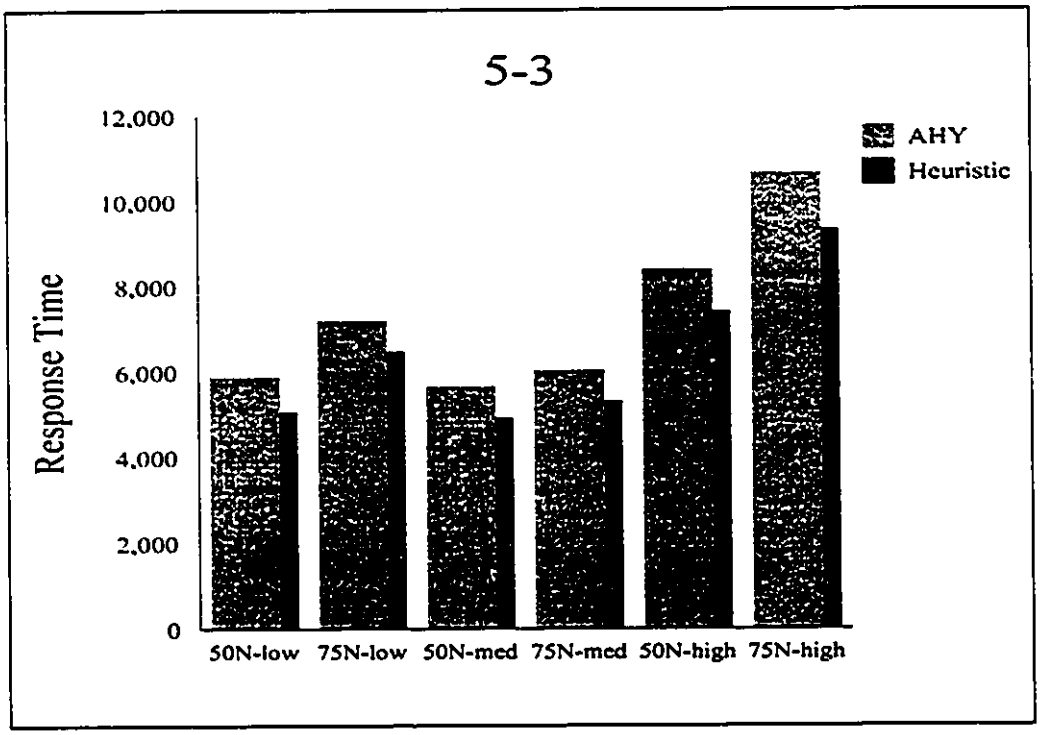

3-4
12,000
10,000
8,000
6,000
4,000
2,000
0
Response Time
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high

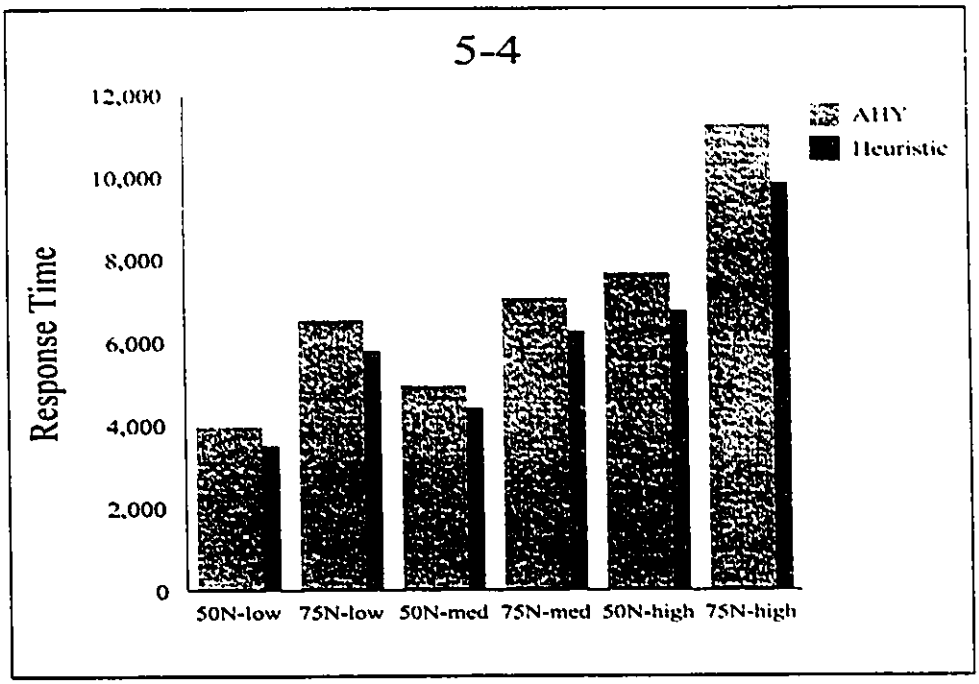

4-2
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Response Time
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high

