Inside the PostgreSQL Query Optimizer

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Outline

- Introduction to query optimization
- Outline of query processing
- Basic planner algorithm
- Planning specific SQL constructs
- Questions welcome throughout

What is query optimization?

- SQL is declarative; the user specifies **what** the query returns, not **how** it should be executed
- There are many equivalences in SQL:
  - Joins can be applied in any order
  - Predicates can be evaluated in any order
  - Subselects can be transformed into joins
- Several different methods of doing the same operation:
  - Three core join algorithms (nested loops, hash join, merge join)
  - Two aggregation algorithms (hashing, sorting)
  - Two scan algorithms (index scan, sequential scan)
- For a non-trivial query there are many alternative plans

Outline of query processing

- Client connects to `postmaster` via TCP or unix domain socket, communicates via frontend-backend protocol
- `fork` new backend to handle connection
- Authentication in new backend
- Enter simple query loop
  - Client submits query
  - Backend executes query, returns result set

Query loop

1. Lex and parse — `flex`, `bison`
   - **Input:** query string
   - **Output:** “raw parsetree”
   - No database access or semantic analysis
2. Analysis
   - **Input:** raw parsetree
   - **Output:** `Query`
     - Essentially, annotated parsetree — do database lookups for metadata
3. Rewriter
   - **Input:** `Query`
   - **Output:** One or more `Query`
   - Apply rewrite rules: `CREATE RULE`, `CREATE VIEW`

Query loop, cont.

- Already done: we understand the syntax of the query and have looked up associated metadata and applied some basic semantic checks
- If this is a "utility command" (`CREATE`, `ALTER`, `DROP`, etc.), hand off to the implementation of the command
- Otherwise, remaining work:
  - Decide how to evaluate the query, produce a `Plan`
  - Evaluate the `Plan` and return result set to client
- The query planner is what determines the best way to evaluate a query; also known as the "query optimizer". This requires:
  1. Determining the set of possible plans
  2. Choosing the "best" plan from this set

