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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA, BERKELEY

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OPTIMIZATION OF NESTED SQL QUERIES REVISITED

R.A. Ganski and H.K.T. Wong

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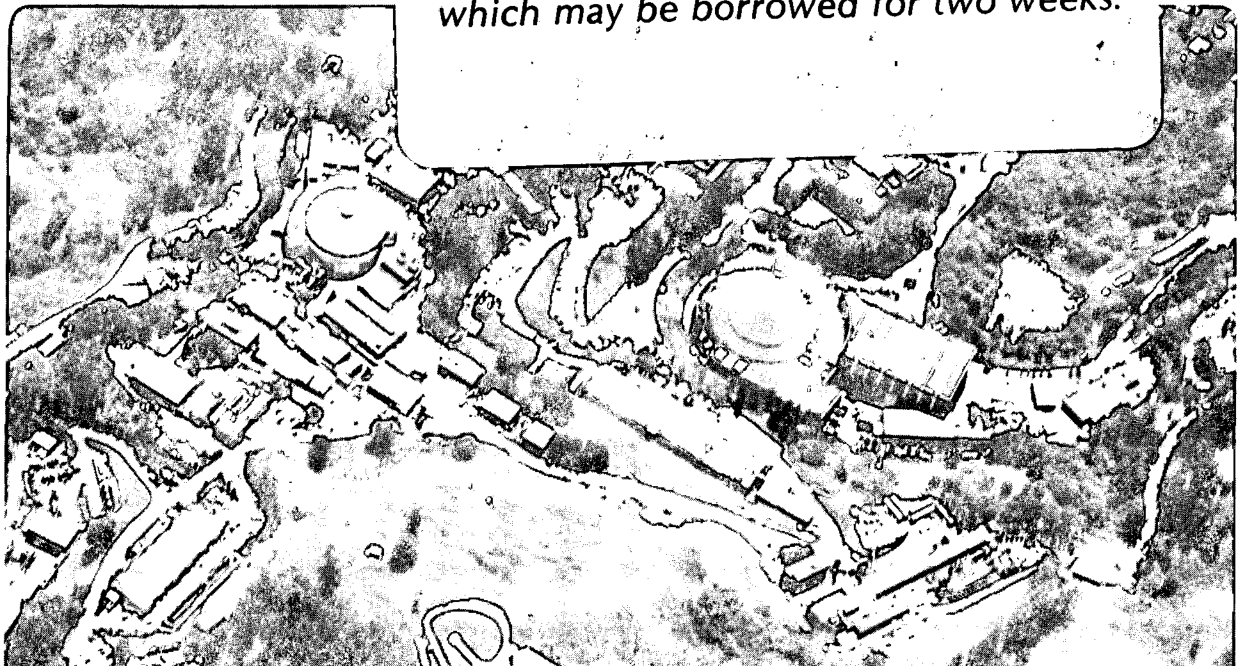

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Optimization of Nested SQL Queries Revisited

Richard A. Ganski
Department of Computer Science
San Francisco State University

Harry K.T. Wong
Lawrence Berkeley Laboratory
University of California
Berkeley, California

Abstract

Current methods of evaluating nested queries in the SQL language can be inefficient in a variety of query and data base contexts. Previous research in the area of nested query optimization which sought methods of reducing evaluation costs is summarized, including a classification scheme for nested queries, algorithms designed to transform each type of query to a logically equivalent form which may then be evaluated more efficiently, and a description of a major bug in one of these algorithms. Further examination reveals another bug in the same algorithm. Solutions to these bugs are proposed and incorporated into a new transformation algorithm, and extensions are proposed which will allow the transformation algorithms to handle a larger class of predicates. A recursive algorithm for processing a general nested query is presented and the action of this algorithm is demonstrated. This algorithm can be used to transform any nested query.

1. Introduction

SQL is a block-structured query language for data retrieval and manipulation developed at the IBM Research Laboratory in San Jose, California [AST 75]. SQL was incorporated into System R, the relational data base management system, also developed at the IBM San Jose Research Laboratory [AST 76].

One of the most powerful features of SQL is the *nesting* of query blocks. For demonstration purposes, assume the following relations:

S(SNO,SNAME,STATUS,CITY) — the Suppliers relation
P(PNO,PNAME,COLOR,WEIGHT,CITY) — the Parts relation
SP(SNO,PNO,QTY,ORIGIN) — the Shipment relation

The primary keys for these relations are SNO, PNO, and SNO,PNO respectively. If we wanted the names of all suppliers who supply part P2 we could say:

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```
SELECT  SNAME
FROM    S                                        (1)
WHERE   SNO IN  (SELECT  SNO
                 FROM    SP
                 WHERE   NO = 'P2');
```

This is an example of a query with a single level of nesting. The basic structure of a SQL query is a *query block*, which consists principally of a SELECT clause, a FROM clause, and zero or more WHERE clauses. The first query block in a nested query is known as the *outer* query block and the next query block is known as the *inner* query block. The WHERE clause specifies the predicates which the tuples retrieved must satisfy. One type of predicate which can appear in the WHERE clause is a *nested predicate*, which is of the form [Ri.Ck op Q], where Q is a query block [KIM 82:445]. Q will always be a form of the SELECT statement. The op may be a scalar or set membership operator. A relation referred to in the inner query block shall be designated as an *inner relation*, and a relation referred to in the outer query block shall be designated as an *outer relation*. Queries can be nested to an arbitrary depth.

In his 1982 paper "On Optimizing an SQL-like Nested Query" [KIM 82], Won Kim showed that the conventional techniques used in implementing query nesting, i.e. the techniques used in System R [SEL 79:33], can be very inefficient: tables referenced in the inner query block of a nested query may have to be retrieved once for each tuple of the relation referenced in the outer query block [KIM 82:450]. As a solution to this problem, Kim proposed query transformation algorithms that would improve the efficiency of nested query evaluation, sometimes by orders of magnitude. His approach was to transform a nested query to a logically equivalent single-level query (i.e. without nesting): this query could then be examined by a query optimizer, such as that described in [SEL 79], for alternative methods of processing, including different methods of performing joins. To introduce Kim's results, his system of classification for nested queries is outlined below.

2. Types of Nested Queries

Won Kim developed a classification of nested query types, four of which are relevant to this paper. They are described here briefly for single-level nested queries, as presented in [KIM 82].

2.1. Type-A Nesting

A nested predicate is type-A if the inner query block Q does not contain a join predicate that references a relation in the outer query block, and if the SELECT clause of Q consists of an aggregate function over a column in an inner relation [KIM 82:446]. The following is an example of a type-A nested query of depth one:

```
SELECT  SNO
FROM    SP
WHERE   PNO =   (SELECT  MAX(PNO)                    (2)
                 FROM    P);
```

Since the inner query block of a type-A nested query does not reference a relation of the outer query block, it may be evaluated independently of the outer query block, and the result of its evaluation will be a single constant [SEL 79:33].

2.2. Type-N Nesting

A nested predicate is type-N if the inner query block Q does not contain a join predicate which references a relation in the outer block, and the SELECT clause of Q does not contain an aggregate function [KIM 82:447]. The following is an example of a type-N nested query:

```
SELECT  SNO
FROM    SP
WHERE   PNO IS IN  (SELECT  PNO                      (3)
                    FROM    P
                    WHERE   WEIGHT > 50);
```

Evaluation of a Type-N Nested Query. This kind of nested query would be processed in System R by first processing the inner query block Q, resulting in a list of values X which can then be substituted for the inner query block in the nested predicate, so that PNO IS IN Q becomes PNO IS IN X. The resulting query is then evaluated by nested iteration [SEL 79:33].

2.3. Type-J Nesting

A type-J nested predicate results when the WHERE clause of the inner query block contains a join predicate which references the relation of an outer query block, and the relation is not mentioned in the inner FROM clause. Another condition is that the SELECT clause of the inner query block does not contain an aggregate function [KIM 82:448]. The following is an example of type-J nesting:

```
SELECT  SNAME
FROM    S
WHERE   SNO IS IN  (SELECT  SNO                      (4)
                    FROM    SP
                    WHERE   QTY > 100 AND
                            SP.ORIGIN = S.CITY);
```

2.4. Type-JA Nesting

Type-JA nesting is present when the WHERE clause of the inner query block contains a join predicate which references the relation of an outer query block, and the inner SELECT clause consists of an aggregate function over an inner relation [KIM 82:449]:

— Select names of parts which have the highest part number in the city from which they are supplied.

```
SELECT  PNAME
FROM    P
WHERE   PNO =   (SELECT  MAX(PNO)                    (5)
                 FROM    SP
                 WHERE   SP.ORIGIN = P.CITY);
```

Evaluation of Type-J and Type-JA Nested Queries. Type-J and type-JA nesting are processed in System R by the nested iteration method: the inner query block is processed once for each tuple of the outer relation which satisfies all simple predicates on the outer relation [SEL 79:33]. This method has the obvious disadvantage that the inner relation (SP in example 4) may have to be retrieved many times: in example 4, it must be retrieved once for each tuple of the outer relation S, since there are no simple predicates in the outer query block. It is this inefficiency which motivated Kim to develop alternative algorithms for processing nested queries.

3. Kim's Algorithms for Processing Nested Queries

Kim observed that for type-N and type-J nested queries, the nested iteration method for processing nested queries is equivalent to performing a join between the outer and inner relations [KIM 82:451]. But nested iteration is only one way of performing a join; for single-level queries System R also performs joins by the *merge join* method, with the decision as to which method to use made by the query optimizer [SEL 79:28]. Kim showed that nested queries could be transformed to logically equivalent single-level queries containing single-level join predicates explicitly, and that now the query optimizer can choose a merge join method in implementing the joins, often at a great reduction of cost over the nested iteration method [KIM 82:461]. Kim's transformation algorithms are summarized in the present section.

3.1. Processing a Type-N or Type-J Nested Query

In his Lemma 1 [KIM 82:451], Kim states that a type-N nested two-relation query is equivalent to a canonical two-relation query with a join predicate:
Let Q1 be

```
SELECT  Ri.Ck
FROM    Ri,Rj
WHERE   Ri.Ch = Rj.Cm;
```

and let Q2 be

```
SELECT  Ri.Ck
FROM    Ri
WHERE   Ri.Ch IS IN  (SELECT  Rj.Cm
                      FROM    Rj);
```

[KIM 82:451]

Kim's Lemma 1 states that Q1 and Q2 are equivalent; that is, they yield the same result [KIM 82:451]. Kim's proof of lemma 1 calls attention to the fact that by definition the inner block of Q2 can be evaluated independently of the outer block, resulting in a list of values. Since this list contains values from column Rj.Cm, the predicate is equivalent to the join predicate Ri.Ch = Rj.Cm [KIM 82:451-452]. From Lemma 1 Kim develops the following algorithm:

Algorithm NEST-N-J

1. Combine the FROM clauses of all query blocks into one FROM clause.
2. AND together the WHERE clauses of all query blocks, replacing IS IN by =.
3. Retain the SELECT clause of the outermost query block.

[KIM 82:452]

The result is a canonical query logically equivalent to the original nested query. The algorithm applies to type-N or type-J nested queries with one or more levels of nesting.

3.2. Processing a Type-JA Nested Query

In his Lemma 2 [KIM 82:455], Kim asserts that a type-JA nested query can be transformed to a type-J nested query which references a new temporary relation:

Let Q3 be

