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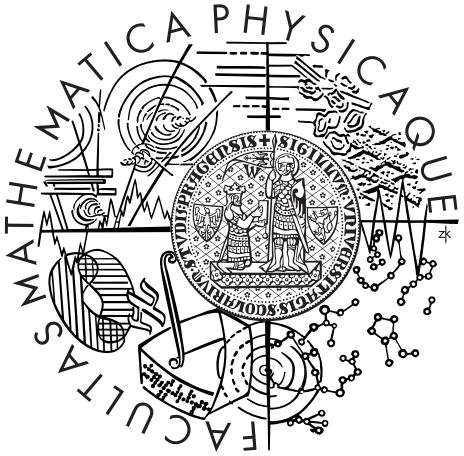

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Evaluating relational queries in pipeline-based environment

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I would like to thank my parents for supporting me in my studies and my supervisor David Bednárek for his advice and help with this thesis.

I declare that I carried out this master thesis independently, and only with the cited sources, literature and other professional sources.

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Název práce: Vyhodnocování relačních dotazů v proudově orientovaném prostředí

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Abstrakt:

Klíčová slova: SQL, Překladač, Relační algebra, Optimalizator, Bobox

Title: Evaluating relational queries in pipeline-based environment

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Department: Název katedry či ústavu, kde byla práce oficiálně zadána

Supervisor: RNDr. David Bednárek, Ph.D.

Abstract: This thesis deals with the design and implementation of optimizer and transformer of relational queries. Firstly, the thesis describes database compiler theory. Following chapter presents data structures and algorithm used in implemented tool. Final chapter specifies important implementation details. Part of the thesis was the selection of used relational algebra operators and design of appropriate input. Input of implemented software is query written in XML file in form of relational algebra. Query is optimized and transformed into physical plan which will be executed in parallel framework Bobox. Developed compiler outputs physical plan written in Bobolang language, which serves as input for Bobox.

Keywords: SQL, Compiler, Relational algebra, optimizer, Bobox

Contents

1. Introduction

Current processors have multiple cores and their single core performance is improving only very slow because of physical limitations. On the other hand, the number of cores is still increasing and we can assume that this trend will continue. Therefore, development of parallel software is crucial for improvement of the overall performance.

Parallelization can be achieved manually or using some framework designed for it. For example, there are frameworks like OpenMP or Intel TBB. Department of Software Engineering at Charles University in Prague developed its own parallelization framework called Bobox[1].

Bobox is designed for parallel processing of large amounts of data. It was specifically created to simplify and speed up parallel programming of certain class of problems - data computations based on non-linear pipeline. It was successfully used in implementation of XQuery, SPARQL[9], and TriQuery[8] engines.

Bobox consists from runtime environment and operators. These operators are called boxes and they are C++ implementation of data processing algorithms. Boxes use messages called envelopes to send processed data to each other.

Bobox takes as input execution plan written in special language Bobolang[2]. It allows to define used boxes and simply connect them into directed acyclic graph. Bobolang specifies the structure of whole application. It can create highly optimized evaluation, which is capable of using the most of the hardware resources.

Most used databases are relational. They are based on the view of data organized in tables called relations. An important language based on relational databases is Structured query language (SQL[10]) which is used for querying data and modifying content and structure of tables.

Architecture of planned SQL compiler is displayed in Figure 1.1. SQL query is written in text parsed into parse tree, which is transformed into logical query plan (Relational algebra). Relational algebra is then optimized and this form is used for generating physical query plan. Physical plan written in Bobolang is input for Bobox for execution. Besides physical plan, we need to provide implementation of physical algorithms (Bobox operators), as well.

Since SQL is a rather complicated language, the aim of this thesis is only implementing optimization and transformation of logical plan into physical plan. This part is displayed as physical plan generator in Figure 1.1.

The main goal of this thesis is to implement part of SQL compiler. The input is a query written in XML format in form of relational algebra. Program reads input and builds relational algebra tree, which is then checked for semantic errors.

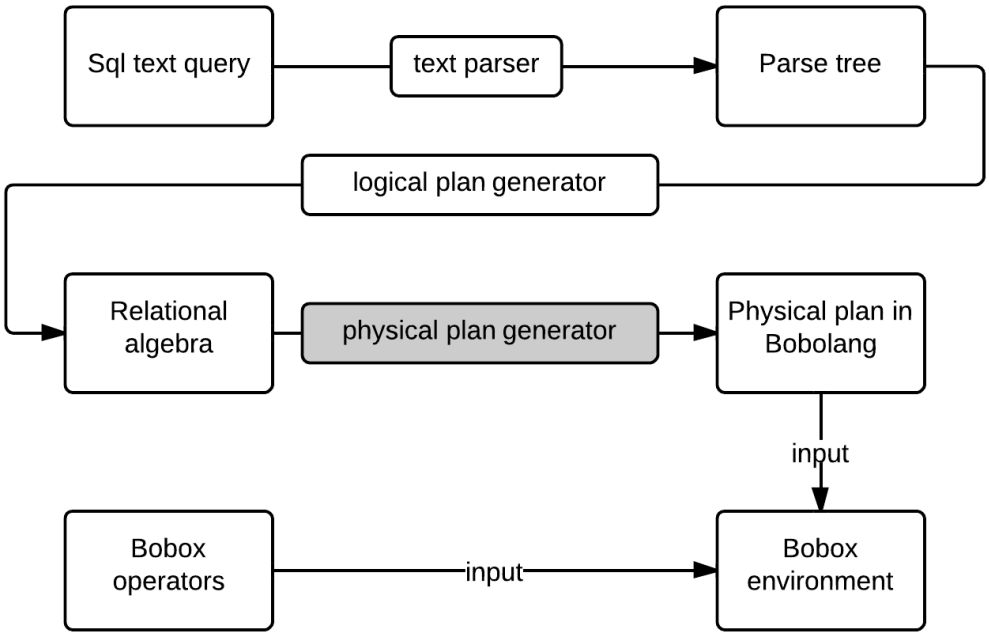

Figure 1.1: SQL compiler architecture.

Then, we improve logical plan by pushing selections down the tree. We generate physical plan from improved relational algebra. In this phase, we assign physical algorithm for every logical plan operator and we also choose the order of joins. The output is an execution plan for Bobox written in Bobolang. The query will be executed in pipeline–based environment[11, 12] of Bobox.

2. Bobox architecture

The purpose of this chapter is description of Bobox framework and Bobolang language.

2.1 Bobox

The purpose of this chapter is description of basic architecture of Bobox. The main source of information for this chapter is the doctoral thesis by Falt [4].

Overall Bobox architecture is displayed in Figure 2.1. Framework consists of Boxes which are C++ classes containing implementation of data processing algorithm. Boxes can be also created as a set of connected boxes. Boxes can have arbitrary number of inputs and outputs. All boxes are connected to a directed acyclic graph.

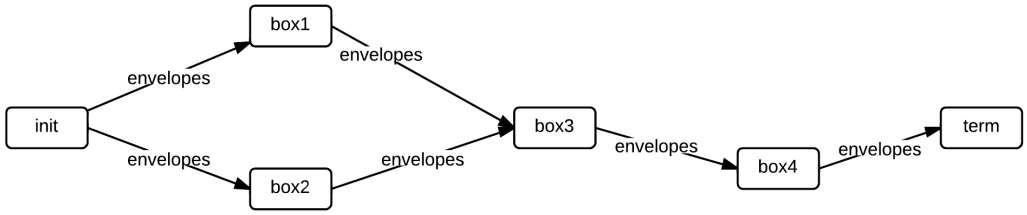

Figure 2.1: Bobox architecture.

Data streams are implemented as streams of data units called envelopes. Envelope structure is displayed in Figure 2.2. It consists of sequence of tuples but internally data are stored in columns. Envelope contains sequence of columns and its data is stored in separate list. In order to read all attributes of the i-th tuple, we have to access all column lists and read its i-th element. Special type of envelope contains a poisoned pill which is sent after all valid data, thus indicating the end of data stream.

There are two special boxes, which have to be in every execution plan:

- *init* - first box in topological order indicating starting box of execution plan.
- *term* - last box in topological order indicating that plan has been completely evaluated.