Representation of query plans

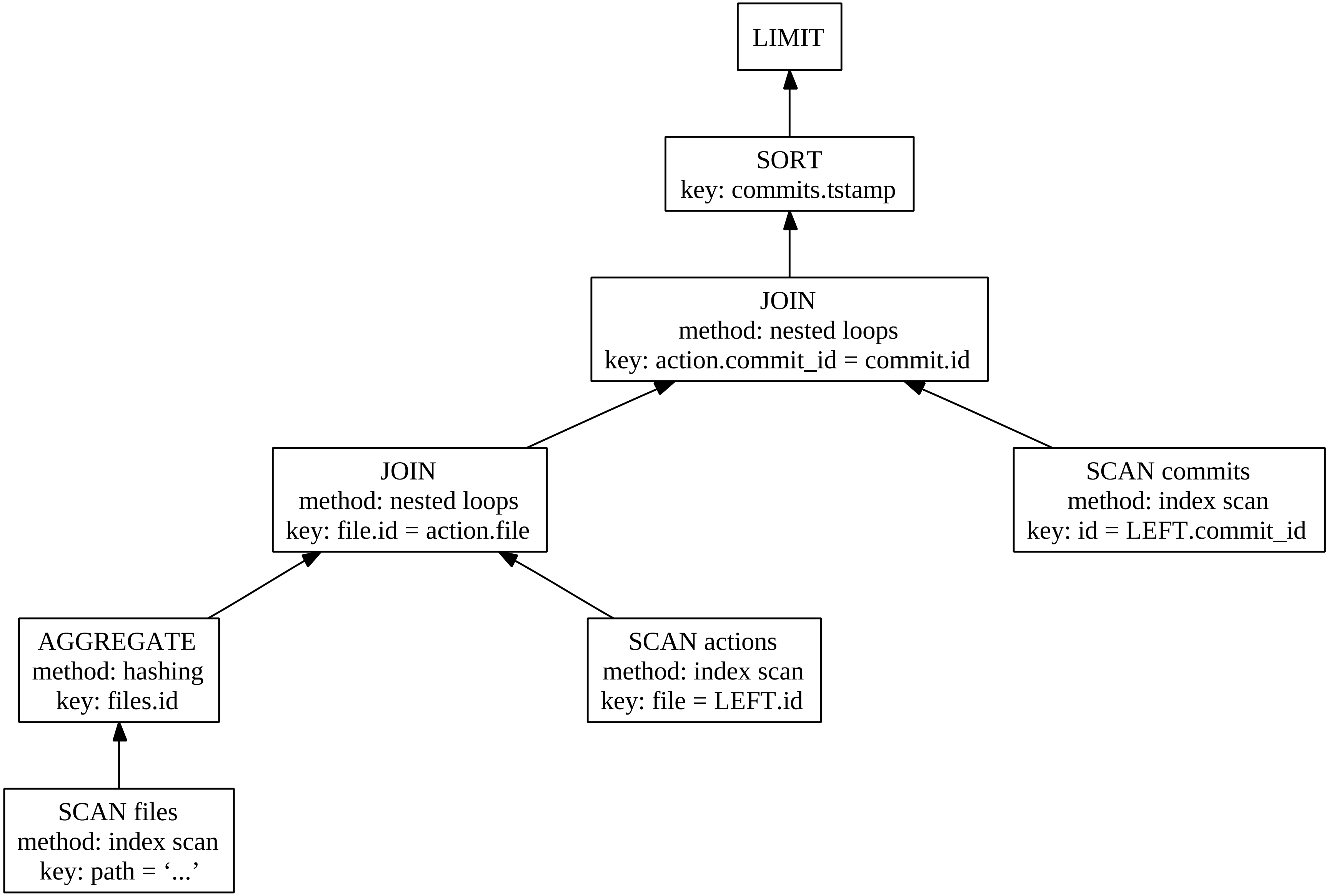
- We represent "how" to execute a query as a tree of plan nodes; each node is a single operation (join, disk scan, sort, etc.)
- Tuples flow from the leaves of the tree (disk scans) up to the root
- Results delivered to parent node "on demand"
  - To get a row, a node "pulls" on its child node, which in turns pulls on its child nodes as needed
- To produce result set, executor just pulls on root node
  - Guts of query execution is in the implementation of plan nodes
- In general, plan nodes are asymmetric: left and right inputs treated differently

Example query

- Database stores CVS commit history
- A commit modifies n files; each such modification is an "action"
- Query: find the timestamp of the latest commit to modify given a file f

`SELECT c.tstamp`	target list
`FROM commits c, actions a`	range table
`WHERE a.file IN`	qualifier
`    (SELECT id FROM files`	`IN`-clause subquery
`     WHERE path = '...')`	
`AND a.commit_id = c.id`	join predicate
`ORDER BY c.tstamp DESC`	sort order
`LIMIT 1;`	limit expression

Example query plan



What makes a good plan?

- The planner chooses between plans based on their estimated **cost**
- **Assumption:** disk IO dominates the cost of query processing. Therefore, pick the plan that requires least disk IO
  - Random IO is (much) more expensive than sequential IO on modern hardware
- Estimate I/O required by trying to predict the size of intermediate result sets, using database statistics gathered by ANALYZE
  - This is an imperfect science, at best
- Distinguish between "startup cost" (IOs required for first tuple) and "total cost"

General optimization principles

- The cost of a node is a function of its input: the number of rows produced by child nodes and the distribution of their values. Therefore:
  1. Reordering plan nodes changes everything
  2. A poor choice near the leaves of the plan tree could spell disaster
     - Keep this in mind when debugging poorly performing plans
  3. Apply predicates early, so as to reduce the size of intermediate result sets
- Worth keeping track of sort order — given sorted input, certain plan nodes are cheaper to execute
- Planning joins effectively is essential