```
SELECT  Ri.Ck
FROM    Ri
WHERE   Ri.Ch =   (SELECT  AGG(Rj.Cm)
                   FROM    Rj
                   WHERE   Rj.Cn = Ri.Cp);
```

and let Q4 be

```
SELECT  Ri.Ck
FROM    Ri
WHERE   Ri.Ch =   (SELECT  Rt.C2
                   FROM    Rt
                   WHERE   Rt.C1 = Ri.Cp);
```

where Rt is a temporary table obtained by

```
Rt(C1,C2) =    (SELECT  Rj.Cn, AGG(Rj.Cm)
                FROM    Rj
                GROUP BY Rj.Cn);
```

[KIM 82:454-455]

Kim's Lemma 2 states that Q3 and Q4 are equivalent [KIM 82:455]. His proof postulates that the action of the nested iteration processing of a type-JA query can be captured in a temporary table formed with a GROUP BY clause, as in Rt: for each tuple of Ri, a tuple is retrieved from Rt whose C1 (formerly Cn) value matches the Cp value of the Rt tuple. The C2 value of the Rt tuple will contain the aggregate value obtained by the GROUP BY clause, and this can be matched with Ri.Ch. [KIM 82:455]

Lemma 2 leads to an algorithm which transforms a type-JA nested query of depth one to an equivalent type-J nested query of depth 1. Assume a type-JA nested query as follows:

```
SELECT  R1.Cn+2
FROM    R1
WHERE   R1.Cn+1 =   (SELECT  AGG(R2.Cn+1)
                     FROM    R2
                     WHERE   R2.C1 = R1.C1 AND
                             R2.C2 = R1.C2 AND
                                  :
                                  :
                             R2.Cn = R1.Cn);
```

[KIM 82:455]

Algorithm NEST-JA

1. Generate a temporary relation Rt(C1,...,Cn,Cn+1) from R2 such that Rt.Cn+1 is the result of applying the aggregate function AGG on the Cn+1 column of R2 which have matching values in R1 for C1,C2, etc.
2. Transform the inner query block of the initial query by changing all references to R2 columns in join predicates which also reference R1 to the corresponding Rt columns. The result is a type-J nested query, which can be passed to algorithm NEST-N-J for transformation to its canonical equivalent.

[KIM 82:455-456]

4. Costs of Kim's Algorithms: Rationale for Transformation

Kim's analyses of his algorithms [KIM 82:461-464] compare the costs of processing N, J, and JA-type nested queries using the nested iteration method and the transformation method followed by merge joins. Kim develops cost functions for each method and for each type of nesting, using variables such as the sizes of relations, available memory buffer space, and selectivity factors. He demonstrates the cost reductions attainable by his transformation method with examples of queries and data base conditions for each type of nesting. The following table summarizes the results Kim obtained in three of his examples [KIM 82:462-463]:

Example Query	Nested Iteration (Page I/O's)	Transformation Followed by Merge Join (Page I/O's)
Type-N	10,220	720
Type-J	10,120	550
Type-JA	3,050	615

Figure 1: Page I/O's Required in Kim's Examples

The comparative costs will of course vary with different queries and data base conditions, but Kim has shown that cost savings of 80% to 95% are possible with his transformation method.

5. Bugs in Kim's Algorithm NEST-JA and their Solutions

5.1. The COUNT bug

In a 1984 U.C. Berkeley Memorandum [KIE 84], Werner Kiessling revealed a problem with Kim's algorithm NEST-JA. The problem arises when a type-JA nested query contains the COUNT function. To illustrate his arguments, Kiessling defines two relations:

PARTS(PNUM,QOH)
SUPPLY(PNUM,QUAN,SHIPDATE)

The following instantiations of these relations are assumed:

PARTS:

PNUM	QOH
3	6
10	1
8	0

SUPPLY:

PNUM	QUAN	SHIPDATE
3	4	7-3-79
3	2	10-1-78
10	1	6-8-78
10	2	8-10-81
8	5	5-7-83

[KIE 84:2]

Kiessling defines Query Q2 as follows:

Query Q2:

Find the part numbers of those parts whose quantities on hand equal the number of shipments of those parts before 1-1-80:

```
SELECT  PNUM
FROM    PARTS
WHERE   QOH = (SELECT  COUNT(SHIPDATE)
               FROM    SUPPLY
               WHERE   SUPPLY.PNUM = PARTS.PNUM AND
                       SHIPDATE < 1-1-80)
```

[KIE 84:4]

Given the example tables PARTS and SUPPLY defined above, query Q2 will give the following result when evaluated using nested iteration:

Result:

PARTS.PNUM
10
8

[KIE 84:4]

Application of Kim's algorithm NEST-JA to Query Q2 results in the following transformation:

```
TEMP' (SUPPNUM,CT) =
      (SELECT  PNUM, COUNT(SHIPDATE)
       FROM    SUPPLY
       WHERE   SHIPDATE < 1-1-80
       GROUP BY PNUM)