Evaluation starts with scheduling *init* box, which sends poisoned pills to all of its output boxes that will be scheduled. They can read data from the hard drive or network, process it and send it to other boxes for further processing. Other

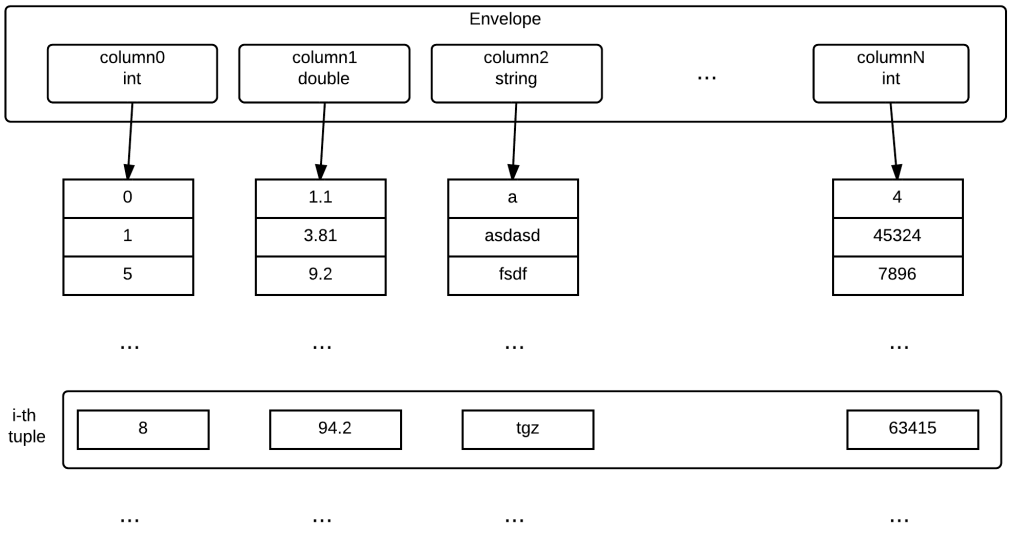

Figure 2.2: Envelope structure.

boxes usually receive data in envelopes in their inputs. Box *term* waits to receive for its every input to receive poisoned pill and then The evaluation ends when the box *term* receives poisoned pill from each of its inputs.

2.2 Bobolang

Syntax and semantics of Bobolang language is explained in this section. The work Falt et al. [2] served as source of information for this text.

Bobolang is a formal description language for Bobox execution plan. Bobox environment provides implementation of basic operators (boxes). Bobolang allows programmer to choose which boxes to use, what type of envelopes are passed between boxes and how the boxes are interconnected.

We can define whole execution plan using operator `main` with empty input and output. An example of complete Bobolang plan:

```
operator main()->()
{
    source()->(int) src;
    process(int)->(int,int,int) proc;
    sink(int,int,int)->() sink;

    input -> src -> proc;
    proc -> sink;
    sink -> output;
```

```
}
```

In the first part, we declare operators and define type of input and output. We provide identifier for every declared operator. Second part specifies connection between declared operators. Code `op1 -> op2` indicates that output of `op1` is connected to input of operator `op2`. In this case, the output type of `op1` has to be equal to the input type of `op2`. Bobolang syntax also allows to create chains of operators like `op1 -> op2 -> op3` with following semantics: `op1 -> op2` and `op2 -> op3`.

There are explicitly defined operators called `input` and `output`. The line `input -> src;` means that input of the operator `main` is connected to the output of operator `src`.

Bobolang also allows to declare operators with empty input or output with the type `()` meaning that they do not transfer any data. These operators transfer only envelopes containing poisoned pills. The box starts working after receiving poisoned pill. Sending the pill means that all data has been processed and the work is done.

Structure of example execution plan can be seen in Figure 2.3. Operators `init` and `term` are added automatically. Operator `init` sends poisoned pill to `source`, which can read data from hard drive or network. Data is sent to the box `process`. Operator `sink` stores data and sends poisoned pill to the box `term` and the computation ends.

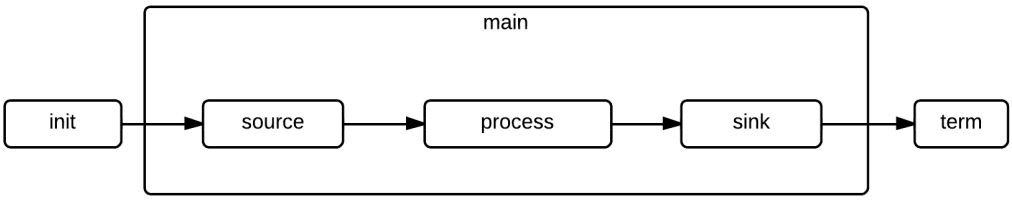

Figure 2.3: Example of execution plan.

3. Related work

The basics of the theory of relational algebra along with its optimizations and physical plan generation are introduced in this chapter. Information for this chapter and compiler implementation was taken from Database systems [3].

3.1 Relational algebra

In this section we introduce and describe relational algebra[3]. Following definitions of relational model can vary depending on used literature.

Definition 1. *Relation is a two dimensional table.*

Definition 2. *Attribute is a column of a table.*

Definition 3. *Schema is the name of the relation and the set of its attributes. For example:* $Movie\ (id, name, length)$.

Definition 4. *Tuple is a row of a relation.*

Relational algebra has atomic operands:

- Variables that are relations.
- Constants which are relations.

In classical relational algebra all operators and expression results are sets. All these operations can be applied also to bags(multi sets). We used relational algebra based on bags in the implemented compiler.

Classical relational algebra operators are:

- Set operations – union, difference, intersection.
- Removing operators – selection, which removes rows and projection that eliminates columns from given relation.
- Operations that combine two relations: all kinds of joins.
- Renaming operations that do not change tuples of the relation but only its schema.

Expressions in relational algebra are called *queries*.

3.1.1 Classical relational algebra operators

Set operations on relations

Sets operations are:

- Union $R \cap_S S$ is a set of tuples that are in R or S.
- Intersection $R \cup_S S$ is a set of tuples that are both in R and S.
- Difference $R -_S S$ is a set of tuples that are in R but not in S.

Considering two relations R and S, if one wants to apply some set operation, both relations must have the same set of attributes. We can also use renaming operations if relations do not have same attribute names.

Projection

Projection operator π_S produces new relation with reduced set of attributes from relation R. Result of an expression $\pi_{(S)A_1,A_3,A_4,...,A_N}(R)$ is relation R with attributes $A_1, A_3, A_4, ..., A_N$. Set version of this operator also eliminates duplicate tuples.

Selection

If the operator selection σ is applied on relation R with condition C, a new relation with the same attributes and tuples, which satisfy given condition, is obtained, for example $\sigma_{A_1=4}(R)$.

Cartesian product

Cartesian product of two sets R and S creates a set of pairs by choosing the first element of pair to be any element from R and second element of pair to be any element of S. Cartesian product of relations is similar. We pair tuples from R with all tuples from S. Relations S and R cannot have attributes with the same name because some columns of expression $R \times S$ could have the same name.

Natural joins

The simplest join is called natural join of R and S ($R \bowtie S$). Let schema of R be $R(r_1, r_2, .., r_n, c_1, c_2, ...c_n)$ and schema of S be $S(s_1, s_2, .., s_n, c_1, c_2, ...c_n)$. In natural join we pair tuple r from relation R to tuple s from relation S only if r and s agree on all attributes with the same name (in this case, $c_1, c_2, ...c_n$).

Theta joins

Natural join forces us to use one specific condition. In many cases we want to join relations with some other condition. The theta join serves for this purpose. The notation for joining the relations R and S based on the condition C is $R \bowtie_C S$. The result is constructed in the following way:

1. Make Cartesian product of R and S.
2. Use selection with condition C.

In principle, $R \bowtie_C S = \sigma_C(R \times S)$. Relations R and S have to have disjunct names of columns.

Renaming

In order to control name of attributes or relation name we have renaming operator $\rho_{A_1=R_1,A_2=R_2,...,A_n=R_n}(R)$. Result will have the same tuples as R and attributes $(R_1, R_2, ..., R_n)$ will be renamed as $(A_1, A_2, ..., A_n)$.

3.1.2 Relational operations on bags

Commercial database systems are almost always based on bags (multiset). The only operations that behave differently are intersection, union, difference and projection.

Union

Bag union of $R \cup_B S$ adds all tuples from S and R together. If tuple t appears m-times in R and n-times in S, then in $R \cup_B S$ t will appear $m + n$ times. Both m and n can be zero.

Intersection

Assume we have tuple t that appears m-times in R and n-times in S. In the bag intersection $R \cap_B S$ t will be $min(m, n)$-times.

Difference

Every tuple t, that appears m-times in R and n-times in S, will appear $max(0, m-n)$ times in bag $R -_B S$.

Projection

Bag version of projection π_B behaves like set version π_S with one exception. Bag version does not eliminate duplicate tuples.

3.1.3 Extended operators of relational algebra

We will introduce extended operators that proved useful in many query languages like SQL.

Duplicate elimination

Duplicate elimination operator $\delta(R)$ returns set consisting of one copy of every tuple that appears in bag R one or more times.

Aggregate operations

Aggregate operators such as sum are not relational algebra operators but are used by grouping operators. They are applied on column and produce one number as a result. The standard operators are SUM, AVG(average), MIN, MAX and $COUNT$.

Grouping operator

Usually, it is not desirable to compute aggregation function for the entire column, i.e. one rather computes this function only for some group of columns. For example, average salary for every person can be computed or the people can be grouped by companies and the average salary in every company is obtained.