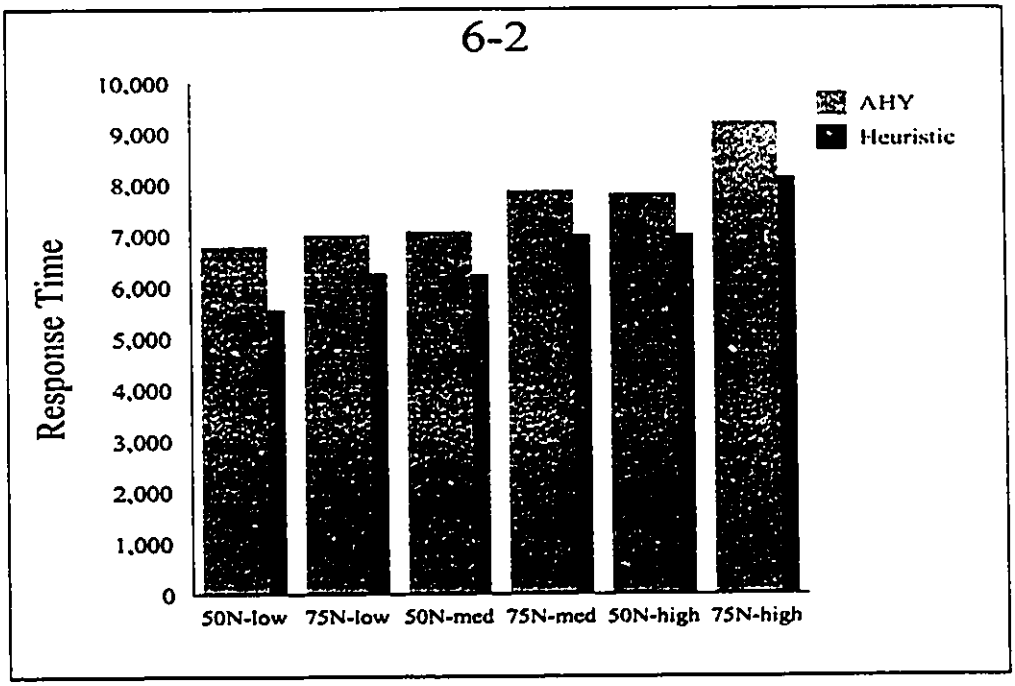

4-3
Response Time
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high

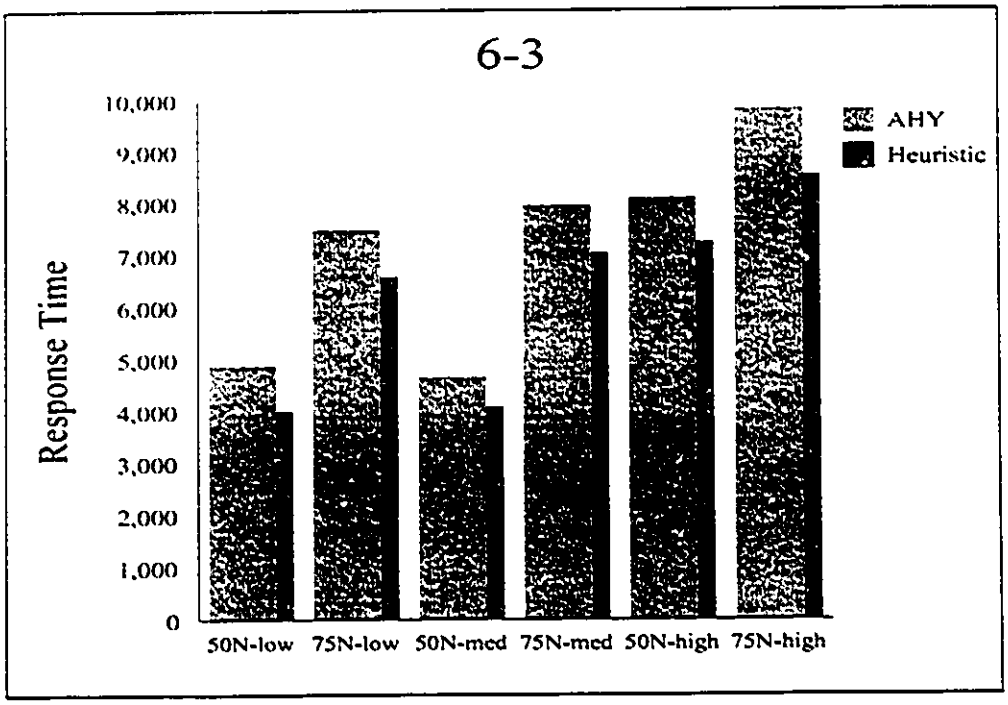

4-4
Response Time
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high

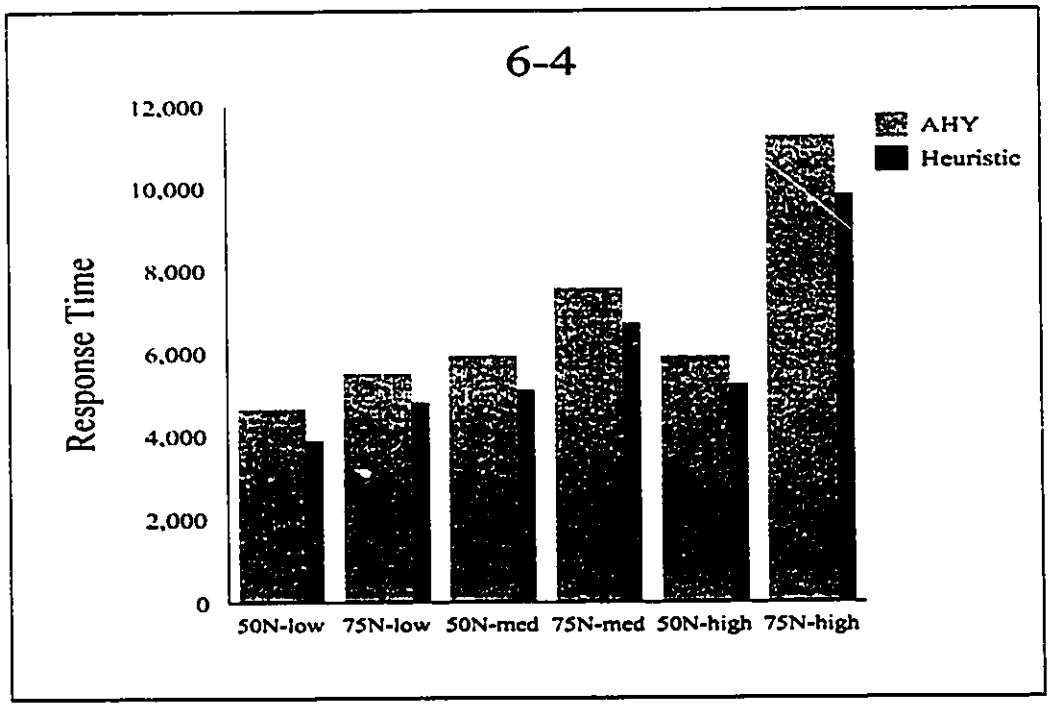

5-2
Response Time
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high


5-3
Response Time
12,000
10,000
8,000
6,000
4,000
2,000
0
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high


5-4
Response Time
12,000
10,000
8,000
6,000
4,000
2,000
0
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high


6-2
Response Time
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high


6-3
Response Time
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high


6-4
Response Time
12,000
10,000
8,000
6,000
4,000
2,000
0
AHY
Heuristic
50N-low
75N-low
50N-med
75N-med
50N-high
75N-high

Importance of Results

The procedure t-tests using the Statistical Analysis System (SAS) were run on all the different types of queries. The mean response times of the new heuristic is less than the AHY algorithm (Response time version) in all the cases. Therefore the new heuristic is better than the AHY algorithm (Response time version). Since the AHY algorithm outperforms the proposed heuristic in 5%-15% of the queries, and also in 10%-15% of the queries both the algorithms give the same response times, it is not surprising to find that the percentage reduction was not found to be significant.

