Recent PostgreSQL Optimizer Improvements

Tom Lane

PostgreSQL - Red Hat Edition Group

Red Hat, Inc.

Outline

I plan to divide this talk into two roughly equal parts:

1. **What's a query optimizer, anyway?**
   - There are multiple possible query plans
   - We need to devise a good plan, as quickly as possible
2. **What's new in PostgreSQL 7.4?**
   - Several important planner improvements are coming
   - Hashing is used much more than before
   - `WHERE foo IN (SELECT ...)` is much smarter than before

Steps of planner operation

Query transformation Try to transform the query into an equivalent, but more-efficient-to-execute, query.

Query analysis Derive information about the query.

Plan generation Systematically consider alternative query plans, estimate execution costs of each one, choose the one with lowest estimated cost.

There is some overlap between query transformation and query analysis, but it’s useful to think of them as separate operations.

Query transformation: flattening sub-SELECTs

The first major step in query transformation is to pull up sub-SELECTs in the FROM clause into the main query. The sub-SELECTs could have been written by the user, or could have been expanded from view references.

For example, suppose we have the original query

```
SELECT ... FROM aview, mytable
WHERE aview.key = mytable.ref;
```

and `aview` is a view defined like this:

```
CREATE VIEW aview AS
    SELECT basetable.key, ...
    FROM basetable, anothertable
    WHERE basetable.key = anothertable.aref;
```

Query transformation: flattening sub-SELECTs

View expansion would transform the query to this:

```
SELECT ... FROM
    (SELECT ... FROM basetable, anothertable
     WHERE basetable.key = anothertable.aref) AS aview,
    mytable
WHERE aview.key = mytable.ref;
```

Now the planner can flatten this into:

```
SELECT ... FROM
    basetable, anothertable, mytable
WHERE basetable.key = anothertable.aref AND
      basetable.key = mytable.ref;
```

Now we have the ability to consider different join orders, which the sub-SELECT form would not let us do.

Query transformation: expand functions in-line

Simple SQL functions (those that just compute a single expression's result) are expanded in-line, like macros.

For example, the built-in function `log(numeric)` is defined as

```
    CREATE FUNCTION log(numeric) RETURNS numeric AS
    'SELECT log(10, $1)' LANGUAGE SQL;
```

so

```
    SELECT log(numfld) FROM foo;
```

becomes

```
    SELECT log(10, numfld) FROM foo;
```

thus avoiding one level of function call at runtime.

This expansion is new in 7.4.

Query transformation: simplify constant expressions

For example, 2+2 is reduced to 4.

This is more useful than it might look. Although perhaps a user wouldn't write a query containing obvious constant subexpressions, the previous transformations often expose opportunities for expression simplification.

Evaluating a subexpression once during planning beats doing it once for each row of the query.

Query analysis

In query analysis operations, we begin to disassemble the query into the pieces that the main planning steps will deal with.

One interesting step examines the equality constraints enforced by the query's WHERE clause. This is useful primarily because it lets the planner make inferences about sort order: if we have `WHERE a = b`, then join output that is sorted by `a` is also sorted by `b`. Knowing this might let us save a sort step.

A valuable byproduct of determining the equality properties is that we can deduce implied equalities. Consider our previous example:

```
SELECT ... FROM
    basetable, anothertable, mytable
WHERE basetable.key = anothertable.aref AND
      basetable.key = mytable.ref;
```

Query analysis: deducing implied equality

We can deduce that `aref` and `ref` must be equal, since they're both equal to `key`. So the query is effectively transformed to

```
SELECT ... FROM
    basetable, anothertable, mytable
WHERE basetable.key = anothertable.aref AND
      basetable.key = mytable.ref AND
      anothertable.aref = mytable.ref;
```

This opens the possibility of joining `anothertable` to `mytable` first, which could be a win if they're both small while `basetable` is large.

Although this appears to add a redundant comparison to the query, whichever comparison ends up being the third to be checked will be discarded; so there's no runtime penalty.

Query analysis: even more implied equality

In 7.3 and earlier, equality deduction only happened for equality clauses relating simple variables, but in 7.4 it happens for equality clauses relating any expressions.[1]

For example, consider

```
SELECT * FROM aview WHERE key = 42;
```

After view expansion and flattening, this becomes

```
SELECT ... FROM basetable, anothertable
WHERE basetable.key = anothertable.aref AND
      basetable.key = 42;
```

[1]Except those containing volatile functions.