For this purpose we have grouping operator $\gamma_L(R)$, where L is a list of:

1. attributes of R by which R will be grouped
2. expression $x = f(y)$, where x is new column name, f is aggregation function and y is attribute of relation. When we use function $COUNT$ we do not need to specify argument.

Relation computed by expression $\gamma_L(R)$ is constructed in the following way:

1. Relation will be partitioned into groups. Every group contains all tuples which have the same value in all grouping attributes. If there are no grouping attributes, all tuples are in one group.
2. For each group, operator produces one tuple consisting of:

(a) Values of grouping attributes.

(b) Results of aggregations over all tuples of processed group.

Duplicate elimination operator is a special case of grouping operator. We can express $\delta(R)$ with $\gamma_L(R)$, where L is a list of all attributes of R.

Extended projection operator

We can extend classical bag projection operator $\pi_L(R)$ introduced in Chapter 3.1.1. It is also denoted as $\pi_L(R)$ but projection list can have following elements:

1. Attribute of R, which means attribute will appear in output.
2. Expression $x = y$, attribute y will be renamed to x.
3. Expression $x = E$, where E is an expression created from attributes from R, constants and arithmetic, string and other operators. The new attribute name is x, for example $x = e * (1 - l)$.

The sorting operator

In several situations we want the output of query to be sorted. Expression $\tau_L(R)$, where R is relation and L is list of attributes with additional information about sort order, is a relation with the same tuples like R but with different order of tuples. Example $\tau_{A_1:A,A_2:D}(R)$ will sort relation R by attribute A_1 ascending and tuples with the same A_1 value will be additionally sorted by their A_2 value descending. Result of this operator is not bag or set since there is no sort order defined in bags or sets. Result is sorted relation and it is essential to use this operator only on top of algebra tree.

Outer joins

Assuming join $R \bowtie_C S$, we call tuple t from relation R or S *dangling* if we did not find any match in relation S or R. Outer join $R \bowtie^{\circ}_C S$ is formed by creating $R \bowtie_C S$ and adding dangling tuples from R and S. The added tuples must be filled with special *null* value in all attributes they do not have but appear in the join result.

Left or right outer join is an outer join where only dangling tuples from left or right relation are added, respectively.

3.2 Optimizations of relational algebra

After generation of the initial logical query plan, some heuristics can be applied to improve it using some algebraic laws that hold for relational algebra.

3.2.1 Commutative and associative laws

Commutative and associative operators are Cartesian product, natural join, union and intersection. Theta join is commutative but generally not associative. If the conditions make sense where they were positioned, then theta join is associative. This implies that one can make following changes to algebra tree:

- $R \oplus S = S \oplus R$
- $(R \oplus S) \oplus T = R \oplus (S \oplus T)$,

where $\oplus$ stands for $\times$, $\cap$, $\cup$, $\bowtie$ or $\bowtie_C$.

3.2.2 Laws involving selection

Selections are important for improving logical plan. Since they usually reduce the size of relation markedly we need to move them down the tree as much as possible. We can change order of selections:

- $\sigma_{C_1}(\sigma_{C2}(R)) = \sigma_{C2}(\sigma_{C1}(R))$

Sometimes we cannot push the whole selection but we can split it:

- $\sigma_{C_1 \ AND \ C_2}(R) = \sigma_{C_1}(\sigma_{C_2}(R))$
- $\sigma_{C_1 \ OR \ C_2}(R) = \sigma_{C_1}(R) \cup_S \sigma_{C_2}(R)$

Last law works only when R is a set.

When pushing selection through the union, it has to be pushed to both branches:

- $\sigma_C(R \cup S) = \sigma_C(R) \cup \sigma_C(S)$

When pushing selection through the difference, we must push it to the first branch. Pushing to the second branch is optional. Laws for difference are:

- $\sigma_C(R - S) = \sigma_C(R) - \sigma_C(S)$
- $\sigma_C(R - S) = \sigma_C(R) - S$

The following laws allows to push selection down the both arguments. Assuming the selection σ_C, it can pushed to the branch, which contains all attributes used in C. If C contains only attributes of R, then

- $\sigma_C(R \oplus S) = \sigma_C(R) \oplus S$,

where $\oplus$ stands for $\times$, $\bowtie$ or $\bowtie_C$. If relations S and R contain all attributes of C, the following law can be also used:

- $\sigma_C(R \bowtie S) = \sigma_C(R) \bowtie \sigma_C(S)$

3.2.3 Laws involving projection

We can add projection anywhere in the tree as long as it only eliminates attributes, which are not used anymore and they are not in query result.

3.2.4 Laws involving joins and products

We have more laws involving selection that follow directly from the definition of the join:

- $\sigma_C(R \times S) = R \bowtie_C S$
- $R \bowtie S = \pi_L(\sigma_C(\pi_X(R) \times \pi_Y(S)))$. $\pi_A(B)$ renames all attributes of relation B from *attributename* to B_*attributename*, where $A \in \{X, Y\}$ and $B \in \{R, S\}$. C is condition that equates each pair of attributes of R and S, which had the same name before renaming. π_L keeps all columns not used in condition C and renames them back by removing prefix $S\_$ or $R\_$. It also keeps all columns used in C which came from relation R and renames them by removing prefix $R\_$.

3.3 Physical plan generation

Physical plan will be created from optimized logical plan. We generate many physical plans and choose the one with the least estimated cost (run time). This approach is called cost–based enumeration.

For every physical plan we select:

1. an order of grouping and joins.
2. an algorithm for each operator, for example, usage of join based on hashing or sorting.

3. additional operators which are not present in logical plan, for example, we can sort relation in order to use faster algorithm which assumes that its input is sorted.

4. the way in which arguments are passed between operators. We can use iterators or store the result on the hard drive.

3.3.1 Size estimations

Estimates used in this section are taken from Database systems [3]. The costs of evaluation of physical plan are based on the estimated size of intermediate relations. Ideally, we want our estimation to be accurate, easy to compute and logically consistent (size of relation does not depend on how relation is computed). We will present simple rules, which will give us good estimates in most situations. The goal of estimation of sizes is not to predict the exact size of relation as even an inaccurate size will help us with plan generation.

In this section we will use the following conventions:

- $T(R)$ is the number of tuples in relation R.
- $V(R, a)$ is the number of distinct values in attribute a.
- $V(R, [a_1, a_2, ..., a_n])$ is the number of tuples in $\delta(\pi_{a_1,a_2,...,a_n}(R))$

Estimating the size of a projection

Bag projection is the only operator for which the size of its result is computable. It does not change the number of tuples but only their lengths.

Estimating the size of a selection

Selection usually reduces the number of tuples. For selection $S = \sigma_{A=c}(R)$, where A is an attribute of R and c is a constant, we can use the following estimation:

- $T(S) = T(R)/V(R, A)$

The selection involving inequality comparison, $S = \sigma_{A<c}(R)$, is more problematic. On average, half of the tuples satisfy the condition $A < c$ but usually, queries select only a small fraction of them from the relation. Typical inequality will return about a third of the original tuples. Therefore, the recommended estimate is:

- $T(S) = T(R)/3$

Selection with condition in the form C_1 *and* C_2 *and ... and* C_N can be treated as a cascade of simple selections and we can use the estimated size from simpler conditions to compute original selection estimate.

In case we have the condition $S = \sigma_{not(C)}(R)$, the following estimate is recommended:

- $T(S) = T(R) - T(\sigma_C(R))$

Estimates for selections with conditions involving logical disjunction are more complicated. Recommended estimated size of relation $S = \sigma_{C_1 \ or \ C_2}(R)$ is:

- $T(S) = T(R)(1 - (1 - \frac{m_1}{T(R)})(1 - \frac{m_2}{T(R)}))$

In order to use this estimate, we assume that conditions C_1 and C_2 are independent. Variable m_i equals $T(\sigma_{C_1}(R))$, where $i \in \{1, 2\}$. Expression $1 - m_1/T(R)$ is the fraction of tuples which do not satisfy the condition C_1 and $1 - m_2/T(R)$ is the fraction of tuples which do not satisfy the condition C_2. Product of these numbers is the fraction of tuples from R which are not included in the result. The fraction of tuples in S is given by the subtraction of the product from unity.

Estimating the size of a join

Considering the case of the natural join $A = R(X, Y) \bowtie S(Y, Z)$, we use the following estimate:

- $T(A) = \frac{T(R)T(S)}{max(V(R, Y), V(S, Y))}$

We can generalize this rule for joining with multiple attributes. For join $R \bowtie S$, where we join R and S using the attributes $(a_1, a_2, ...a_n)$, we use this estimate:

- $T(R \bowtie S) = \frac{T(R)T(S)}{\prod_{k=1}^{n} max(V(R, a_k), V(S, a_k))}$

When we join using multiple attributes, then the result of this estimate can be smaller than one. Such estimate indicates that the relation will be very small or possibly empty.