In the table, the runs in which it was not possible to disprove the null hypothesis are indicated by a X. We can see clearly that the proposed heuristic works very well

- when the selectivity is above 50% and the delays in the network are high
- when the selectivity is above 75% and the delays in the network are high

Therefore the results are only significant when the differences in delays are changed by 25% in the network. We also see that it is significant in only some cases when the differences in delays are changed by 10%.

Query	50N-high	75N-high	50N-med	75N-med	50N-low	75N-low
3-2	X	X	-	-	-	-
3-2	-	X	-	-	-	-
3-4	X	X	-	-	-	-
4-2	X	X	-	-	-	-
4-3	X	X	-	-	-	-
4-4	-	X	X	-	-	-
5-2	X	-	X	X	-	-
5-3	X	X	-	X	-	-
5-4	X	X	X	-	-	-
6-2	-	-	X	X	-	-
6-3	-	X	-	X	-	-
6-4	X	X	X	X	-	-

Table 19 Statistical relevance of differences between the heuristic & AHY algorithm

CHAPTER 5
CONCLUSIONS AND FUTURE WORK

There are many possible strategies for processing queries, especially complex queries, and a substantial amount of time and effort is needed to select an optimal strategy. In the earlier distributed DBMSs the objective was to minimize the transmission costs in terms of the message size. In this thesis a new heuristic which takes into account both the network load and also the size of the data to be transmitted is presented. The heuristic uses a static strategy and takes the delays which are present at the time of formulating the semijoin execution strategy. From the results, it is shown that the new heuristic is comparatively efficient and cost effective. In the heuristic, if the worst time is greater than the time to communicate the relations to the query site, then those relations are not considered for further reductions since it is futile. It is important to point out that the AHY outperforms this heuristic for about 5%-15% of the queries.

FUTURE WORK

Finding the actual network delays was not possible using the PING and the FTP. Therefore work can be done to provide the actual network delays between any source-destination pair maintained by the network manager.

APPENDIX A

DESIGN OF THE SIMULATOR

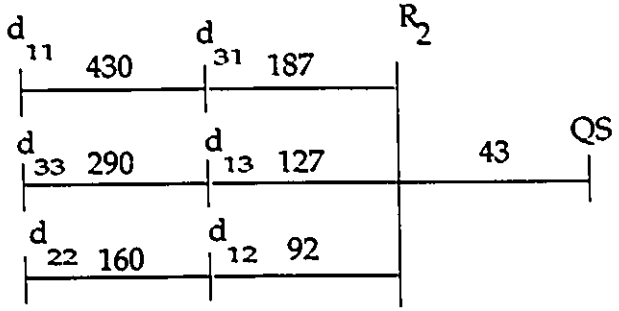
In this thesis, a network simulator was developed which was written in C programming language. The response time is calculated using this simulator. The description of this simulator is described in this appendix. The delays are changed at regular intervals of time to reflect the changes in the network load. Here we just assume a point-to-point network. The input to this simulator is the schedule from the AHY algorithm and the heuristic. The output of this simulator is the response time for each of the schedules.

The simulator takes the schedules which are generated by the heuristics in the form of an adjacency list. The term schedule represents the sequence of transmissions which is generated using the AHY algorithm or our Heuristic. An example of an adjacency list is shown below.

```
1 0 1 1 1 -->  3 630 3 1 2 -> NULL
2 1 3 3 1 -->  2 187 2 -1 7 -> NULL
3 0 3 3 3 -->  1 290 1 3 4 -> NULL
4 1 1 1 3 -->  2 127 2 -1 7 -> NULL
5 0 2 2 2 -->  1 160 1 2 6 -> NULL
6 1 1 1 2 -->  2 92 2 -1 7 -> NULL
7 3 2 3 -1 -->  5 43 -1 -1 0 -> NULL
```

It indicates the physical_id, the indegree, the source site, the relation number and attribute number of the attribute; if a relation is being considered the attribute number is represented as —1. Then it indicates the destination site, the number of packets that

are being transmitted, the relation number and the attribute number (the attribute or the relation being reduced) at the destination and the logical_id. The corresponding schedule for the adjacency list is shown below.



In the program, first the indegree of the schedules are checked, the schedules which have indegree zero are considered and a separate structure is constructed. The generate function is used to generate the packets from a given source that have to be transmitted to the destination; the receive function is used to confirm that the packet which is transmitted has arrived at the destination. A global event queue called EVENT_LIST is maintained, where each node is stored and processed one at a time. A complete description of each of the functions used in the simulator is explained below. Also an example is shown explaining how the simulator actually works.

It consists of the following four functions.

1. *Check_indegree* : This function takes the input in the form of an adjacency list from the AHY algorithm or heuristic and checks the indegrees of all the elements; whichever has the indegree zero is picked up from the list and a node is created with current_time+1, pointer to the function generate and the data (the source, destination

and the number of packets that have to be transmitted). This is inserted into the EVENT_LIST.

2. *Generate* : This function creates two structures and inserts them into the queue EVENT_LIST. It creates the first structure with the current_time + the delay from the source to the destination, a pointer to the function receive, and the data (the source, destination and the number of packets). The packets will be the number of packets that are remaining to be received at the destination. It also creates another structure only if there are packets which are remaining to be transmitted, with current_time + the round trip delay from source to destination, pointer to the function generate, and the data (the source, destination and the number of packets remaining to be transmitted). When considering the delays, the round trip delay is considered assuming that the packets are transmitted from the source to the destination without any loss of packets.