Query analysis: even more implied equality

Implied equality deduction will (in 7.4) expand this to:

```
SELECT ... FROM basetable, anothertable
WHERE basetable.key = anothertable.aref AND
      basetable.key = 42 AND
      anothertable.aref = 42;
```

and now the `key = aref` comparison is found to be redundant, leaving:

```
SELECT ... FROM basetable, anothertable
WHERE basetable.key = 42 AND
      anothertable.aref = 42;
```

In this form the query is trivial to build an efficient plan for. Note that the user could not have expressed the query in this way to begin with; `aview` might not have exposed `anothertable.aref` to him at all.

Query analysis: distribution of WHERE clauses

Next we attach WHERE clauses to the lowest level at which they can be evaluated. A clause mentioning just a single table (`a.x = 42`) is attached to that table. It will get used when we prepare scan plans for that table. Join clauses (`a.x = b.y`) are attached to data structures representing the sets of tables they mention; they'll be used when we form a join including all the tables mentioned.

If we have a WHERE clause that mentions only outputs of a sub-SELECT (one that's not been flattened), we try to push it down inside the sub-SELECT. There are semantic restrictions on whether we can do this without changing the results, though. 7.4 analyzes the situation more carefully than prior releases and is able to push down such clauses in more cases.

The main planning process

After all the preparatory work is done, we generate possible plans and estimate costs.

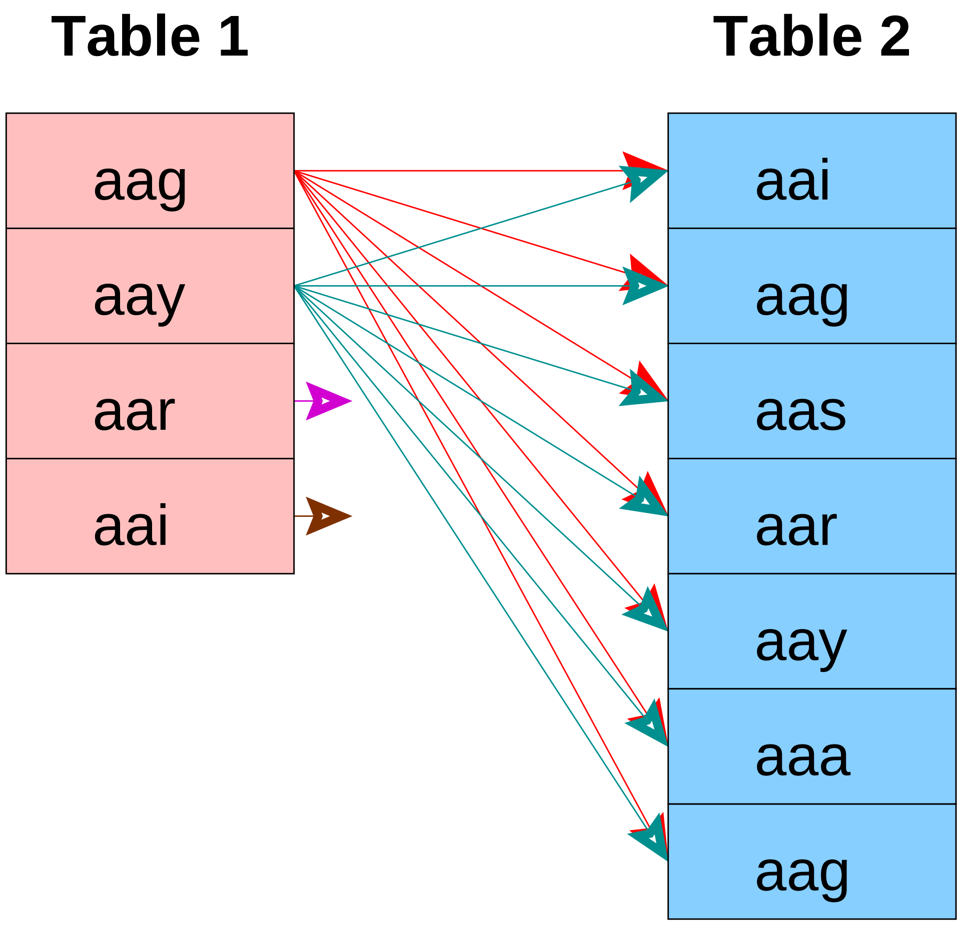
First, generate possible scan plans for each individual table: simple sequential scan is always possible, as well as index scans using each of the indexes that are relevant to the query. Estimate execution cost for each.