Planner algorithm

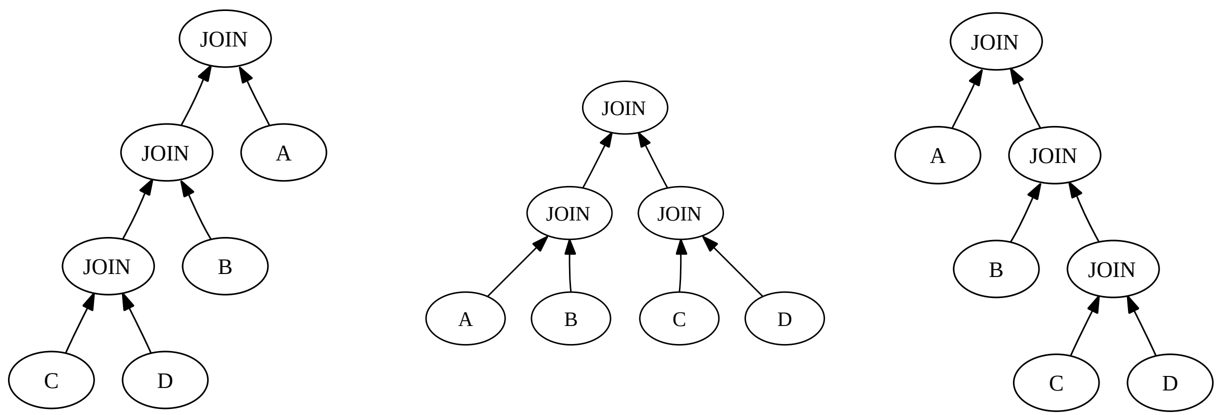
- Conceptually, three phases:
  1. Enumerate all the available plans
  2. Assess the cost of each plan
  3. Choose the cheapest plan
- Naturally this would not be very efficient
- “System R algorithm” is commonly used — a dynamic programming algorithm invented by IBM in the 1970s
- Basic idea: find “good” plans for a simplified query with n joins. To find good plans for $n + 1$ joins, join each plan with an additional relation. Repeat

System R algorithm

1. Consider each base relation. Consider sequential scan and available index scans, applying predicates that involve this base relation. Remember:
   - Cheapest unordered plan
   - Cheapest plan for each sort order
2. While candidate plans have fewer joins than required, join each candidate plan with a relation not yet in that plan. Retain:
   - Cheapest unordered plan for each distinct set of relations
   - Cheapest plan with a given sort order for each distinct set of relations

System R algorithm, cont.

- Grouping (aggregation) and sorting is done at the end
- Consider "left-deep", "bushy", and "right-deep" plans (some planners only consider left-deep plans)



- The number of plans considered explodes as the number of joins increases; for queries with many joins (≥ 12 by default), a genetic algorithm is used ("GEQO")
  - Non-exhaustive, non-deterministic search of possible left-deep join orders

Planning outer joins

- Outer join: like an inner join, except include unmatched join tuples in the result set
- Inner join operator is both commutative and associative: $A \bowtie B \equiv B \bowtie A$, $A \bowtie (B \bowtie C) \equiv (A \bowtie B) \bowtie C$
- In general, outer joins are neither associative nor commutative, so we can't reorder them
- Main difference is fewer options for join order; a pair of relations specified by `OUTER JOIN` is effectively a single base relation in the planner algorithm
- Sometimes outer joins can be converted to inner joins: `SELECT * FROM a LEFT JOIN b WHERE b.x =` k
- **Tip:** you can force join order for inner joins by using `JOIN` syntax with `join_collapse_limit` set to 1

Planning subqueries

- Three types of subqueries: `IN`-clause, `FROM`-list, and expression
- We always "pull up" `IN`-clause subqueries to become a special kind of join in the parent query
- We try to pull up `FROM`-list subqueries to become joins in the parent query
  - This can be done if the subquery is simple: no `GROUP BY`, aggregates, `HAVING`, `ORDER BY`
  - Otherwise, evaluate subquery via separate plan node (`SubqueryScan`) — akin to a sequential scan

FROM-list subquery example

```
SELECT * FROM t1,
    (SELECT * FROM t2 WHERE t2.x = 10) t2
  WHERE t1.id = t2.id;

-- converted by the optimizer into
SELECT * FROM t1, t2
  WHERE t1.id = t2.id and t2.x = 10;
```

- Subquery pullup allows the planner to reuse all the machinery for optimizing joins
- Integrating subquery qualifiers into the parent query can mean we can optimize the parent query better