3. *Receive* : This function first checks the number of packets. If the number of packets is zero, then it checks the destination node with the source node in the adjacency list and also it checks if the logical_id is the same as the physical_id. If both are equal it reduces the indegree by 1. Later it checks the indegree of the source_ node. If the indegree is zero then it creates a structure with current_time + 1, (After all the packets have been transmitted, for the next semijoin schedule to be executed, we assume that the new packet is generated after 1 unit of time), pointer to a function generate, the data (the source, destination and the number of packets to be transmitted). This structure is inserted into the queue EVENT_LIST.

4. *Process_Event_List* : This is the main function which processes the elements which

are stored in the EVENT_LIST. It picks up the first node from the EVENT_LIST and then checks the function that has to be processed; if it is generate, then the generate function is called; otherwise, the receive function is called. When all the elements in the EVENT_LIST are processed, the transmission time is output.

To illustrate how the simulator works, the example for the given adjacency list is shown below. Since the delay values are required, the following delay table is considered.

		Destination			
		R_1	R_2	R_3	QS
Source	R_1		2	5	3
	R_2	1		7	2
	R_3	5	6		4

Table 20 Delay Table

Step 1 : The indegrees are checked by scanning through the entire list. There are three schedules with indegree zero. Therefore the structures as shown in the figure below is created.

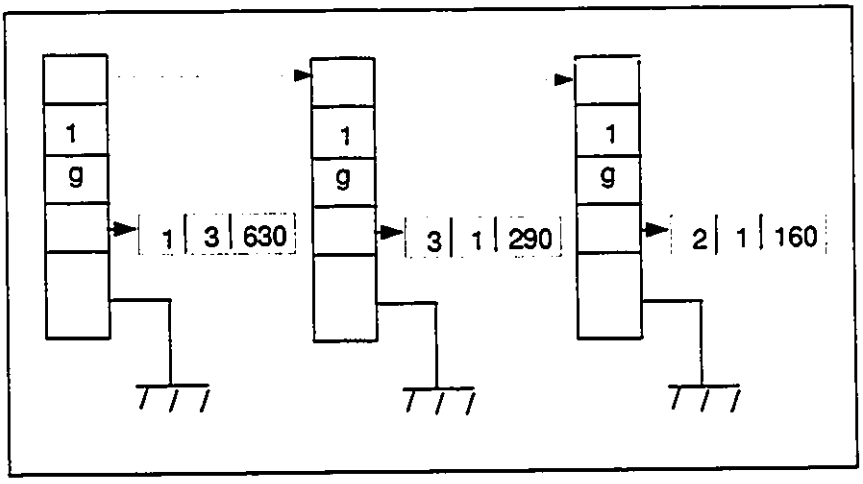


Figure 7 Structures created and placed in EVENT_LIST

Here the current time is taken as zero, therefore the time for each of the structures is taken as 1. The structure is stored as the EVENT_LIST queue.

Step 2 : The execution of a schedule starts after a warm-up time. Then the actual simulation takes place, that is the *process_event_list* starts. It takes the first structure from the queue and checks the function which has to be carried out. Since it is the generate function, the generate function is executed and the two structures are created and inserted in the EVENT_LIST as shown in the figure below.

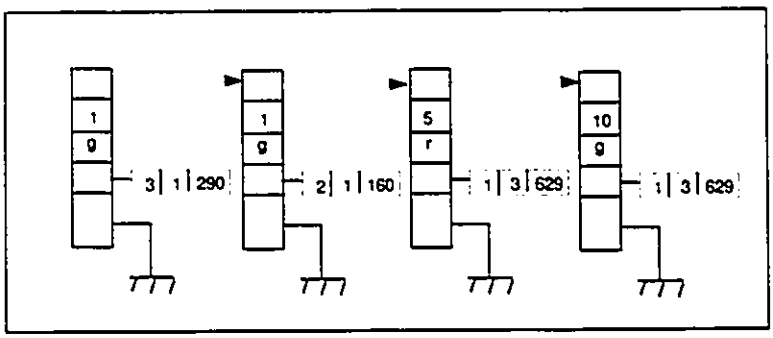


Figure 8 After initial execution of the first structure from the EVENT_LIST queue

The structures created are the structures with the function generate, with the delay from the source 1 to destination 3, and the structure with the function receive with the round trip delay from the source 1 to destination 3. When all the packets from the given source to a destination have been transmitted, the receive function checks the logical_id and the physical_id. Consider the case, when all the 160 packets have been transmitted from source 2 to destination 1; then the receive function checks if the logical_id (6), i.e. the attribute being reduced (relation_number and attribute_number, d_{12}) is the same as the physical_id on the left hand side in the adjacency list. If both are same then the indegree

is reduced to one. For the example considered, the indegree where the physical_id is 6 is reduced to zero.

```
Before reducing the indegree :
6 1 1 1 2 -->  2 92 2 -1 7 -> NULL
After reducing the indegree:
6 0 1 1 2 -->  2 92 2 -1 7 -> NULL
```

If the indegree is zero then the receive function creates a structure and places it in the EVENT_LIST. In other words, the indegree represents the expected number of transmissions at the destination node.

There are many algorithms to handle the routing of a packet from one node to another. In this simulator, the adaptive Djikstra's Algorithm, which can compute the shortest path, is used to transmit the packets from one node to another. This algorithm consists of two routing techniques. One is adaptive and the other is the shortest path routing. The term adaptive means that the algorithm attempts to change its routing decisions to reflect changes in the current traffic. A detailed description of this algorithm can be found in [39].

In this simulator, the shortest path between two nodes is based on recent changes in the network traffic. The program has an array "DELAY_TABLE" which stores the delays from all the source and the destination nodes. This array is updated at regular intervals. Table below is an example of a DELAY_TABLE. Djikstra's algorithm uses this array to determine the routing. The results of these calculations are stored in another array called "SHORTEST_PATH". This array allows us to determine the shortest path between any two nodes in the network. In this array, the delays are stored between every source and

destination without considering which route it takes for the packet to be transmitted.