If there’s only one table, we’re done — just take the cheapest plan.

If there’s more than one table, generate join plans for each pair of tables. We can do simple nestloop, nestloop with inner index scan, merge join, or hash join. Merge join needs sorted inputs, so there are multiple possibilities depending on whether we perform explicit sort steps or use presorted inputs (for instance, the result of an index scan is already sorted, if it’s a btree index).

Types of join plans

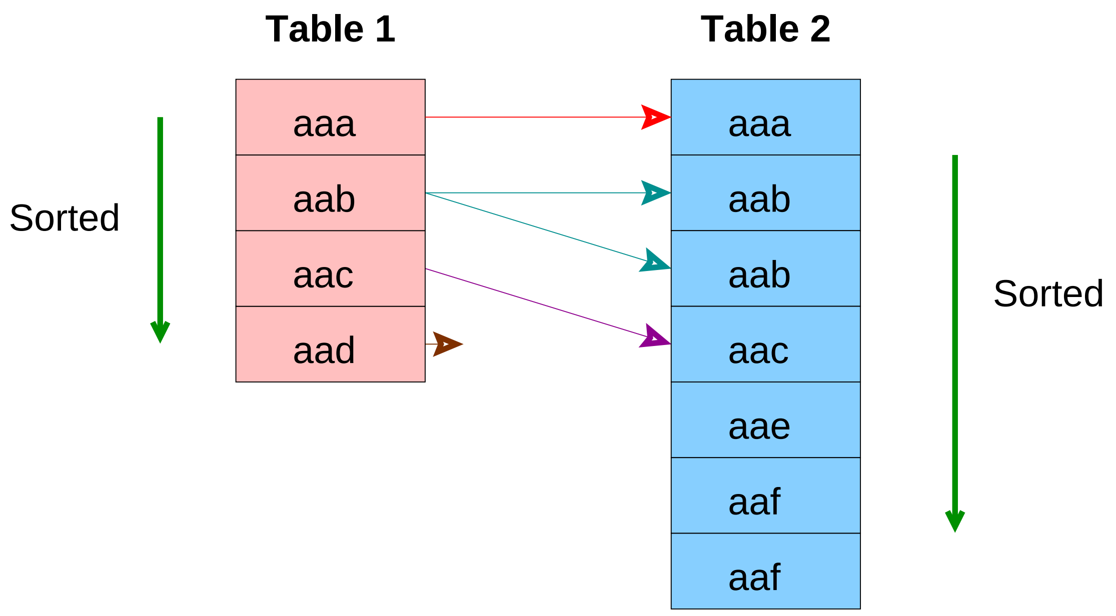
Nested Loop



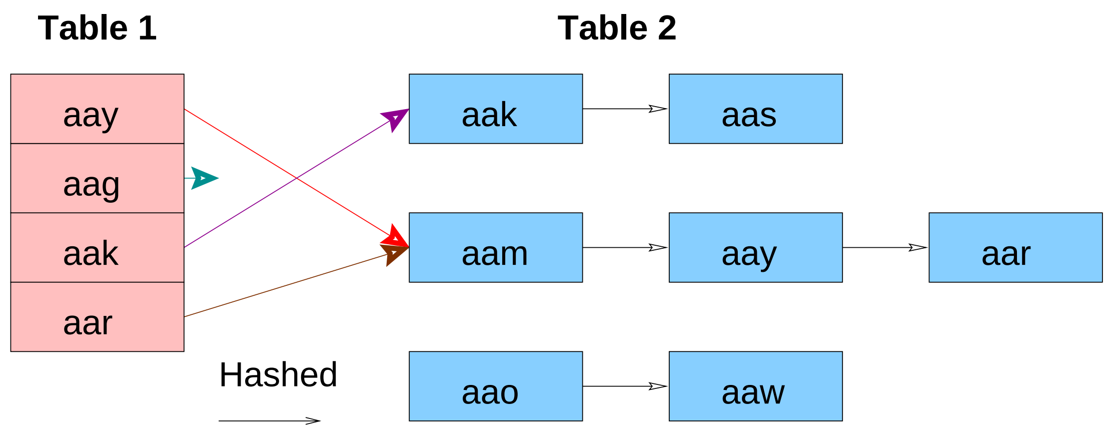
Nested loop with inner index scan uses an index on Table 2 to fetch just the rows matching the current Table 1 row.