If we consider other types of join, e.g. theta join, we can use the following rules for their estimation:

1. The size of the Cartesian product is the product of sizes of relations involved.
2. Equality conditions can be estimated using techniques presented for natural joins.
3. An inequality comparison can be handled like expression $\sigma_{A<c}(R)$. We assume that one third of the tuples will satisfy the condition.

Estimating the size of an union

Estimated size of expression $R \cup_B S$ is a sum of sizes of the relations R and S. Size of the set union $R \cup_S S$ comes from the interval $\langle max(T(R), T(S)), T(R) + T(S) \rangle$. Recommended estimate is the midpoint of given interval.

Estimating the size of intersection

Size of relations $R \cap_S S$ and $R \cap_B S$ can be between 0 and $min(T(R), T(S))$. Recommend estimate is to take half of the size of smaller relation:

- $min(T(R), T(S))/2$.

Estimating the size of a difference

Result of expression $R - S$ can be as big as $T(R)$ and as small as $T(R) - T(S)$. Following estimate can be used for bag or set version of difference operator:

- $T(R - S) = T(R) - \frac{T(S)}{2}$.

Estimating the size of a grouping

Size of the result of expression $\gamma_L(R)$ is $V(R, [g_1, g_2, ..., g_n])$, where g_x are grouping attributes of L. This statistic is almost never available and for this case we need another estimate. Size of $\gamma_L(R)$ can be between 1 and $\prod_{k=1}^{n} V(R, g_k)$. Suggested estimate is:

- $T(\gamma_L(R)) = min(\frac{T(R)}{2}, \prod_{k=1}^{n} V(R, g_k))$

Estimation of duplicate elimination can be handled exactly like grouping.

3.3.2 Enumerating plans

For every logical plan there is an exponential number of physical plans. This section presents ways to enumerate physical plans such that the plan with the least estimated cost can be chosen. There are two broad approaches:

- Top–down: We work down the algebra tree from the root. For each possible implementation for algebra operation at the root, we consider best possible algorithms to evaluate its subtrees. We compute costs of every combination and choose the best one.

- Bottom–up: We proceed up the algebra tree and we enumerate plans based on the plans generated for its subexpressions.

These approaches do not differ considerably. However, one method eliminates plans that other method cannot and vice versa.

Heuristic selection

We use the same approach for generating physical plan as we used to improve logical plan. We make choices based on heuristics, for example:

- If a join attribute has an index, we can use joining by this index.
- If one argument of join is sorted, then we prefer using the merge join algorithm to the hash join algorithm.
- If we compute intersection or union of more than two relations, we process smaller relations first.

Branch–and–bound plan enumeration

Branch–and–bound plan enumeration is often used in practice. We begin by finding physical plan using heuristics and denote its cost C. We can consider other plans for sub–queries. We can eliminate any plan for sub–query with cost greater than C. If we get plan with lower estimated cost than C, we use this plan instead.

The advantage is that we can choose when to stop searchings for a better plan. If C is small, then we do not continue looking for other plan. On the other hand, when C is large, it is better to invest some time in finding a faster plan.

Hill climbing

First, we start with heuristically selected plan. Afterwards, we try to do some changes, for example, change of the order of joins or replacement of the operator using hash table for sort–based operator. Provided that such a plan is found, that no small modification results in a better plan, we choose that physical plan.

Dynamic programming

Dynamic programming is a variation of bottom–up strategy. For each subexpression, we keep only the plan with the least estimated cost.

Selinger–Style Optimization

Selinger–Style Optimization is an improvement of dynamic programming approach. For every subexpression, we keep not only the best plan, but also other plans with higher costs, the results of which are sorted in some way. This might be useful in the following situations:

1. The sort operator τ_L is on the root of tree and we have a plan, which is sorted by some or all attributes in L.

2. Plan is sorted by attribute used later in grouping.

3. We are joining by some sorted attribute.

In this situations, either we do not sort the input or we use only partial sort. This way, we can use faster algorithms which takes advantage of the sorted input.

3.3.3 Choosing the join order

We have three choices how to choose the order of joins of multiple relations:

1. Consider all possible options.

2. Consider only a subset of join orders.

3. Pick one heuristically.

Algorithms, that can be used for choosing join order, are presented in this section.

Dynamic programming algorithm

Dynamic programming algorithm requires the use of a table for storage of the following information:

1. Estimated size of a relation.

2. Cost to compute current relations.

3. Expression of the way how the current relation was computed.

Every input relation with estimated cost 0 is stored in the table. For every pair of relations, we compute their estimated size and cost of join and store it in the table, see Section 3.3.1.

The next step is the computation of join trees of sizes $(3, 4, ...n)$. If we want to consider all possible trees, we need to divide relations in current join R into two non–empty disjoint sets. For each pair of sets, we compute the estimated size and cost of their join to get the join R. We use data already stored in our table for this purpose. The join tree with least estimated cost will be stored in the table. When we are estimating joins of k relations, then all joins of $k-1$ relations must have been already estimated.

Example: for estimating join $A \bowtie B \bowtie C \bowtie D$ we try to join the following trees:

1. A and $B \bowtie C \bowtie D$
2. B and $A \bowtie C \bowtie D$
3. C and $A \bowtie B \bowtie D$
4. D and $A \bowtie B \bowtie C$
5. $A \bowtie B$ and $C \bowtie D$
6. $A \bowtie C$ and $B \bowtie D$
7. $A \bowtie D$ and $B \bowtie C$

Dynamic programming algorithm does not have to enumerate all possible trees, but only left–deep trees. A tree is called left–deep if all of its right children are leafs. Right–deep tree is tree, where all left children are leafs.

Computation differs only in division of processed relation R in two non–empty disjoint subsets. One of the subsets can contain only one relation.

In order to estimate join $A \bowtie B \bowtie C \bowtie D$, we try to join the following subsets:

1. A and $B \bowtie C \bowtie D$
2. B and $A \bowtie C \bowtie D$
3. C and $A \bowtie B \bowtie D$
4. D and $A \bowtie B \bowtie C$

Greedy algorithm

Time complexity of using dynamic programming to select an order of joins is exponential. Thus, we can use it only for small amounts of relations. If less time consuming algorithm is desired, one can use faster greedy algorithm. However, the disadvantage of greedy algorithm is that in some cases it outputs slower plan then dynamic programming algorithm.

Greedy algorithm stores the same information as the dynamic programming algorithm for every relation in the table. We start with a pair of relations R_i, R_j, for which the cost of $R_i \bowtie R_j$ is the smallest. We denote this join as our current tree. For other relations, that are not yet included, we find a relation R_k, such that its join with the current tree gives us the smallest estimated cost. We continue until all relations in our current tree are included. Greedy algorithm will create left–deep or right–deep join tree.

3.3.4 Choosing physical algorithms

To complete a physical plan we need to assign physical algorithms to operations in the logical plan.

Choosing selection algorithms

We try to use index for scanning table instead of reading the whole table. We can use the following heuristics for picking selection algorithm:

- For selection $\sigma_{A \oplus c}$, relation R which has index on attribute A, and constant c, we scan by index instead of scanning the whole table and filtering the result. Sign $\oplus$ denotes $=$, $<$, $\leq$, $>$ or $\geq$.
- More generally, for selections containing condition $A \oplus c$ and selected relation with index on columns A, we can scan by index and filter the result by other parts of condition.

Choosing join algorithms

We recommend to use the sort join when:

1. One or both join relations are sorted by join attributes.
2. There are more joins on the same attribute. For join $R(a, b) \bowtie S(a, c) \bowtie T(a, d)$ we can use sort based algorithm to join R and S. If we assume that $R \bowtie S$ will be sorted by attribute a, then we use second sort join for $R \bowtie S$ and relation T.

If we have join $R(a, b) \bowtie S(b, c)$ and we expect the size of relation to be small and S has index on attribute b, we can use join algorithm using this index. If there are no sorted relations and we do not have any indices on any relations, it is probably the best option to use the hash based algorithm.

Choosing scanning algorithms

Leaf of algebra tree will be replaced by one of scanning operators:

- $TableScan(R)$ – operator reads the entire table.
- $SortScan(R, L)$ – operator reads the entire table and sorts by attributes in the list L.

- $IndexScan(R, C)$ – C is a condition in form $A \oplus c$, where c is a constant, A is an attribute and $\oplus$ stands for $=$, $<$, $\leq$, $>$, $\geq$. Operator reads tuples satisfying condition C using an index on A and the result is sorted by columns on the used index.

- $TableScan(R, A)$ – A is an attribute. Operator reads the entire table using an index on A and the result will be sorted by columns on the used index.

We choose the scan algorithm based on the need of sorted output and availability of indices.

Other algorithms

Usually, sort and hash versions of algorithm are used. The following rules can be used for replacement of algebra operator with physical algorithm:

- We use the hash version of algorithm if the input is not sorted in a way we need or if the output does not have to be sorted.

- We use the sort version of algorithm if we have the input sorted by some of requested parameters or we need sorted output. In case the input is only sorted by some of the needed attributes, we can still use the fast partial sort and apply sort based algorithm.