SELECT  PNUM
FROM    PARTS, TEMP'
WHERE   PARTS.QOH = TEMP'.CT AND
        PARTS.PNUM = TEMP'.SUPPNUM
```

[KIE 84:4]

TEMP' evaluates to

TEMP':

SUPPNUM	CT
3	2
10	1

and the final result is

PARTS.PNUM
10

[KIE 84:5]

This result differs from that obtained using nested iteration. The reason why the transformation fails is that in the formation of the temporary relation, no tuples appear which do not match the predicates applied to the inner relation. Thus, the COUNT function will never return zero, since the only groups it is applied to are groups of tuples matching the predicates. Thus CT in the temporary relation will never be zero.

Kiessling explored a trial correction of the bug which involved ORing a predicate to the WHERE clause of the transformed query in order to a posteriori find where an empty set occurs to satisfy the predicate, but the trial correction failed on a query with more than one level of nesting [KIE 84:5]. Kiessling concludes that in attempting to use Kim's algorithm NEST-JA for transforming type-JA nested queries, "...there seems to be no general way to recover values lost by COUNTs on a correlation level greater than 1." [KIE 84:7]. While this does seem to be true in the context of the SQL language as specified in [AST 76], the problem can be solved if the outer join operation is available in the processing of the query.

5.2. Solution to the COUNT bug using outer joins

If either internally or through extensions to the query language an *outer join* operation may be specified as the join operation, the COUNT bug can be solved by performing an outer join in the creation of the temporary relation. The operation of outer join is defined in [COD 79:407]: the outer join includes *all* values from columns participating in join, with NULLs in the opposite column if there is no match for a column value. For example, assume the following relations:

R:

X
A
B

S:

Y
B
C
E

An outer join between R and S, which will be designated R.X $\dot{=}$+ S.Y, will have the following result:

X	Y
A	^
B	B
^	C
E	^

where ^ is the special null value. The outer join operation is implemented in at least one commercial data base management system with which the authors are familiar [ORA 86].

To solve the COUNT bug an outer join may be used in the creation of the temporary relation. Kiessling's query Q2 could be transformed to give the following:

```
TEMP3 (SUPPNUM,CT) =
        (SELECT  PARTS.PNUM, COUNT(SUPPLY.SHIPDATE)
         FROM    PARTS,SUPPLY
         WHERE   SUPPLY.SHIPDATE < 1-1-80 AND
                 PARTS.PNUM =+ SUPPLY.PNUM
         GROUP BY PARTS.PNUM);
```

Query T3:

```
SELECT  PNUM
FROM    PARTS,TEMP3
WHERE   PARTS.QOH = TEMP3.CT AND
        PARTS.PNUM = TEMP3.SUPPNUM;
```

Before looking at the result of this new query, let us look at the result of the outer join between PARTS and SUPPLY with the conditions given in the creation of the temporary relation TEMP3:

PARTS.PNUM	PARTS.QOH	SUPPLY.PNUM
3	6	3
3	6	3
10	1	10
8	0	^

SUPPLY.QUAN	SUPPLY.SHIPDATE
4	7-3-79
2	10-1-78
1	6-8-78
^	^

Note that the condition which applies to only one relation (SUPPLY.SHIPDATE < 1-1-80) must be applied before the join is performed. Otherwise the join would not contain the last row, and the result would be incorrect. This may happen if the join is performed first to take advantage of indices on the join columns. To ensure restriction, we can explicitly build a temporary table applying simple predicates. This temporary table will be a restriction and projection of the inner table:

```
TEMP2 (PNUM) =  (SELECT  PNUM
                 FROM    SUPPLY
                 WHERE   SHIPDATE < 1-1-80);
```

and TEMP3 is changed to

```
TEMP3 (SUPPNUM,CT) =
        (SELECT  PARTS.PNUM, COUNT(TEMP2.SHIPDATE)
         FROM    PARTS,TEMP2
         WHERE   PARTS.PNUM =+ TEMP2.PNUM
         GROUP BY PARTS.PNUM);
```

Thus, TEMP3 will look like this:

TEMP3:	SUPPNUM	CT
	3	2
	10	1
	8	0

and the result of query T3 will be:

PARTS.PNUM
10
8

which matches the result obtained by nested iteration. This solution has been tested successfully on queries with more than a single level of nesting, including Kiessling's query Q3 [KIE 84:6].

If the type-JA query with a COUNT function contains a nested join predicate with a scalar comparison operator other than equality, the correct result is obtained if the scalar operator is used in the outer join operation to create the temporary relation and the join predicate in the original query is changed to equality.

5.2.1. Query Blocks with COUNT(*)

If the SELECT clause of the inner query block contains COUNT(*) instead of COUNT(column name) then this approach must be modified. For example, if query Q2 contained a COUNT(*) instead of a COUNT(SHIPDATE), then the temporary table would look like this:

TEMP3:	SUPPNUM	CT
	3	2
	10	1
	8	1

This would be semantically incorrect, and the final result would be incorrect. To avoid this error the SELECT clause used in the creation of the table must contain COUNT(col-name) instead of COUNT(*), where col-name is the name of some column in the inner relation. Since the join column of the inner relation will always be present in the original query and may be the only one that is, let col-name be the name of the join column of the inner relation. In our example it would be COUNT(TEMP2.PNUM).

5.3. Another Bug: Relations other than Equality

For aggregate functions other than COUNT Kim's algorithm NEST-JA works correctly for nested join predicates containing the equality operator. However, if we consider other operators, we discover another bug in Kim's algorithm.

Assume the PARTS and SUPPLY tables:

PARTS:		SUPPLY:		
PNUM	QOH	PNUM	QUAN	SHIPDATE
3	0	3	4	7-3-79
10	4	3	2	10-1-78
8	4	10	1	6-8-78
		9	5	3-2-79

and the following type-JA query:

Query Q5:

```
SELECT  PNUM
FROM    PARTS
WHERE   QOH = (SELECT  MAX(QUAN)
               FROM    SUPPLY
               WHERE   SUPPLY.PNUM < PARTS.PNUM AND
                       SHIPDATE < 1-1-80);
```

This is the same as Kiessling's query Q1 [KIE 84:1] except for the substitution of the "<" operator for "=" operator in the join predicate. The result according to nested iteration semantics, assuming MAX({ }) = NULL, is

PARTS.PNUM
8

Kim's algorithm results in the following temporary table and transformed query:

```
TEMP5 (SUPPNUM, MAXQUAN) =  SELECT  PNUM, MAX(QUAN)
                            FROM    SUPPLY
                            WHERE   SHIPDATE < 1-1-80
                            GROUP BY PNUM;
```

Query T5:

```
SELECT  PNUM
FROM    PARTS, TEMP
WHERE   QOH = TEMP.MAXQUAN AND
        TEMP.SUPPNUM < PARTS.PNUM;
```

and the following results:

TEMP5:

SUPPNUM	MAXQUAN
3	4
10	1
9	5

final result:

PARTS.PNUM
10
8

which does not match the results obtained by nested iteration. The problem is that the temporary table created by Kim's algorithm contains only aggregate information about tuples with the same join column value, whereas query Q5 asks for aggregate information about a *range* of join column values.

5.3.1 Solution to the Relations-other-than-Equality Bug

The solution to this bug is similar to the solution to the COUNT bug: perform a join in the creation of the temporary relation, only this time it need not be an outer join, unless the aggregate function is COUNT. The join in effect causes the temporary table to include aggregate values over the proper range of join column values. As before, the join predicate in the original query must be changed to equality. This implies that only the equality operator may bethe outer relation and the temporary relation.

If this solution is applied to query Q5 and the last SUPPLY table, the outcome is:

```
TEMP6 (SUPPNUM, MAXQUAN) =
          SELECT  PARTS.PNUM, MAX(SUPPLY.QUAN)
          FROM    PARTS, SUPPLY
          WHERE   SHIPDATE < 1-1-80 AND
                  SUPPLY.PNUM < PARTS.PNUM
          GROUP BY PARTS.PNUM;
```

and query Q5 is transformed to

Query T6:

```
SELECT  PNUM
FROM    PARTS, TEMP
WHERE   PARTS.QOH = TEMP.MAXQUAN AND
        PARTS.PNUM = TEMP.SUPPNUM;
```

with the following results:

TEMP6:

SUPPNUM	MAXQUAN
10	5
8	4

final result:

PARTS.PNUM
8

This matches the result obtained by nested iteration.

5.4. A Problem with Duplicates

The methods outlined above to solve the COUNT bug work correctly if the outer relation of the nested query contains no duplicates in the join column, but a problem arises if it does contain duplicates. Assume the following PARTS and SUPPLY relations:

PARTS:

PNUM	QOH
3	6
3	2
10	1
10	0
8	0

SUPPLY:

PNUM	QUAN	SHIPDATE
3	4	8/14/77
3	2	11/11/78
10	1	6/22/76

For this example let us again assume Kiessling's query Q2. If we apply query Q2 to the above relations, the result by nested iteration would be:

PARTS.PNUM
3
10
8

If we apply our new modified version of Kim's algorithm, the results would be:

TEMP3:

SUPPNUM	CT
3	4
10	2
8	0

final result:

PARTS.PNUM
8

This does not match the result obtained by nested iteration. The problem arises because duplicates in the outer relation increase the COUNT over that column in the temporary relation. This problem does not arise with the MAX and MIN functions, but it does arise with the COUNT, AVG and SUM functions.

5.4.1. Solution to the Duplicates Problem

In order to match the results obtained by nested iteration semantics for relations with duplicates in the outer join column, our algorithm must be modified to remove duplicates before the join in the creation of the temporary table is performed. This can be accomplished by projecting the join column of the outer relation, and using the projection instead of the outer relation in any join required to build a temporary table. This is part of the procedure followed in INGRES [STO 76] for nested QUEL queries [KIE 84:8]. The efficiency of the algorithm can be improved by applying all simple predicates to the outer relation in the creation of the projection. In query Q2 this rule will have no effect since there are no simple predicates in the outer query block.

Using Kiessling's query Q2 as an example again, let TEMP1 be defined as follows:

```
TEMP1(PNUM) =   (SELECT   DISTINCT PNUM
                 FROM     PARTS);
```

TEMP1 is the projection of the PNUM column from PARTS. TEMP3 will now be defined as:

```
TEMP3 (SUPPNUM,CT) =
        (SELECT   TEMP1.PNUM, COUNT(SUPPLY.SHIPDATE)
         FROM     TEMP1,SUPPLY
         WHERE    SUPPLY.SHIPDATE < 1-1-80 AND
                  TEMP1.PNUM =+ SUPPLY.PNUM
        GROUP BY TEMP1.PNUM);
```

and query T3 remains the same. The results are:

TEMP1: PNUM	TEMP3: SUPPNUM	CT	final result: PARTS.PNUM
3	3	2	3
10	10	1	10
8	8	0	8

which matches the result obtained by nested iteration.

6. Modified algorithm NEST-JA2

6.1 The Algorithm

The solutions to the bugs described in the previous section suggest a modified algorithm for transforming type-JA nested queries, which shall be called *algorithm NEST-JA2*. This algorithm consists of three major parts:

Algorithm NEST-JA2

1. Project the join column of the outer relation, and restrict it with any simple predicates applying to the outer relation.
2. Create a temporary relation, joining the inner relation with the projection of the outer relation. If the aggregate function is COUNT, the join must be an outer join, and the inner relation must be restricted and projected before the join is performed. If the aggregate function is COUNT(*), compute the COUNT function over the join column. The join predicate must use the same operator as the join predicate in the original query (except that it must be converted to the corresponding outer operator in the case of COUNT), and the join predicate in the original query must be changed to =. In the SELECT clause, select the join column from the outer table in the join predicate instead of the inner table. The GROUP BY clause will also contain columns from the outer relation.
3. Join the outer relation with the temporary relation, according to the transformed version of the original query.

To illustrate the action of algorithm NEST-JA2, let us apply it to Kiessling's query Q2. The three steps are then as follows:

```
1. TEMP1 (PPNUM) = SELECT   DISTINCT PNUM
                   FROM     PARTS;
2. TEMP2 (PNUM) = (SELECT   PNUM
                   FROM     SUPPLY
                   WHERE    SHIPDATE < 1-1-80);

   TEMP3 (PNUM,CT) =
          (SELECT   TEMP1.PNUM, COUNT(TEMP2.SHIPDATE)
           FROM     TEMP1, TEMP2
           WHERE    TEMP1.PNUM =+ TEMP2.PNUM
           GROUP BY TEMP1.PNUM);

3. SELECT   PNUM
   FROM     PARTS,TEMP3
   WHERE    PARTS.QOH = TEMP3.CT AND
            PARTS.PNUM = TEMP3.PNUM;
```

If these three steps are applied to the PARTS and SUPPLY relations with duplicates considered above, the results are:

TEMP1: PNUM	TEMP3: SUPPNUM	CT	final result: PARTS.PNUM
3	3	2	3
10	10	1	10
8	8	0	8

which matches the result obtained by nested iteration.

7. Analysis of Modified Algorithm NEST-JA2

The total cost of processing a type-JA nested query using the new algorithm NEST-JA2 will consist of three major sub-costs:

1. The projection and restriction of the outer table Ri, resulting in temporary table Rt2.
2. The creation of temporary relation Rt by projecting and restricting inner relation Rj, joining this with temporary table Rt2, and performing a GROUP BY operation on the result.
3. Joining temporary table Rt with outer table Ri.

These costs will be examined in detail below. For simplicity it will be assumed that nested queries are of depth one. The analyses will be presented using Kim's notation [KIM 82:462]: Ri denotes the relation of the outer query block, Rj the relation in the FROM clause of the inner query block, and Rt the temporary relation obtained by intermediate processing on Rj. Pk is the size in pages of relation Rk, and Nk is the number of tuples in Rk. Let f(i) denote the fraction of the tuples of Ri that satisfy all simple predicates on Ri. B denotes the size in pages of available main-memory buffer space. When it is necessary to sort a relation, a (B-1)-way multi-way merge sort is used, which requires $2*P*\log_{B-1}P$ page I/O's to sort a relation R [KIM 82:462]. The measure of performance is the number of disk page I/O's required, and for simplicity relations Ri and Rj are scanned sequentially.

7.1. Projection and Restriction of the Outer Table

The cost of creating a projection and restriction Rt2 from Ri, with duplicates removed, is

$$Pi + Pt2 + 2*Pt2*\log_{B-1}Pt2 \text{ page I/O's}$$

where the last term is the cost of removing duplicates using a (B-1)-way merge sort. This also sets up Rt2 in join column order for a merge join. Pt2 will be some fraction of Pi. Since Rt2 contains only tuples satisfying the simple predicates on Ri, Pt2 will be some fraction of f(i)*Pi, the fraction depending on the size of the column compared to the size of a tuple.

7.2. Creation of Temporary Table Rt

In the modified algorithm NEST-JA2, a join is required in the creation of the temporary relation from the inner relation. If the aggregate function in the inner block is COUNT(), this join will be an outer join. The inner relation is denoted Rj and Rt3 will designate a temporary relation created by projecting and restricting Rj. Rt3 is used to perform the join with Rt2, followed by the GROUP BY operation, to create the temporary relation Rt.

The cost of this join will depend on whether the nested iteration or the merge join method is used. The nested loops method will be efficient if the temporary relation Rt3 can fit into B-1 memory pages, with a cost of

$$Pj + Pt2 + Pt4 \text{ page I/O's},$$

where Rt4 is the result of the join. If, however, Rt3 does not fit into B-1 pages, Rt3 will have to be retrieved once for each tuple of Rt2, since Rt2 has already been restricted. The cost will be

$$Pj + Pt3 + Pt2 + Nt2*Pt3 + Pt4 \text{ page I/O's},$$

where the first two terms are the cost of creating Rt3.

If the merge join method is used, the cost will be

$$Pj + Pt3 + 2*Pt3*\log_{B-1}Pt3 + Pt2 + Pt3 + Pt4 \text{ page I/O's},$$

where the first three terms are the cost of building Rt3, sorting it and removing duplicates, and the last three terms are the cost of merge joining Rt2 with Rt3 and storing the result. The cost of sorting Rt2 is not included in the merge join cost, since this cost is subsumed by the cost of creating it with duplicates removed. In addition, performing a merge join to create Rt4 obviates the need to sort it for the GROUP BY operation, since the GROUP BY column is the join column.

If the aggregate function in the inner SELECT clause is COUNT(), an outer join must be used in the creation of temporary table Rt4. The merge join method of performing an outer join will have a cost function identical to that for a standard join, since the two relations are scanned in sorted order, and no extra cost is involved in determining which tuples have no matching tuples in the opposite relation. Rt4, the result of the join, may be slightly larger than if a standard join were performed, adding a small amount to the cost of the join. As in Kim's analyses, the joins performed following transformation will be assumed to be merge joins.

7.3. Join of Rt and Ri

The cost of joining temporary table Rt and outer table Ri will also depend on the kind of join used, but as will be seen below, a merge join of these relations can be particularly efficient, since Rt is already in join column order: a merge join will cost

$$2*Pi*\log_{B-1}Pi + Pi + Pt \text{ page fetches},$$

assuming Ri is not reduced in size, while a nested iteration join would cost

$$Pi + f(i)*Ni*Pt \text{ page fetches}.$$

7.4. Total Cost

The total cost of processing a single-level type-JA nested query using the modified algorithm NEST-JA2 will depend on the type of join used to create temporary relation Rt4 as shown above; it will also depend on the type of join used between the outer relation Ri and the temporary relation Rt. Thus there are four possible total costs for a single-level query, each of which may be estimated by the optimizer. One of these evaluation methods in particular is worthy of note: the use of two merge joins in the evaluation of the query. In evaluating the query by this method there will be cost savings in the merge joins from sorting relations earlier in the process: Rt2 is created in join column order, so it does not have to be sorted for the join with Rt3; Rt4 is created in GROUP BY column order, so it does not have to be sorted for the GROUP BY operation; and Rt is created in join column order, so it does not have to be sorted for the merge join with Ri. The total cost for this method is

$$\begin{aligned}&Pi + Pt2 + 2*Pt2*\log_{B-1}Pt2 +\\&Pj + Pt3 + 2*Pt3*\log_{B-1}Pt3 + Pt2 + Pt3 + 2*Pt4 + Pt +\\&2*Pi*\log_{B-1}Pi + Pi + Pt,\end{aligned}$$

assuming Ri is not reduced in size, and where the first three terms are the cost of projecting and restricting Ri, resulting in Rt2; the next eight terms are the cost of creating temporary table Rt, including the GROUP BY operation; and the last three terms are the cost of performing the final join.

The modified algorithm can be compared to the nested iteration method in the following example. Let the query to be evaluated be Kim's query Q3 [KIM 82:454] where the aggregate function is MAX(). Let Pi = 50, Pj = 30, Pt2 = 7, Pt3 = 10, Pt4 = 8, Pt = 5, B = 6, and f(i)*Ni = 100. The nested iteration method of processing Q3 costs 3050 page fetches in the worst case. The transformation approach, using the modified algorithm and two merge joins, costs about 475 page fetches.

8. Extensions: the Predicates EXISTS, NOT EXISTS, ANY, and ALL

In presenting his transformation algorithms, Kim considered nested predicates containing scalar and set inclusion operators. If the language is extended to include the useful operators EXISTS, ANY, and ALL, some extensions to the transformation algorithms must be implemented. The extensions proposed in this section are transformations of the predicates to predicates containing simple scalar or set containment operators. The query can then be processed by the transformation algorithms presented above.

8.1 EXISTS and NOT EXISTS

A nested predicate of the form