Types of join plans

Merge Join



Hash Join



The main planning process, continued

Next (if there's at least three tables) look for ways to join pairs of tables to individual tables to make three-way joined relations, using the cheapest pairwise joins we found before.

For example, given

```
    SELECT ... FROM tab1, tab2, tab3
    WHERE tab1.col1 = tab2.col2 AND tab1.col3 = tab3.col4;
```

the first pass generates sequential and index scan plans for each of `tab1`, `tab2`, `tab3` separately. The second pass generates plans that join `tab1` and `tab2`, as well as plans that join `tab1` and `tab3`. (We could also consider plans that join `tab2` and `tab3`, but this avenue is rejected because there is no WHERE clause that constrains that join, so we'd have to generate the entire cross-product of those two tables.) Finally, the third pass generates plans that combine `tab3` with the join of `tab1` and `tab2`, and also plans that combine `tab2` with the join of `tab1` and `tab3`.

The main planning process, continued

Any of these sequences might be the cheapest way to compute the result, depending on factors such as the sizes of the tables, the constraints specified in the query's WHERE clause, and the available indexes.

If we have more tables, we next look for ways to make four-way joins, five-way joins, etc, until we have joined all the tables in the query. Each pass uses the results of prior passes.

Once we have the best plans for the complete join set, we are almost done. We just add on any additional steps needed for grouping, aggregation, or sorting (if specified by the query), and we're done.

Which plans do we need to keep at each level?

It turns out that it's not sufficient to remember just the cheapest plan for each set of joined tables. Because mergejoin needs sorted input, it may be better to use a more-expensive subplan that delivers appropriately sorted results than to use the cheapest subplan and then do an explicit sort.

For example, if we need to join on a clause like `WHERE tab1.col1 = tab2.col2`, and there is an index on `tab1.col1`, then the cheapest plan for scanning `tab1` is a sequential scan. A full index scan using the index on `col1` is certainly going to be slower. But the indexscan could be used directly as an input for merge join, so it might be better to use that than to do a sequential scan and sort.

We end up keeping the cheapest plan for each interesting sort order (where "interesting" means "is related to a candidate merge join clause or an `ORDER BY` or `GROUP BY` key"). So usually there will be several plans for a given table or join set that survive for consideration at the next level.

Better implementation of WHERE foo IN (SELECT . . .)

We used to implement `IN (SELECT ...)` in the crudest way possible: each time the value of the condition is needed (possibly once for every row of the outer query), run the sub-SELECT to see if it produces a row matching the left-hand side. This is essentially a nestloop join, and it's really slow if either the outer query or the sub-SELECT has a lot of rows.

Some people hand-optimize `IN` into `EXISTS`:

```
SELECT ... WHERE col IN (SELECT subcol FROM subtab);
```

becomes

```
SELECT ... WHERE
EXISTS (SELECT * FROM subtab WHERE subcol = col);
```

This still is a nestloop — but if `subtab.subcol` is indexed, you can at least make it be a nestloop with inner indexscan.

Better implementation of WHERE foo IN (SELECT . . .)

7.4 has several other ways to do `IN`:

Special-purpose hash table code Load the rows of the sub-SELECT into an in-memory hash table, and then probe the hash table for each outer row.

Semi-join Convert the `IN` to a semi-join and apply the standard planning process to discover the best join plan. ("Semi-join" is a join that emits only those left-hand rows that join to at least one right-hand row, and only once each.)

DISTINCT followed by regular join Run the output of the sub-SELECT through a DISTINCT filter (to eliminate duplicate rows) and then treat the `IN` like a simple equality join.

Better IN (SELECT . . .): special-purpose hash table

The nasty thing about `IN` is that the SQL spec dictates that certain cases involving NULLs in the sub-SELECT result should cause the `IN` to yield “unknown” (NULL) rather than “false” when it’s unable to find matching rows. An ordinary hash join can’t handle this, especially not for a multi-column `IN` where rows may be only partly NULL.