		Destination				
		1	2	3	4	5
Source	1	-	2	0	2	4
	2	4	-	4	0	1
	3	2	3	-	2	3
	4	3	0	3	-	4
	5	1	3	2	3	-

Table 21 An example showing the DELAY_TABLE

		Destination				
		1	2	3	4	5
Source	1	-	6	3	7	4
	2	4	-	7	4	1
	3	2	4	-	6	5
	4	3	5	4	-	4
	5	1	3	6	4	-

Table 22 An example showing the SHORTEST_PATH

APPENDIX B

DESCRIPTION OF THE ALGORITHM GENERAL (RESPONSE TIME)

This appendix describes our implementation of the AHY algorithm. The data structure, the input parameters and the output parameters are discussed.

THE DATA STRUCTURE OF THIS PROGRAM

The schedule for a particular relation is stored as an n-ary binary tree. Each structure consists of ten items. These items are:

- the relation number
- the attribute number
- the original size of the relation or attribute
- the selectivity of the attribute considered
- the changed size (size after a relation or attribute is reduced)
- the indegree
- the reduced relation number
- the reduced attribute number
- a pointer to the child list
- a pointer to the sibling list

For the attribute or the relation which is reduced after the semijoin, the reduced number and the attribute number are also included in the structure. If the relation is being reduced, then the attribute number is represented as —1. The indegree gives the value of

the number of transmissions. If the indegree is one, then it means there is a transmission before this one. Figure below shows an example of the segment.

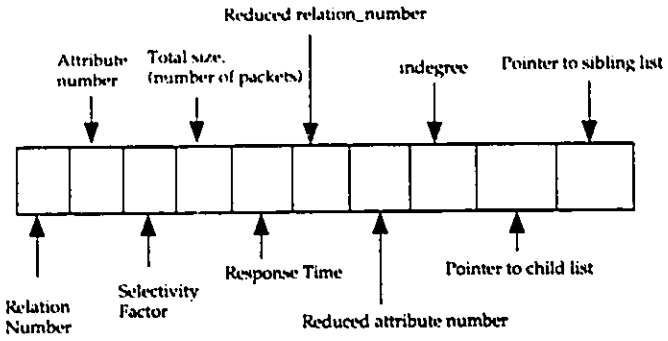


Figure 9 The data field of the structure

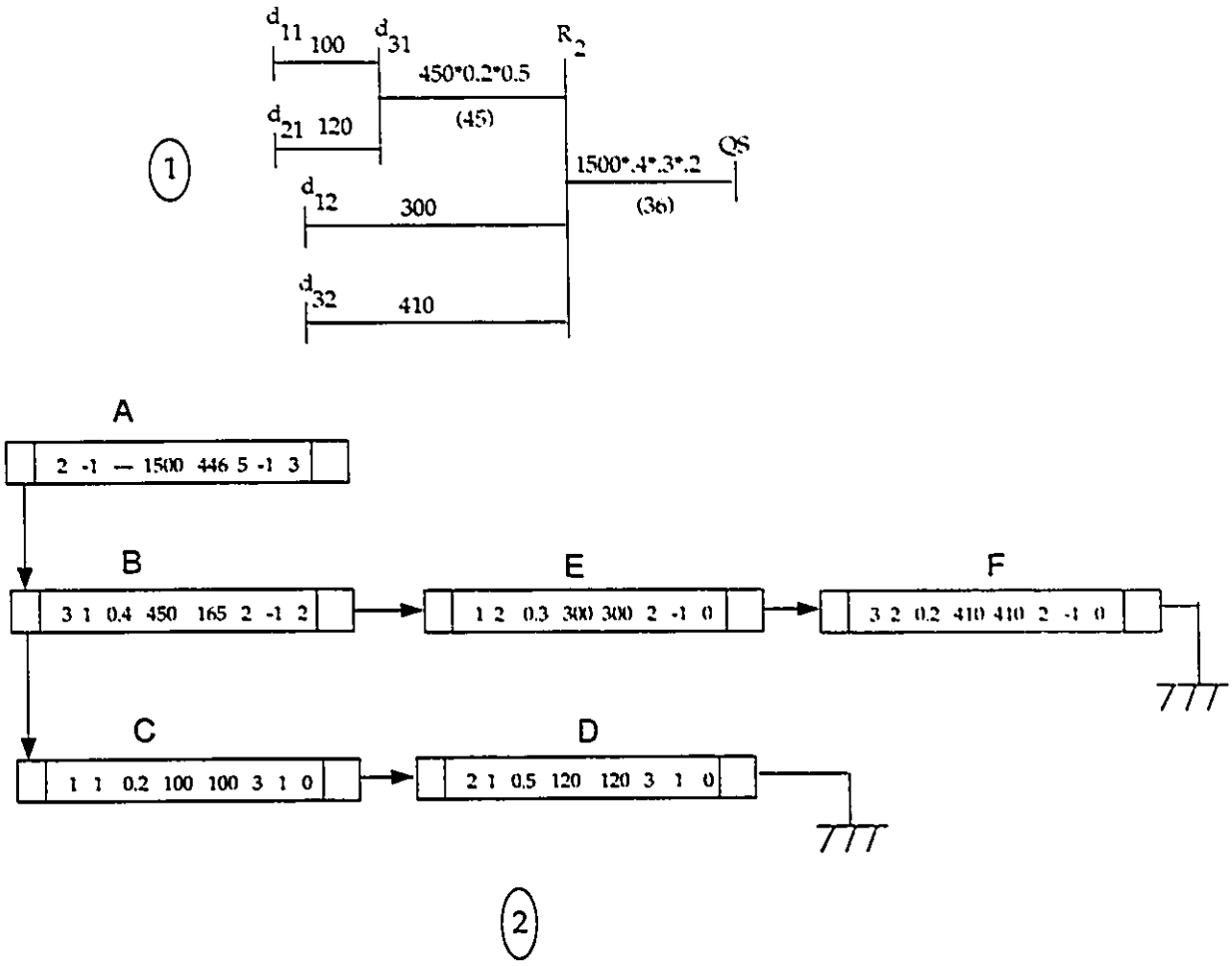


Figure 10 An example showing how the data structure is stored

For the given schedule shown in figure 1, the corresponding figure 2 shows how the schedule is stored using the data structure. If any two attributes are sent in parallel to the site where the relation or attribute resides, then they are stored as siblings, here segment B, E and F are siblings and are the children of parent A, and also C and D are the children of B and are siblings.

THE DESCRIPTION OF THE PROGRAM IN ALGORITHM PARALLEL

This program is based on Algorithm GENERAL. The following are the steps of this

program.