4. Analysis

Used data structures and algorithms in the implemented compiler are discussed in this chapter.

4.1 Format of relational algebra

In this section we present relation algebra operators which are the input of the compiler. Our relational algebra contains the following operators:

1. Projection – we used extended projection π_L which removes columns, computes new ones from expressions and renames attributes.

2. Table reading operator which is a leaf of the algebra tree. For this operator we need to provide the following arguments:

   - table name.
   - information about indices (name, columns and sort order).
   - read columns.

3. Join - we used theta join $\bowtie_C$ operator where C is condition having following format:

   - Condition can be empty and in this case join represents Cartesian product.
   - $a_1 = b_1$ *and* $a_2 = b_2$ *and* $a_3 = b_3$ *and...and* $a_n = b_n$, where a_k belongs to the first relation and b_k belongs to the other relation.
   - $a_1 \oplus b \ominus a_2$, where a_1 and a_2 belongs to one input and b belongs to second input. Signs $\oplus$ and $\ominus$ mean $<$ or $\leq$.

   In addition to condition, we need to specify output attributes of join. These attributes can come from both inputs and we can optionally assign them new name. Assigning new attribute name is useful when some of the attributes have the same name.

   The other types of joins are not directly supported, but they can be replaced with the cross join followed by desired selection.

4. Anti join operator which was not presented with other join algorithms. Output of expression $R \ltimes_C S$ is relation with tuples from R, for which do not exist any tuple from S that satisfies condition C. We can use join and anti join can be used to express outer join.

The anti join can replace difference operator. The expression $R - S$ equals $R \ltimes_C S$, where C is condition that equates each pair of attributes of R and S, which had have same name.

Including the anti join in our relation algebra eliminates the need of usage the outer join and the difference and our relational algebra si simpler.

Condition C of anti join $R \ltimes_C S$ has the following format:

- $a_1 = b_1$ *and* $a_2 = b_2$ *and* $a_3 = b_3$ *and...and* $a_n = b_n$, where a_k belong to first the relation and b_k belongs to the other relation.

In every anti join we need to specify its output attributes with optional new name. The anti join can output only columns from first relation.

5. Group operator γ_L, where L is non empty list of group attributes and aggregate functions. Supported aggregate functions are *min*, *max*, *sum* and *count*. The function *avg* is not supported but it can easily computed using *sum* and *count*. All mentioned functions except *count* take one input attribute and function *count* has empty input.

   As mentioned before, group operator is more general version of the duplicate elimination which is not included in our algebra.

6. Sort operator τ_L, where L is a non empty list of attributes with sort directions.

7. Bag union $\cup$. Both input relations has to have same names and types of attributes. The set union can be computed using bag union and grouping operator for duplicate elimination.

8. Selection used in our algebra does not differ from selection from classical relational algebra.

Designed relational algebra works with bags.

4.2 Physical algorithms

In this section we enumerate and describe compiler's output algorithms. We assume that execution environment has enough memory and physical operators do not have to store intermediate result on hard drive.

Here is a list on algorithms:

- `Filter` - this algorithm reads input tuples and outputs tuples satisfying given condition. Output does not have to be sorted the same way as input.

- `Filter keeping order` - this algorithm reads input tuples and outputs tuples satisfying given condition. Output has to be sorted the same way as input.

- `Hash group` - operator groups tuples using hash table and for every group of tuples aggregate functions are computed.

- `Sorted group` - operator groups sorted tuples and computes aggregate functions. Input has to be sorted by group attributes.

- `Column operations` - this is an implementation of extended projection algebra operator.

- `Cross join` - operator computes Cartesian product of two relations.

- `Hash join` - operator uses hash table to compute join of two relations R and S with condition C, where C has the following format: $r_1 = s_1 and r_2 = s_2 and ... r_n = s_n$. Attributes $(r_1, r_2, ..., r_n)$ belong to the relation R and $(s_1, s_2, ..., s_n)$ are from the relation S.

- `Merge equijoin` - algorithm takes advantage of sorted inputs to compute join with condition C, where C has same format like condition in `Hash join`.

- `Merge non equijoin` - operator computes theta join with condition $a_1 \oplus b \ominus a_2$, where a_1 and a_2 belong the first input and b belongs to the second input. Signs $\oplus$ and $\ominus$ means $<$ or $\leq$. Input relations has to be sorted by the attributes in the join condition.

- `Hash anti join` - algorithm computes anti join with condition C using hash table. Condition C have the same format like condition in `Hash join`

- `Merge anti join` - operator takes advantage of sorted inputs to compute anti join with condition C, where C has same format like condition in `Hash join`.

- `Table scan` - operator scans whole table from hard drive.

- `Scan and sort by index` - operator scans whole table from hard drive using index. Output will be sorted by columns on used index.

- `Index Scan` - this algorithm uses index to read tuples from table satisfying given condition.

- `Sort` - this algorithm sorts input. Input can be presorted and in this case operator sorts only by not yet sorted attributes.
- `Union` - algorithm is an implementation of bag union.

4.3 Architecture

The architecture of implemented tool is displayed in the figure 4.1.

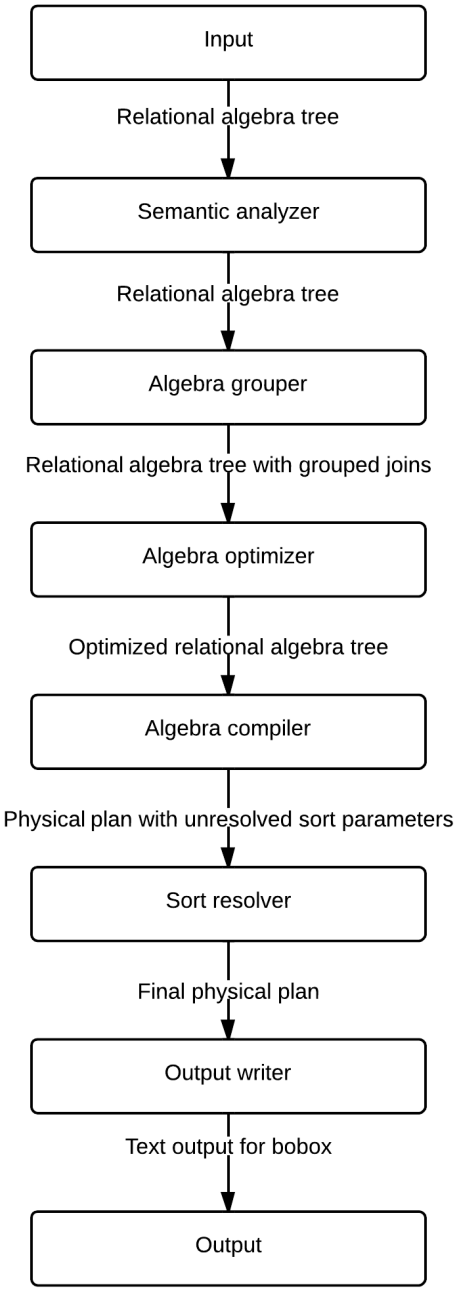

Figure 4.1: Compiler architecture.

The relational algebra tree is read from XML file. For this format we decided for the following reasons:

- XML has tree–like structure.
- For validation we only need to write schema.
- There are already implemented tools for parsing.
- There is no need to write input parser.

The relational algebra tree is checked in the `Semantic analyzer`. This component checks if all of used the attributes are in the input relation. Semantic analyzer searches for duplicate named attributes and reports it as an error.

Semantically correct tree is processed by component `Algebra grouper` that groups neighboring joins into one. Thanks to this operation so we can later choose fastest way to join multiple relations.

Algebra tree with grouped joins is optimized. We implemented one most important optimization: pushing selections down the tree. This component pushes selections to the join node if selection contains condition C where C is in the following format $a = b$. Attribute a is from the first join relation and b belong to the second join relation.

Optimized algebra tree is processed by compiler, which generates physical plan, which is not final. Its sort operator's parameters does not have to be final. For example if we want to sort relation before grouping we can sort it in different directions and than later decide what direction is better.

Final plan is an output of the component named `Sort resolver`. This component resolved unknown sort order of sort operators and produces final plan, which is converted too Bobolang language.

Implemented tool does not check types because it will be the back end of the compiler. We assume that the front end parsing the text will handle types. Types of columns are only copied to the output and we assume that column types do not contain any errors.

4.4 Data structures

Data structures used in implementing tool are presented in this section.

Relational algebra si stored in polymorphic tree. Every node stores it's parameters pointer on parent in the tree and zero or more pointers on children node. No other structure was considered for this representation since this is efficient way to store logical plan. It allows easily to add new types of relational algebra operators and it is not hard to manipulate with the tree. We can remove or add new

node very easily. Example of this representation can be found in figure 4.2. It's representing simple query reading whole table, then grouping it and computing some aggregation functions. The result is sorted at the end. Leaf of the tree also stores some information about indexes on read table, list of columns with their types and number of unique values. Other important parameter is size of relation which is displayed in number of rows parameter.