By making special entries for rows that are wholly or partly NULL, we were able to make the special-purpose hash table code produce fully spec-compliant results for `IN`. Therefore, we can also use this code for `NOT IN` and for cases where the `IN` operator is nested inside other boolean operations.

A limitation is that the hash table will perform badly, or even fail outright, if the sub-SELECT produces more rows than will fit in memory.

Better IN (SELECT . . .): semi-join

In the semi-join approach, we plan the query as if the `IN` were a simple equality join; that is,

```
SELECT ... FROM tab
WHERE foo IN (SELECT bar FROM subtab)
```

is almost the same as

```
SELECT ... FROM tab, subtab
WHERE foo = bar;
```

The main difference is that we only want one output row for each `tab` that has one or more matches in `subtab`. We handle this by applying a special “join rule” in the join plan step. The join rule requires that `tab` be the outer side of the join, and it just stops looking for inner matches as soon as it finds one. (This is sort of the reverse of what happens for a left outer join.)

Better IN (SELECT . . .): semi-join

When we implement `IN` this way, we cannot tell the difference between cases where `IN` should deliver a FALSE result and cases where it should deliver a NULL result. Therefore the semi-join approach can only be used when `IN` appears at the top level of WHERE (and it can't be `NOT IN`). In that context the difference between FALSE and NULL doesn't matter.

Considering again

```
   SELECT ... WHERE col IN (SELECT subcol FROM subtab);
```

where `subtab.subcol` is indexed, one of the semi-join possibilities is to use a nestloop with inner index scan on `subtab`. Thus, the system can now automatically discover the alternative that you used to have to use `EXISTS` to get it to take notice of. Not only that, but it can also consider merge or hash joins, which might be considerably superior depending on the numbers of rows involved.

Better IN (SELECT . . .): DISTINCT followed by join

If we eliminate duplicate rows from the result of the sub-SELECT, then we can just join it to the outer query with a regular equality join — we've ensured there can't be multiple output rows for a single outer-query row.

Again, this only works at the top level of WHERE. Its advantage over the semi-join way is that the distinct-ified sub-SELECT can be either the inner side or the outer side of the resulting join plan.

Consider

```
SELECT * FROM big_table
WHERE key IN (SELECT id FROM small_table);
```

If `big_table.key` is indexed, then it's probably going to be best to change the sub-SELECT to SELECT DISTINCT and use the result as the outer side of a nestloop with inner index scan. This is the only implementation that can avoid reading all the rows of `big_table`.

Better IN (SELECT . . .): which way should we use?

When `IN` appears at the top level of WHERE, the 7.4 planner converts the `IN` to either a semi-join or DISTINCT-and-join plan. It uses its normal approach of estimating costs to choose which plan to use.

When we have `NOT IN` at top level, or either `IN` or `NOT IN` below the top level of WHERE, we use the specialized hash table code if we estimate the table will fit into `SORT_MEM` kilobytes of memory. Otherwise we fall back to the old nested-loop implementation.

There isn't any need to consider the specialized hash code as an alternative for a top-level `IN`, since a semi-join using a hash join plan does approximately the same thing. We don't need to explicitly consider falling back to the old nestloop-like implementation either, since a semi-join using a nestloop join plan is equivalent to that. These possibilities will be automatically considered along with the other alternatives.

Hash-based grouping and grouped aggregation

In 7.3 and before, if you write `GROUP BY foo`, the implementation always involves scanning the input in order by `foo` (via either an explicit sort or an indexscan). Then group boundaries are detected by comparing the `foo` column or columns in successive rows. If we are aggregating, we run the aggregate accumulation functions on each row as it arrives, then emit results when the end of a group is detected.

In 7.4, there is another alternative, which is to load the incoming data into an in-memory hash table indexed by the grouping columns. After we have read all the input data, we traverse the hash table and emit one result row for each hash entry; that is, one result for each group.

Hash-based grouping and grouped aggregation

If we are aggregating, we still run the accumulation functions on each row as it arrives. The hash table entry for each group has to hold the transient state for each aggregate. So this way is more memory-intensive than the old way, but as long as there are not too many groups, it's not a problem.