```
WHERE EXISTS    (SELECT   selitems
                 FROM     fromitems
                 WHERE    whereitems)
```

can be transformed to the semantically equivalent nested predicate

```
WHERE 0 <   (SELECT   COUNT (selitems)
             FROM     fromitems
             WHERE    whereitems)
```

Similarly, a nested predicate of the form

```
WHERE NOT EXISTS    (SELECT   selitems
                     FROM     fromitems
                     WHERE    whereitems)
```

is transformed to the semantically equivalent predicate

```
WHERE 0 =   (SELECT   COUNT (selitems)
             FROM     fromitems
             WHERE    whereitems)
```

The resulting predicate is then processed as a type-A or type-JA predicate, depending on the details of the inner query block.

8.2 ANY and ALL

A predicate of the form

```
< ANY   (SELECT   selitem
         FROM     fromitems
         WHERE    whereitems)
```

can be transformed to the logically (but not necessarily semantically) equivalent form

```
<   (SELECT   MAX(selitem)
     FROM     fromitems
     WHERE    whereitems)
```

The same transformation is performed when the operator is <= or !>. Conversely,

```
< ALL   (SELECT   selitem
         FROM     fromitems
         WHERE    whereitems)
```

is transformed to the logically equivalent predicate

```
<   (SELECT   MIN(selitem)
     FROM     fromitems
     WHERE    whereitems)
```

and the same transformation is performed when the operator is <= or !>. If the operator is >, >=, or !<, the transformation is the reverse:

```
> ANY (SELECT selitem
```

is transformed to

```
> (SELECT MIN(selitem)
```

and

```
> ALL (SELECT selitem
```

is transformed to

```
> (SELECT MAX(selitem).
```

More simply, a predicate of the form =ANY is transformed to IN, and a predicate of the form !=ANY is transformed to NOT IN.

9. Processing a General Nested Query

Algorithm NEST-JA2 applies to type-JA queries with a single level of nesting. The extension of the algorithm to type-JA queries with more than one level of nesting is not as simple as it was for algorithm NEST-N-J: the aggregate function and the join predicate may appear at any level of nesting, and not necessarily at the same level. Kim approaches the problem by means of *query graphs*: his algorithm NEST-G for transforming a general nested query gives the correct canonical result by inspecting and reducing the query graph for the query [KIM 82:465]. Rather than going into Kim's notations and methods, we will propose an alternative method for processing a general nested query, a direct postorder recursive algorithm which we believe is conceptually simple and which solves the problem of processing type-JA queries with greater than a single level of nesting.

9.1. Processing a General Nested Query: a Recursive Approach

The recursive version of algorithm NEST-G is described in the following pseudocode procedure *nest_g*(query_block), where the parameter *query_block* is a pointer to a SQL query block, possibly with descendant *inner query blocks* nested within it. The procedure is initially called with a pointer to the outermost query block (the beginning) of the query.