1. Perform the following on each of the common join attributes in the query in order to generate the schedule for each of the attributes.

   a. The first schedule is to send the attribute directly to the query site.

   b. Find the schedule with the smallest response time.

   c. Find the next smallest common join attribute and do the semijoin with the previous schedule.

   d. Repeat step 1c until all of that attributes are considered.

   e. Find the schedule with minimum response time from step 1c as the result.

2. Perform the following on each of the relations in order to generate a schedule for each of the relations.

   a. Collect the *valid* common join attributes from step 1. The term "valid common join" attribute means that :

      - If relation R_i is processed, then all the common join attributes with the relation number i will not be considered.

   b. Order the schedules which are generated in step 2a in ascending order.

   c. Find the schedule with the minimum response time from step 2b and do the semijoin with the current relation.

   d. Find the schedule with the next smallest response time from step 2b and do the semijoin with the previous schedule.

   e. Repeat step 2d until all the valid attributes of the current relation are considered.

f. Find the schedule with the minimum response time from step 2d as the result for the current relation.

The following relation table is the example for the illustration of Algorithm PARALLEL.

Relation	Size	d_{i1}		d_{i2}	
R_i	S_i	b_{i1}	p_{i1}	b_{i2}	p_{i2}
R_1:	1000	400	0.4	100	0.2
R_2:	2000	400	0.4	450	0.9
R_2:	3000	900	0.9	-	-

Table 23 Relation Table

The complete result can be found in the example of Algorithm PARALLEL in Section 2.4.

To find the minimum time for the attributes, attributes d_{11}, d_{21} and d_{31} which are in the same domain are considered. The attributes are arranged in increasing order of size. The schedule for attribute d_{11} is constructed by sending d_{11} to the query site. This schedule is placed in the ATTRIB_SCHEDULE_LIST. The next smallest attribute d_{21} is chosen and a schedule is constructed by sending it to the query site; also another schedule is constructed by sending d_{11} to reduce the attribute d_{21}. The schedule with the minimum response time is determined and placed in the ATTRIB_SCHEDULE_LIST. In a similar way the schedules for the attribute d_{31} are constructed. The one which has got the minimum response time is chosen and placed in the list ATTRIB_SCHEDULE_LIST. In a similar way the schedules with minimum response times for the attributes d_{12} and d_{22} are found and placed in the list.

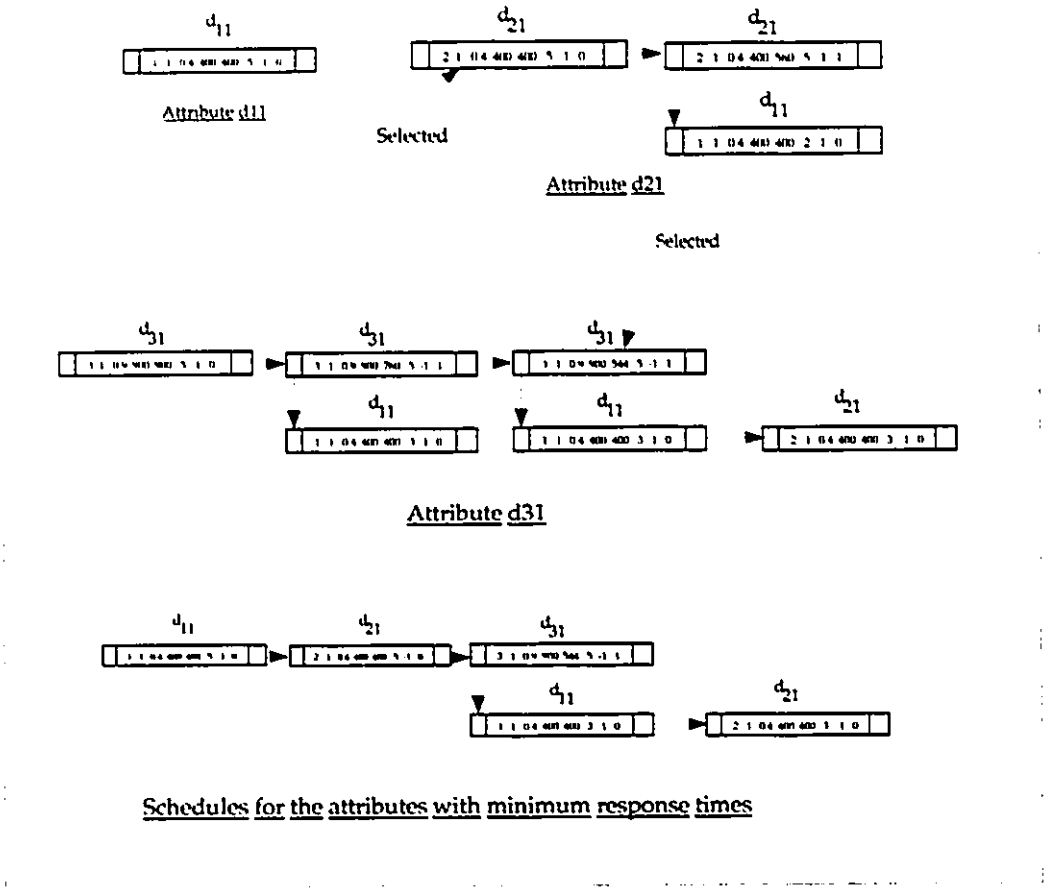


Figure 11 Example showing how the schedule for an attribute is constructed

For each of the relations being considered, the valid common join attributes are considered and the schedules for these attributes are picked from the ATTRIB_REDUCER_LIST. These schedules are stored in ascending order of response time in RELATION_REDUCER_LIST. The schedule for each attribute is constructed by doing the semijoin with the current relation. Each of the schedules considered is stored in the SCHEDULE_LIST. The schedule which gives the minimum response time is determined and is placed in the list FINAL_SCHEDULE. The program stops after

all the relations have been examined. The figure below shows how the schedule with minimum response time is chosen for relation R_3.