Planning expression subqueries

- Produce nested `Plan` by recursive invocation of planner
- An “uncorrelated” subquery does not reference any variables from its parent query; it will therefore remain constant for a given database snapshot.

```
SELECT foo FROM bar WHERE bar.id =
  (SELECT baz.id FROM baz
   WHERE baz.quux = 100);
```

- If uncorrelated, only need to evaluate the subquery once per parent query

```
$var = SELECT id FROM baz WHERE quux = 100;
SELECT foo FROM bar WHERE id = $var;
```

- If correlated, we need to repeatedly evaluate the subquery during the execution of the parent query

Planning functions

- Planner mostly treats functions as “black boxes”
  - For example, set-returning functions in the `FROM` list are represented as a separate plan node (`FunctionScan`)
  - Can’t effectively predict the cost of function evaluation or result size of a set-returning function
- We can inline a function call if:
  - Defined in SQL
  - Used in an expression context (not `FROM` list — room for improvement)
  - Sufficiently simple: “SELECT ...”
- If invoked with all-constant parameters and not marked “volatile”, we can preevaluate a function call

Function inlining example

```
CREATE FUNCTION mul(int, int) RETURNS int AS
    'SELECT $1 * $2' LANGUAGE sql;
SELECT * FROM emp
    WHERE mul(salary, age) > 1000000;

-- after function inlining, essentially
SELECT * FROM emp
    WHERE (salary * age) > 1000000;
```

- The inlined form of the query allows the optimizer to look inside the function definition to predict the number of rows satisfied by the predicate
- Also avoids function call overhead, although this is small anyway

Planning set operations

- Planning for set operations is somewhat primitive
- Generate plans for child queries, then add a node to concatenate the result sets together
- Some set operations require more work:
  - `UNION`: sort and remove duplicates
  - `EXCEPT [ ALL ], INTERSECT [ ALL ]`: sort and remove duplicates, then produce result set via a linear scan
- Note that we never consider any alternatives, so planning is pretty simple (patches welcome)

Potential improvements

Hard:

- Database statistics for correlation between columns
- Function optimization
- Rewrite GEQO

Crazy:

- Online statistics gathering
- Executor $\rightarrow$ optimizer online feedback
- Parallel query processing on a single machine (one query on multiple CPUs concurrently)
- Distributed query processing (over the network)

Questions?

Thank you.

Using EXPLAIN

- `EXPLAIN` prints the plan chosen for a given query, plus the estimated cost and result set size of each plan node
- Primary planner debugging tool; `EXPLAIN ANALYZE` compares planner's guesses to reality
  - Executes the query with per-plan-node instrumentation

EXPLAIN output

```
EXPLAIN ANALYZE SELECT c.tstamp FROM commits c, actions a WHERE a.file IN
    (SELECT id FROM files WHERE path = '...')
AND a.commit_id = c.id ORDER BY c.tstamp DESC LIMIT 1;

Limit (cost=135.79..135.80 rows=1 width=8)
      (actual time=4.458..4.459 rows=1 loops=1)
 -> Sort (cost=135.79..135.84 rows=20 width=8)
         (actual time=4.455..4.455 rows=1 loops=1)
    Sort Key: c.tstamp
    -> Nested Loop (cost=5.91..135.36 rows=20 width=8)
                   (actual time=0.101..4.047 rows=178 loops=1)
       -> Nested Loop (cost=5.91..74.84 rows=20 width=4)
                      (actual time=0.078..0.938 rows=178 loops=1)
          -> HashAggregate (cost=5.91..5.91 rows=1 width=4)
                           (actual time=0.050..0.052 rows=1 loops=1)
             -> Index Scan on files (cost=0.00..5.91 rows=1 width=4)
                                    (actual time=0.035..0.038 rows=1 loops=1)
          -> Index Scan on actions a (cost=0.00..68.68 rows=20 width=8)
                                     (actual time=0.022..0.599 rows=178 loops=1)
       -> Index Scan on commits c (cost=0.00..3.01 rows=1 width=12)
                                  (actual time=0.012..0.013 rows=1 loops=178)
Total runtime: 4.666 ms
```