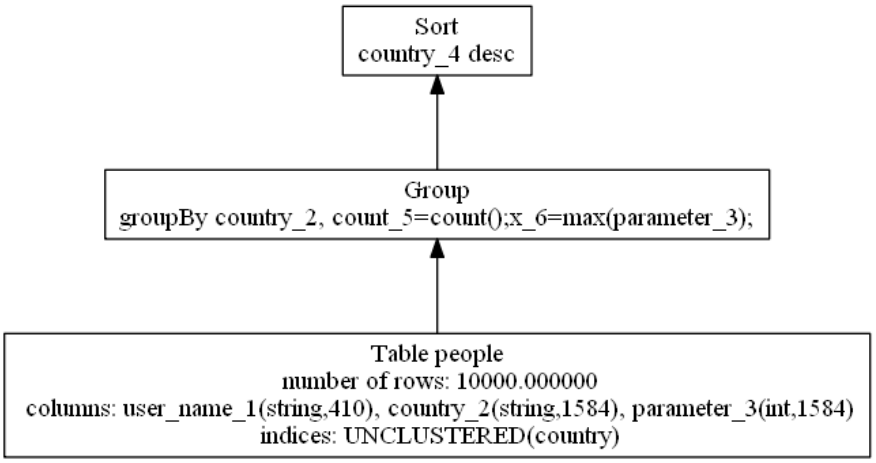

Figure 4.2: Example of relational algebra structure.

We choose same structure for physical plan. Physical plan usually doesn't have to change. The advantage of storing it into polymorphic tree is to ability to easily add new root node. Example of this representation can be found in figure 4.3. This figure contains one of possible physical plans for relational algebra in figure 4.2. For reading we used algorithm table scan, then we hashed input by requested columns and at the end, we sorted it using sort operator. Every nodes stores additional information like output attributes, estimated time and size of output relation.

Physical and logical plan also contain expressions. Expressions are stored in polymorphic expression tree. We have example of this structure in figure 4.4. This structure represents expression $X * Y + 874$.

More complicated structure was used to storing parameters. This structure is stored in every sort physical operator to determine what columns should relation be sorted by.

If we want to use group operator based on sort and it groups by three columns, we don't know which sort direction to use. Let's have expression $\gamma_{x,y}(R)$. There is four way to sort expression before calling group operator. This ways are:

- $x : A, y : A$
- $x : A, y : D$

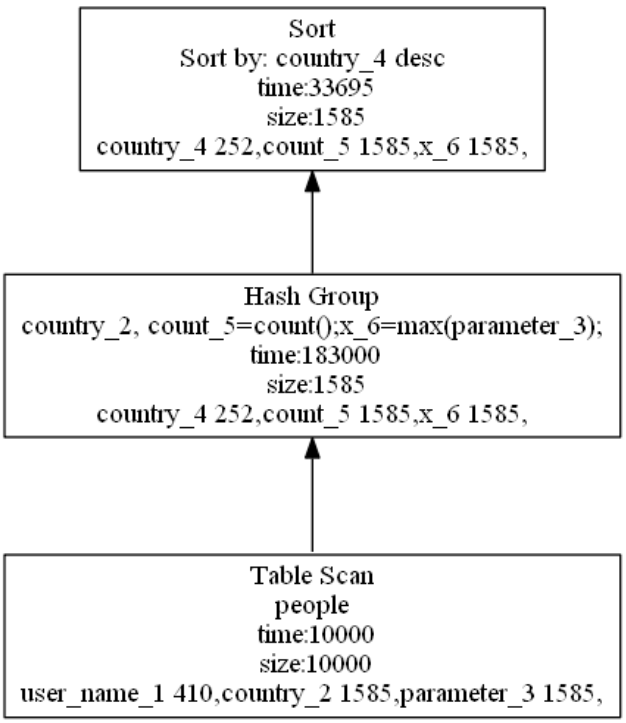

Figure 4.3: Example of physical plans structure.

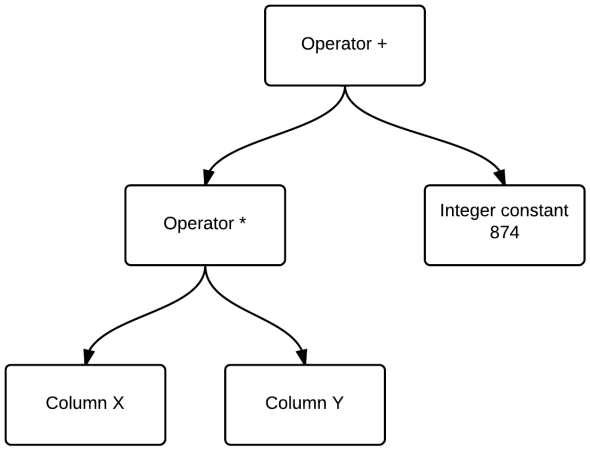

Figure 4.4: Example expression tree.

- $x : D, y : A$
- $x : D, y : D$

A means ascending and D is abbreviation for descending.

If we want to use merge join, joining on two attributes, we don't know direction and also which column should be first and which second. For example let's have $R \bowtie_{r_1=s_1 \ and \ r_2=s_2} S$. In this case we can sort relation R following way:

- r_1, r_2

- r_2, r_1

Order, how to sort columns is also unknown.

We also want to store information about equality of sort column. After merge join $R \bowtie_{r_1=s_1} S$ is result sorted by r_1 or s_1.

All this requirements were use to design structure to store sort parameter without enumerating all possible sort orders.

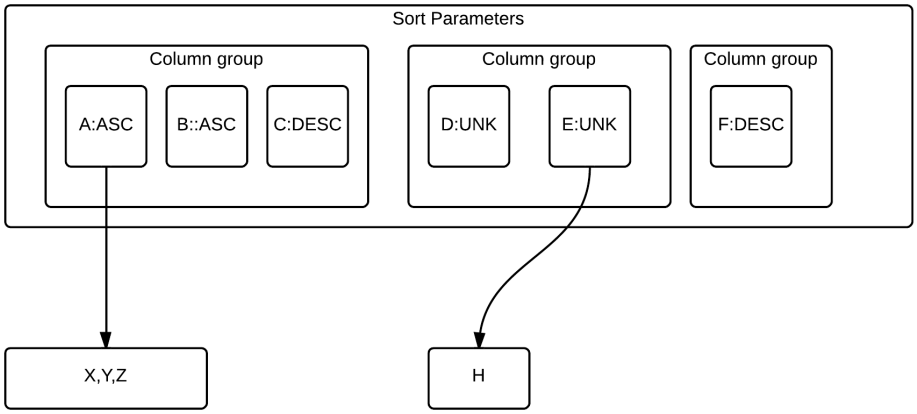

Figure 4.5: Structure storing parameters for sort.

In figure 4.5 we display an example of sort parameters, which sorts by 6 columns. It usually contains from 1 or more columns group. The order of columns groups cannot be changed. Order of columns in groups is arbitrary. It means that F has to be on sixth place, but column E can be on forth of fifth. Every column contains information about sort order: ASC (ascending), $Desc$ (descending) or UNK (unknown - can be ascending or descending). Every column also can be list of attributes which are equal to it. If we for example in projection remove attribute A, we still have attributes X, Y and Z which are equal to it, so one can take it's place.

Figure 4.5 represents many sort order possibilities we enumerate only some of them:

1. $A : ASC, C : DESC, B : ASC, H : DESC, D : ASC, F : DESC$
2. $C : DESC, B : ASC, Z : ASC, H : DESC, D : DESC, F : DESC$
3. $B : ASC, C : DESC, A : ASC, E : ASC, D : DESC, F : DESC$
4. $C : DESC, B : ASC, Y : ASC, D : ASC, H : ASC, F : DESC$

4.5 Optimization

In this section we describe algebra optimization, which wes implemented to improve logical plan.

Before we start with optimizations we need to prepare logical plan for it. We group joins algebra nodes and expressions connected with *and* and *or*.

Basically we go from top of the tree. If we find join we convert to it grouped join. If on of it's children is join we merge it. This representation is used for choosing faster way to order join. We do the same thing for conditions. From expression tree $a = 2$ *and* $(b = 2$ *and* $c = 2)$ we create $AND(a = 2, b = 2, c = 2)$. This representation is useful for splitting condition into simpler conditions.