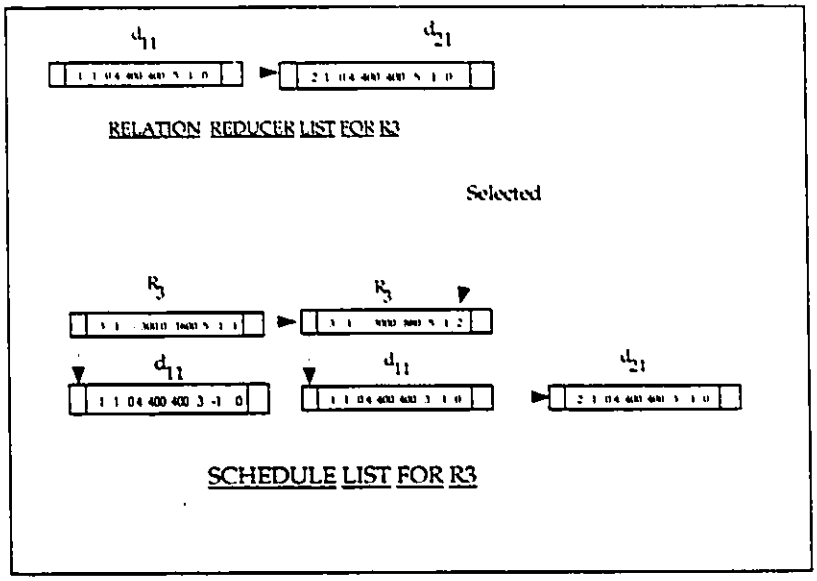


Figure 12 Example showing how the schedule for a relation is constructed.

APPENDIX C

DESCRIPTION OF THE HEURISTIC

The function ***find_best_schedule*** will create a schedule and try to reduce the time to communicate the relation ***R*** to query site ***QS*** to a value less than Worst_time ***W***. If that is possible, the function will not attempt any more optimization. Otherwise it will try to reduce the time to communicate relation ***R*** to ***QS*** as much as possible. The function returns the estimated time to communicate ***R*** to ***QS***.

First the list of potential reducers for the relation being reduced is found. For each of the potential reducers the communication time is calculated. The way the communication time is calculated is given below.

$$C_{time} = time_{r_i \rightarrow R_j} + sel_{r_i} * size(R_j) * Delay(R_j, QS)$$

Here *time* $(r_i \rightarrow R_j)$ is the sum of the

- delay to send all tuples in the reducer r_i the site of R_j
- delay to send reduced R_j to query site

The reducer r_i which gives the minimum communication time is chosen.

```
Given a Relation Table which contains the size of Relations, Si, site where the relation exists
Sitei, pij, and dij for the jth attribute of relation i.
Given a DELAY[1..NUM_NODE, 1..NUM_NODE]
{Compute the communication time for each relation}
For i = 1 to NUM_REL do
      Communication_Time[i] = size[i] * DELAY[site[i], QS]
{Find the relation which has the largest communication time}
max = Communication_Time[1]
For j = 1 to NUM_REL do
      if ( max < Communication_Time[j])
            max = Communication_Time[j]
            rnum = j
{initialise the boolean check_rel for all relations as FALSE }
For i = 1 to NUM_REL do
      check_rel[i] = FALSE
Worst_time = 0;
check_rel [rnum] = TRUE
time = max
While NUM_REL <> 0
      if(time < Worst_time )
            check_rel[rnum] = FALSE
            Calculate the schedules of the other relations.
      Insert the data associated of relation rnum in SCHEDULE
      response_time = find_best_schedule( QS, rnum, Worst_time);
      if ( response_time > Worst_time)
            Worst_time = response_time
      Remove the relation rnum from the list of relations
Print the final schedules of the relations
```

Table 24 Algorithm of Main Program

This reducer is passed to the function ***find_best_reducer_schedule***. The function ***find_best_reducer_schedule*** checks whether the communication time of the reducer r_i

may be reduced further. The potential reducers for the reducer are found out and stored in REDUCER_LIST. Then the communication time for each of the reducer in REDUCER_LIST is calculated by sending the reducer to the r_i. Also we calculate the time by sending the different reducers in parallel to reduce r_i. The reducer which gives the best improvement in time (the communication time is less than the worst time) is chosen and passed back to the function ***find_best_schedule***. If the time is less than the communication time of sending only r_i to R_j and R_j to QS, then it is appended to the schedule of relation R_j.

In a similar way, the next reducer which gives the best improvement in time is found out and the process is carried out until all the reducers have been examined. The function uses semijoins, to reduce, to a value less than time W, the time to communicate the needed tuples of R_j, to QS. As soon as the objective of reducing the communication time to below W is realized, the function does not attempt further optimization since such optimization is futile.

The process is repeated for the relation having the next largest communication time. The process stops when there does not exist a relation which

- has not been examined so far and
- has a communication cost more than the reduced relation having the worst communication time.

```
function find_best_schedule ( Query site QS, relation R, Worst_time W)
{Find the number of potential reducers for relation r}
num_reducers = 0;
For i = 1 to NUM_ATTR
        if ( b[R][i] != 0) { to check if attribute size is not equal to 0)
        For j = 1 to NUM_REL
                if ( j != mum and b[j][i] != 0) { to check not the same relation
                                                        or the same attribute }
{Compute the communication time for each reducer }
For i = 1 to num_reducers
        time[i] = Size[reducer] * DELAY[site[reducer], site[R]
                        + Size[R] * selectivity[reducer] * DELAY[site[R], QS]
Find the reducer which gives the minimum communication time, time[reducer_num].
best_time[i] = find_best_reducer_schedule(QS, r, reducer_num, Worst_time)
If ( best_time[i] < (Size[R] * DELAY[site[R], QS])
        Insert this schedule to SCHEDULE of relation R
time[reducer_num] = 9999999;
improvement_possible = 1;
While (improvement_possible)
{
        For i = 1 to num_reducers
                next_best = 9999990
                if ( next_best > time[i]) next_best = i
                        if ( next_best = 9999990) improvement_possible = 0;
                        else
                                best_time = find_best_reducer_schedule(QS, R, i, W)
                                Check if new_reducer gives the best improvement in time
                                If its best, insert schedule of this reducer to SCHEDULE.
                        time[next_best] = 9999999
}
```

Table 25 Function find_best_schdedule.

function ***find_best_reducer_schedule (QS, relation, reducer, Worst_time)***
This function checks if the communication time / selectivity of reducer may be further reduced by some other semijoin. An attribute r_j is said to be a reducer of attribute r_i, if they are defined on the same domain.