The big advantage of the hash-based approach is that we don't have to pre-sort the input. A disadvantage is that the output will appear in no particular order. So if you asked for `GROUP BY foo ORDER BY foo`, we have to do an explicit sort of the output instead. This can still be a big win though, since there are likely to be many fewer output rows than input rows.

The planner chooses between these two approaches in its usual way: estimate the costs of both and pick the cheaper one. It also checks whether the hash table is expected to fit in `SORT_MEM` kilobytes — if not, it won't use hashing.

Merge and hash joins on expressions

The merge and hash join methods were formerly considered only for join clauses that equated two simple variables (`a.x = b.y`). Now they are considered for join clauses that equate any expressions over different sets of tables.

For example,

```
    SELECT * FROM a, b WHERE a.foo = b.bar + 1;
```

is now a candidate for merge or hash joining, whereas before 7.4 it would always have been done as a brute-force nestloop join.

Also, a hash join can use multiple hash keys rather than only one.

Explicit JOIN syntax decoupled from execution plans

Postgres supports the SQL92-spec syntax for joins:

```
SELECT ... FROM tab1 LEFT JOIN tab2 ON condition ...
SELECT ... FROM tab1 [INNER] JOIN tab2 ON condition ...
```

When there are nested JOIN constructs, the 7.3 planner does not search for the best join order — it only considers the join order that corresponds to the JOIN syntax structure. This is semantically necessary for many situations involving outer joins, but if the joins are all INNER then JOIN is really just another way to write FROM tab1, tab2 . . . WHERE . . .

Explicit JOIN syntax decoupled from execution plans

On the plus side, this behavior can cut planning time dramatically for many-table queries.

On the minus side, you may get a very bad plan if the forced join order isn't a good choice.

As of 7.4, the default behavior will be to consider only outer JOINs as constraining the join order. When you write nested inner JOINs you'll get a search for the best join order.

If you already have a good join order and you need to cut planning time, you can get the old behavior by setting `JOIN_COLLAPSE_LIMIT` to 1.

A success story

A few months ago, the Ars Digita guys (who now work at Red Hat) came to me for help with porting their ACS system to PostgreSQL. They had problems with four queries that were used in displaying web pages in ACS. These queries each took several seconds to execute in PostgreSQL, making the performance unacceptable. The same queries ran fine in Oracle.

But . . . they were testing on PostgreSQL 7.2.

I was able to tell them that all their problems were already solved.

A success story

Measured runtimes for the problem queries (same data, same machine):

	PG 7.2	PG 7.3	As of 14-Mar-03
Query 1	4560.62 msec	4461.84 msec	213.14 msec

Win from: searching for good join order instead of following JOIN structure

	PG 7.2	PG 7.3	As of 14-Mar-03
Query 2	6612.94 msec	1.27 msec	1.05 msec

Win from: pushing down WHERE clauses into UNION (already done in 7.3)

	PG 7.2	PG 7.3	As of 14-Mar-03
Query 3	10375.64 msec	3276.02 msec	3.23 msec

7.3 win from: evaluating IN last among clauses attached to same plan node

7.4 win from: converting IN to special-purpose hash table

	PG 7.2	PG 7.3	As of 14-Mar-03
Query 4	3314.57 msec	2729.78 msec	0.54 msec

Win from: searching for good join order

A success story

Mind you, these are pretty ugly queries — here’s the first one:

```
select *
from (select *
      from vc_objects join acs_objects
      on (vc_objects.object_id=acs_objects.object_id)
      join cms_items
      on (vc_objects.object_id=cms_items.item_id)) results
where (cms_items__ancestors<='19056/')
      and (cms_items__ancestors=substr('19056/',1,
                length(cms_items__ancestors)))
order by cms_items__ancestors;
```

But they are real-world examples.

Summary

There's lots of good new stuff coming in 7.4.

Since internal hash tables are options in many more places than before, and each one can use up to `SORT_MEM` kilobytes, it's more important than ever to make sure you set that parameter intelligently. Too small will handicap performance by preventing hash-based plans from being considered, but too large can drive your system into swap hell.

If you've hand-optimized `IN` queries into `EXISTS` queries, you might want to think about switching back. Under 7.4 using `EXISTS` could be a de-optimization, because it constrains the planner to use only one of the types of plans it would consider if you used `IN`.