We implemented very important optimization: pushing selection down the tree. Every selection is spitted into selections with simpler conditions. For every such selection we try to move it down the tree as much as possible. In this phase we used following rules (σ_C is being pushed down):

1. $\sigma_C(\sigma_D(R)) = \sigma_D(\sigma_C(R))$
2. $\sigma_C(\pi_L(R)) = \pi_L(\sigma_C(R))$, it works only if C doesn't contains new computed columns in extended projection. We also need to rename columns in condition C in case there was some renaming.
3. $\sigma_C(R \bowtie_D S)$ can be rewritten as
   (a) $\sigma_C(R) \bowtie_D S$ if C contains only columns from R.
   (b) $R \bowtie_D \sigma_C(S)$ if C contains only columns from R.
   (c) $R \bowtie_{D\ and\ C} S$ if C is in form $a = b$ where a is from R and b is from S.
4. $\sigma_C(R \ltimes_C S) = \sigma_C(R) \ltimes_C S$ if C contains only columns from R, which is always because output of $R \ltimes_C S$ can contain only columns R.
5. $\sigma_C(R \cup S) = \sigma_C(R) \cup \sigma_C(S)$

4.6 Generating physical plan

We try to choose easiest method for generating plans. The decision was between heuristic method and dynamic programming. From amount of code it was probably the same. We chose dynamic programming, because it can give better results. We just generate all possible plans for each node and choose the fastest.

We process logical plan from leafs. For every leafs we generate all possible physical algorithms and we insert resulting plans into heap, where we keep c fastest plans for current node, where c is constant set in compiler.

For every node we use plans generated in it's children to generate new plan. This way we go up the logical plan tree up to the root.

For comparing physical plans we estimated run time. For every node we store how long it will run. Estimated time for plan is sum of estimated times of all nodes.

Very important are equations, which compute estimated time for nodes. They depend from size of input relation. Modifying them can resolve in getting better physical plans. For example if physical algorithm hash join takes too much time because of lot random accessing memory, we can modify estimated time so sort with merge join will be preferred.

Crucial are informations about size of tables. If they are not in input we use default value and physical plan will be probably worse. Other important parameter is number of unique values in table column. Size of join depends on it and since joins usually takes significant amount of time, it is important to have as precise values as possible.

4.6.1 Join order selecting algorithm

In section 3.3.3 we presented algorithm choosing join order. We should choose this order and then assign join algorithms. We do it in one phase for following reason. In case we don't have information about table sizes, we cannot determine join order because all are the same. In this situation we can first join relations which are sorted some way to get a faster plan.

In this section we describe algorithm for selecting join order. We are using Two algorithms dynamic programming and greedy algorithm. For dynamic programming we use version where we enumerate all possible trees. This algorithm can give us very good plans but has exponential complexity and that's why we use it only if number of joined relations in grouped join node is small. If we join more relations we use greedy algorithm, which only generated left or right deep trees but it's complexity is not exponential only polynomial.

Input in both algorithm are set of plans for every input join relation.

Dynamic programing for selection join order

We use a variation of algorithm described in section 3.3.3. We number then input relations from 1 to n. For actual computation we use table, where we store plans. Key of the table is non empty subset of set $1..n$.

For every table entry we only store k best plans. It represents best plans for, that were created by joining input in key of table.

In begin we store input plans into table entry identified by set containing input number. In first iterator we fill tables entries, which key have two values by combining plans from entries with key size 1.

Then we compute plans for entries, which have key size $3, 4...n$. We do so by spiting set in key of the entry in all possible pairs of non empty disjunctive subsets. We take plans from this subsets and we generate new plans combining them. We only store k fastest plans.

We do this until we compute plans for table entry $1..n$. This is our result.

Time complexity is at least exponential since we generate all subsets of n relations, this number is 2^n.

Greedy algorithm for selection join order

This is also a variation of algorithm described in section 3.3.3. It beginning we create joins of every pair of relations. From them we choose best k trees.

In every following iteration for every tree we generate new trees by adding new relation to tree. In following iteration we continue only with best k join trees. At the end we have maximal k plans.

Time complexity is $O(n^2)$. In every iteration we generate from every tree maximal n new trees, but we keep only k of them for next iteration. Number of iteration is $n - 1$, because all trees grow by one in every iteration. Number k is a constant so it doesn't change time complexity.

4.6.2 Resolving sort parameters

After we generated physical plan we need to decide what sort parameters in sort operator to use.

To do this we go down the tree and store information about how relations is sorted. Based on that we adjust sort parameters or just choose arbitrary order if possible.

5. Implementation

In this chapter we describe implementation details in developed software it's functionality using examples. More implementation details can be found on the CD in generated doxygen[7] documentation. We will use following example to describe optimizations and plan generation:

```
select
    l_orderkey,
    sum(l_extendedprice*(1-l_discount)) as revenue,
    o_orderdate,
    o_shippriority
from
    customer,
    orders,
    lineitem
where
    c_mktsegment = '[SEGMENT]'
    and c_custkey = o_custkey
    and l_orderkey = o_orderkey
    and o_orderdate < date '[DATE]'
    and l_shipdate > date '[DATE]'
group by
    l_orderkey,
    o_orderdate,
    o_shippriority
order by
    revenue desc,
    o_orderdate;
```

This example is taken from benchmark[5]. $[DATE]$ and $[SEGMENT]$ are constants. Tables do not have any indices in this benchmark. Columns starting with o_ are from table order, columns beginning with l_ are from table lineitem and columns with prefix c_ belongs table customers.

5.1 Input

Input is XML file containing logical query plan. In this section we describe its structure.

5.1.1 Sort

On root of every tree is sort operator, even if output does not have to sorted. In this case sort has empty parameters. Example of sort in algebra tree:

```
<?xml version="1.0" encoding="utf-8"?>
<sort xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
 xsi:noNamespaceSchemaLocation="algebra.xsd">
  <parameters>
    <parameter column="revenue" direction="desc" />
    <parameter column="o_orderdate" direction="asc" />
  </parameters>
  <input>
   ...
  <input>
</sort>
```

Sort is a root element of XML file. Inside parameters is specified how to sort relation. In this example we have sort $\tau_{revenue:desc,o\_orderdate:asc}(...)$. In element input there should be one other algebra tree node.

5.1.2 Group

Next example contains group node:

```
<group>
  <parameters>
    <group_by column="l_orderkey"/>
    <group_by column="o_orderdate" />
    <group_by column="o_shippriority"/>
    <sum argument="x" output="revenue"/>
  </parameters>
  <input>
   ...
  <input>
</group>
```

This node represents expression $\gamma_{l\_orderkey,o\_orderdate,o\_shippriority,x=sum(x)}(...)$. Group element has to have at least one group by parameter or at least one aggregate function. Inside element input there should be one other operator.

5.1.3 Selection

This is an example of selection:

```
<selection>
  <parameters>
    <condition>
      <lower>
        <constant type="date" value="today"/>
        <column name="l_shipdate"/>
      </lower>
    </condition>
  </parameters>
  <input>
   ...
  </input>
</selection>
```

This example represent following expression: $\sigma_{today<l\_shipdate}$. In condition element we can have multiple conditions connected by *and* or *or* elements. Input algebra supports operators $=, <$ and $\leq$. In the leafs of expression tree there can be only column or constant element. We also can call a boolean function from condition, which is represented in following example.

```
<condition>
  <boolean_predicate  name="like">
    <argument>
      <column name="x"/>
    </argument>
    <argument>
      <constant type="int" value="445" />
    </argument>
  </boolean_predicate>
</condition>
```

Using boolean predicate it has to be supported by runtime(Bobox operators). Compile doesn't check it's existence.

5.1.4 Join

Join without condition is considered to be cross join. We can use join with multiple equal conditions or with simple unequal condition. First example contains

equal conditions:

```
<join>
  <parameters>
    <equal_condition>
      <equals>
        <column name="a"/>
        <column name="b"/>
      </equals>
      <equals>
        <column name="c"/>
        <column name="d"/>
      </equals>
    </equal_condition>
    <column name="a" input="first"/>
    <column name="b" input="second"/>
    <column name="c" input="first"/>
    <column name="d" input="second" newName="e" />
  </parameters>
<input>
...
</input>
```

This example represents join with condition $a = b$ *and* $c = d$. In join equal conditions has to be first column from first relation and second column from second relation. In example a and c are from first input and b and d are from the other one. Joins doesn't copy to output all column from both input relations. After condition we have to specify non empty sequence of columns. In every column we specify it's name and number of input. We can also rename join output column by using attribute *newName*. In example we renamed column d to e.

Next example shows also join but with inequality condition:

```
<join>
  <parameters>
    <less_condition>
      <and>
        <lower_or_equals>
          <column name="a1"/>
          <column name="b"/>
        </lower_or_equals>
```

```
        <lower_or_equals>
          <column name="b"/>
          <column name="a2"/>
        </lower_or_equals>
      </and>
    </less_condition>
    <column name="a1" input="first"/>
    <column name="b" input="second"/>
    <column name="a2" input="first"/>
</parameters>
<input>
...
</input>
</join>
```

This example represents join with condition $a1 \leq b \leq a2$. In first sub condition first column has to be from first input, but in second sub condition first column has to be from second input. Also instead *lower_or_equals* we can use just *lower* condition. Rules for output column are same like in join with equal conditions.

In element *input* there have to be two operators.