{ find the potential reducers for the reducer ***reducer*** }
For i = 1 to NUM_REL
    If (b[i][reducer] != 0 and i != relation) { not the reducer being considered
                                and attribute size is not zero}
        Get the potential reducers and store in REDUCER_LIST
Calculate the communication_time for each reducer in REDUCER_LIST.
Also calculate the communication time by sending the reducers parallely to the ***reducer***
Consider the reducer[reducers] which gives the best improvement in time
Pass the new communication time to ***find_best_schedule***

Table 26 Function find_best_reducer_schedule

APPENDIX D

SUMMARY OF RESULTS

The tables below shows the number of times the heuristic showed an improvement over AHY algorithm, and, the number of times the response time was equal, for all the query types and the different cases.

QUERY_TYPE	50N(100 Queries)			75N(100 Queries)		
	AHY	EQUAL	HEURISTIC	AHY	EQUAL	HEURISTIC
3-2	16	22	62	12	8	80
3-3	22	20	58	9	15	76
3-4	17	18	55	12	13	75
4-2	19	14	67	18	15	67
4-3	21	15	64	22	14	66
4-4	18	14	68	12	16	72
5-2	12	21	67	22	15	63
5-3	15	22	63	12	15	73
5-4	11	16	73	8	18	74
6-2	19	20	61	8	17	75
6-3	16	17	67	11	13	76
6-4	15	16	69	11	15	74

Table 27 The table showing the comparisons when unit delays are considered

QUERY_TYPE	50N(100 Queries)			75N(100 Queries)		
	AHY	EQUAL	HEURISTIC	AHY	EQUAL	HEURISTIC
3-2	9	15	76	5	17	78
3-3	9	12	79	6	14	80
3-4	7	16	77	8	19	73
4-2	8	19	73	10	11	79
4-3	7	16	77	10	21	69
4-4	8	20	73	6	17	77
5-2	8	15	77	7	10	83
5-3	6	19	75	7	16	77
5-4	10	10	80	10	17	73
6-2	6	12	82	10	17	70
6-3	6	13	81	9	20	71
6-4	8	18	74	12	19	69

Table 28 The table showing the comparisons when delays are changed by 10%.

QUERY_TYPE	50N(100 Queries)			75N(100 Queries)		
	AHY	EQUAL	HEURISTIC	AHY	EQUAL	HEURISTIC
3-2	11	20	69	6	12	82
3-3	12	11	77	6	11	83
3-4	9	18	73	6	10	84
4-2	8	19	73	5	9	86
4-3	8	16	76	8	5	87
4-4	8	12	80	7	5	86
5-2	6	16	78	5	11	84
5-3	9	11	80	9	12	79
5-4	7	12	81	4	13	83
6-2	9	15	76	8	8	64
6-3	7	19	74	5	9	86
6-4	7	14	79	7	13	80

Table 29 The table showing the comparisons when delays are changed by 25%.

The tables 26, 27 and 28 shows the average response times of the heuristic and the AHY algorithm. The percentage reduction in the response time using the heuristic compared to the AHY algorithm is also given, for all the query types and for the different cases.

QUERY_TYPE	50N(100 Queries)			75N(100 Queries)		
	AHY	HEURISTIC	% DIFF	AHY	HEURISTIC	% DIFF
3-2	7518	6427	14.09	3687	3136	14.94
3-3	8948	7413	12.25	5127	4548	11.29
3-4	7348	6349	13.63	5226	4698	12.10
4-2	7183	6276	12.67	6193	5503	11.12
4-3	7356	6445	12.34	7591	6235	15.01
4-4	6403	5761	14.89	4142	3565	13.91
5-2	5314	4526	14.84	6746	5937	11.92
5-3	5884	5053	14.11	7207	6478	10.15
5-4	3969	3499	11.84	6549	5788	11.62
6-2	6190	5546	10.41	7009	6253	10.78
6-3	4789	4043	15.23	7487	6573	12.2
6-4	4446	3877	12.79	5497	4786	12.87

Table 30 The table showing the comparisons taking average response time when unit delays are considered and percentage improvement.

QUERY_TYPE	50N(100 Queries)			75N(100 Queries)		
	AHY	HEURISTIC	% DIFF	AHY	HEURISTIC	% DIFF
3-2	5806	5154	11.22	6762	5905	12.67
3-3	8106	7040	13.1	6221	5462	12.23
3-4	6304	5633	10.04	7729	6945	10.14
4-2	7786	6904	11.32	7042	6078	13.84
4-3	8008	7036	12.34	8878	7740	12.61
4-4	6736	5974	11.31	6534	5645	13.6
5-2	7398	6540	11.52	8207	7237	11.87
5-3	5666	4916	13.26	6042	5308	12.24
5-4	4948	4391	11.25	7055	6243	11.50
6-2	7079	6222	12.10	7873	6983	11.31
6-3	4665	4080	12.54	7856	7034	10.11
6-4	5925	5090	14.09	7659	6686	12.73

Table 31 The table showing the comparisons taking average response time when delays are changed by 10% and percentage improvement.

QUERY_TYPE	50N(100 Queries)			75N(100 Queries)		
	AHY	HEURISTIC	% DIFF	AHY	HEURISTIC	% DIFF
3-2	7790	6927	11.07	12,776	11172	12.55
3-3	6700	5829	13.01	11,464	10022	12.56
3-4	5929	5205	12.13	10041	8614	14.23
4-2	5964	5299	12.61	9201	7893	14.21
4-3	6298	5613	1072	8448	7351	12.98
4-4	4713	4188	11.18	9028	7797	13.63
5-2	8032	7051	12.23	8282	7202	13.07
5-3	8409	7423	11.75	10665	9336	12.46
5-4	7649	6742	11.82	11,277	9835	12.78
6-2	7802	7006	10.23	9219	8128	11.83
6-3	8109	7240	10.71	9826	8519	13.30
6-4	5906	5217	11.61	11,245	9812	12.74

Table 32 The table showing the comparisons taking average response time when delays are changed by 25% and percentage improvement.

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