```
procedure nest_g(query_block)
  for each predicate in the WHERE clause of query_block
    if predicate is a nested predicate (i.e. contains inner query block)
    nest_g(inner_query_block)
      /*
       * Determine type of nesting, and call appropriate
       * transformation procedure.
       */
      if SELECT clause of inner_query_block contains aggregate function
        if inner_query_block contains join predicate referencing a relation
        which is not in its FROM clause
          /*
           * nesting is type-JA
           */
          nest_ja2(inner_query_block)
          nest_n_j(query_block,inner_query_block)
        else
          /*
           * nesting is type-A
           */
          nest_a(inner_query_block)
      else
  nest_n_j(query_block,inner_query_block)
  return
```

Three procedures are called by nest_g(): *nest_a()*, which evaluates inner_query_block, replacing it with the resulting constant; *nest_ja2()*, which executes algorithm NEST-JA2; and *nest_n_j()*, which executes Kim's algorithm NEST-N-J, combining the two query blocks query_block and inner_query_block. In explaining procedure *nest_g()* it is useful to model a nested query with a multi-way tree whose nodes are query blocks, where the outermost query block (the beginning of the SQL statement) is the root and the innermost query blocks are the leaves. Procedure *nest_g()* searches down through the levels of a nested query from the outermost query block until it finds the innermost query blocks (the leaves of the query tree). It then examines the leaf block to determine the type of nesting present, and transforms the parent to canonical form by calling the appropriate transformation procedures. After this is done for all nested predicates in query_block, the recursion then unwinds one level and the query block immediately above is processed in the same way, continuing the unwinding until lastly the outermost, or root, query block is transformed.

The algorithm represented in procedure *nest_g()* solves the problem of correctly transforming a type-JA query with multiple levels of nesting. To demonstrate this, let us assume the following query tree:

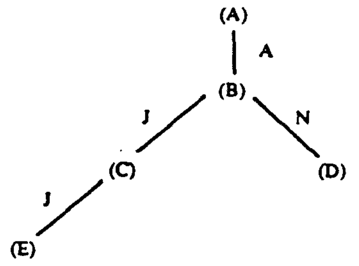

Figure 2: Example Query Tree

The edges of the tree are labelled with the kind of nesting present at that level. Query block B contains an aggregate function in its SELECT clause, and both C and E contain join predicates referencing tables in query blocks at a higher level. So far the most important feature with regard to processing the query has not been mentioned: does C or E contain a reference to a table in the FROM clause of A? This is important because it indicates whether there is typ-JA nesting present in the query: if one of the inner blocks, including B, contains a reference to a table in A, then type-JA nesting is present. In other words, a join predicate reference must span a query block containing an aggregate function for type-JA nesting to be present.

For example, assume the example query tree contains a reference in B, C, or E to a table in the FROM clause of A. Let us assume that E contains this reference, in a join predicate. Procedure *nest_g()* will travel down to E, unwind and apply algorithm NEST-N-J, combining C and E. This moves the reference to the table in A to block C. Then blocks C and B are combined, then blocks D and B. Now query block B has inherited the join predicate in block E, so that it contains both an aggregate function *and* a join predicate which references a table not found in the FROM clause of B: this is the definition of type-JA nesting. Thus, procedure *nest_ja2()* is called, which creates a temporary table with a GROUP BY clause as specified in algorithm NEST-JA2, and removes the aggregate function, replacing it with a reference to the column in the temporary table which results from the application of the aggregate function. This reduces the type-JA nesting to type-J nesting, and procedure *nest_n_j()* is immediately called to finish the job of reducing the query to canonical form. Thus type-JA nesting of deeper than one level can be detected by examining a single query block, which has inherited the "trans-aggregate" join predicate by the recursive transformation of inner query blocks, and the type-JA nested query can be transformed to canonical form by applying the single-level algorithm NEST-JA2.

From this example it can be seen that the advantage of the recursive algorithm presented in procedure *nest_g()* is simplicity: the information needed to transform a query block containing a nested predicate is confined to two levels of the query: the outer level (the level containing the nested predicate) and the inner.

10. Summary

The nested iteration method of evaluating nested SQL queries can be inefficient for many queries: a relation referred to in an inner query block may have to be retrieved many times, possibly once for each tuple in the outer query block. Won Kim classified nested queries and proposed algorithms to reduce the cost of evaluating them [KIM 82]. The objective of his algorithms is to reduce the nested query to an equivalent single-level, or canonical, form. The resulting canonical query will contain explicit joins which capture the nested-iteration semantics of the original query, and can now be passed to a query optimizer which will determine an efficient order and method for the evaluation of the query. Kim compared the cost of evaluating a nested query by nested iteration and the cost of evaluating a transformed query using merge joins in several examples. The transformation method resulted in costs sometimes an order of magnitude smaller than the costs required by the nested iteration method. However, a bug in

Kim's algorithm NEST-JA was discovered by Werner Kiessling [KIE 84]. Another bug in the same algorithm has been demonstrated in section 5. These bugs can be solved by performing a join in the creation of the temporary table which contains the aggregate information. If the aggregate function is COUNT, the join must be an outer join. This solution requires the join to be performed on a projection of the outer table in order to avoid an increase in the aggregate values due to duplicates in the outer table. The solutions to these bugs are incorporated into algorithm NEST-JA2, which retains Kim's strategy of building a temporary table to capture aggregate information, and which yields a cost reduction similar to that achieved by Kim in his example. The transformation algorithms have been extended to handle a larger class of predicates, and a recursive algorithm has been presented which will apply the transformations to a nested query of arbitrary complexity.

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