5.1.5 Anti join

```
<antijoin>
  <parameters>
    <equal_condition>
      <equals>
        <column name="d"/>
        <column name="b"/>
      </equals>
    </equal_condition>
    <column name="d"/>
  </parameters>
<input>
...
<input>
</antijoin>
```

This is an example of antijoin with simple condition $d = b$. Structure is the almost same like join. Output columns can be only from first relation and we can

also rename this columns.

5.1.6 Table

This is a leaf of algebra tree. It specifies name of read table, its columns and indexes. We can specify number of rows in the table to get better plans. If it is not specified we will assume that table has 1000 tuples. For every column we have to specify name and it's type. Other optional parameter is *number_of_unique_values*. This number is important for estimating size of join. If it is not given, we will assume, that *number_of_unique_values* is size of table to power of $\frac{4}{5}$. This assumption is only experimental, since number of unique values can be from 0 to size of table. Index can be clustered or unclustered. Table can have only one clustered index. In every index we specify on what attribute it is created. Here is an example of table algebra node:

```
<table name="orders" numberOfRows="1500000">
  <column name="o_orderdate" type="int"/>
  <column name="o_shippriority"
  type="int" number_of_unique_values="30000"/>
  <column name="o_orderkey" type="int"/>
  <column name="o_custkey" type="int" />
  <index type="clustered" name="index">
    <column name="o_orderdate" order="asc" />
    <column name="o_shippriority" order="asc" />
  </index>
</table>
```

5.1.7 Union

Union doesn't have any parameters, but columns from both input have to have the same names. Here is an example:

```
<union>
  <input>
   ...
  </input>
</union>
```

5.1.8 Extended projection

Following example of extended projection represents expression $\pi_{l\_orderkey,o\_orderdate,o\_shippriority,x=l\_extendedprice*(1-l\_discount)}(...)$.

```
<column_operations>
  <parameters>
    <column name="l_orderkey"></column>
    <column name="o_orderdate"></column>
    <column name="o_shippriority"></column>
    <column name="x">
      <equals>
        <times>
          <column name="l_extendedprice" />
          <minus>
            <constant type="double" value="1" />
            <column name="l_discount" />
          </minus>
        </times>
      </equals>
    </column>
  </parameters>
  <input>
  ...
  </input>
</column_operations>
```

Extended projection contains list of columns. If columns is new computed values it contains elements representing expression tree. It can also contain function call, which has to be supported by Bobox operators. Following example displays function call:

```
<column_operations>
  <parameters>
    <column name="x">
      <equals>
        <aritmetic_function name ="sqrt" returnType="double">
          <argument>
            <constant type="double" value="2" />
          </argument>
        </aritmetic_function>
      </equals>
    </column>
  </parameters>
  <input>
```

```
    ...
  </input>
</column_operations>
```

We compute new column named x with values $\sqrt{2}$.

5.2 Building relational algebra tree

In this section we describe in more details structure storing logical plan and it's building.

Relational algebra operators are represented by children of abstract class `AlgebraNodeBase`. It has following abstract subclasses:

- `UnaryAlgebraNodeBase` - abstract class for algebra operator with one input
- `BinaryAlgebraNodeBase` - abstract class for algebra operator with two inputs
- `GroupedAlgebraNode` - abstract class for algebra operator with variable number inputs
- `NullaryAlgebraNodeBase` - abstract class for algebra tree leafs

All operators are children of one of mentioned classes. Every operator has pointer to it's parent in tree and smart pointers to it's children if it has any.

Expressions in nodes are represented by polymorphic trees. All expression nodes are children of class `Expression`.

For manipulating and reading expression and algebra tree we used visitor pattern. All nodes (algebra and expression) contains method `accept`. This method calls visitor method on class `AlgebraVisitor`/`ExpressionVisitor`. All classes, which manipulate algebra tree, are children of class `AlgebraVisitor`.

In figure 5.1 we have example of algebra tree of query presented in beginning in this chapter. We have rewritten it as cross join of tree tables. After that we apply selection with condition in where clause. From the result we compute new column. After that we apply grouping compute aggregate functions and sort the result. In table reading operator we can see that they store additional information, like name of table. Every attribute has $\_ - 1$, behind name. It is it's unique identifier but after building tree from XML it is not assigned yet and that's why it contains default value -1. Columns in expressions also contains number in parenthesis. This number stores information from which input this columns it. Inputs are numbered from 0. Here we can see that all columns in selection are from 0^{th} input. This information is useful mainly in joins.

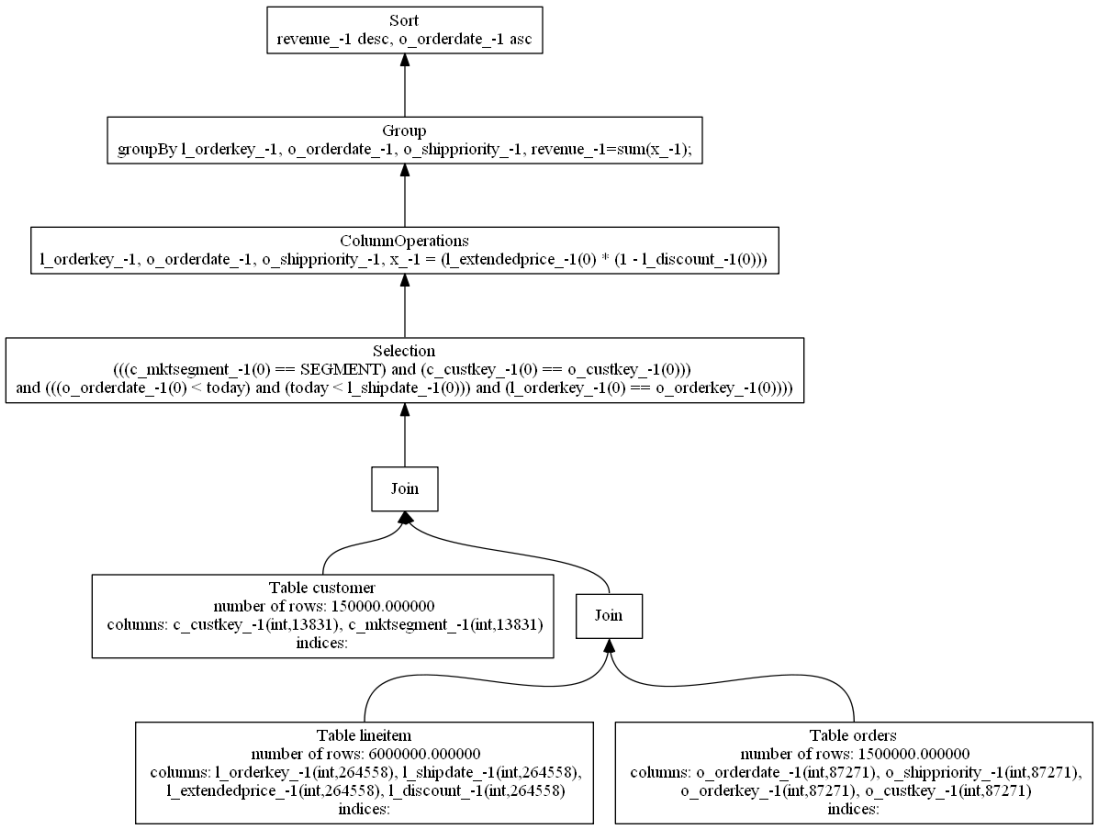

Figure 5.1: Example of algebra tree.

For parsing and validating input XML file we used library Xerces version 3.1.1[6]. It parses input file and create DOM tree. This tree has to be validated so we know it contains valid relational algebra tree. All this functionality is in class `XmlHandler`.

We know that every tree has to have sort operator on the top. We call `Sort` constructor on it. This method takes all information from DOM tree and call method, which decide that constructor to call next on it's children. This way we recursively build algebra tree.

5.3 Semantic analysis and node grouping

This phase in processed by class `SemanticChecker`. It checks columns used in expression exist. It also checks if output columns of operator has unique name. During this checking we assign unique identifier to every column. After this phase we don't need attribute names only this identifier.

Logical plan is after that visited by `GroupingVisitor`. In this phase are replaced joins represented by class `Join` by `grouped join` with two or more input relations. This node is represented by class `GroupedJoin`. Also in every expression we apply `GroupingExpressionVisitor`. It groups expression with

and and *or* operators. This is done for simplifying splitting condition into sub conditions.

5.4 Algebra optimization

We need to prepare logical tree for optimizing it by pushing down selections. To do this we split selection into smaller conditions using rule:

- $\sigma_{A\ and\ B}(R) = \sigma_A(\sigma_B(R))$

From every selection we created chain of selections. This operation is done by `SelectionSpitingVisitor`.

After that we call `SelectionColectingVisitor`. This visitor stores pointer of all selection in relational algebra tree. This pointers are input into `PushSelectionDownVisitor`. It pushes all selections down the tree as much as possible and also converts cross joins into regular joins if we have selection with equal condition. At this moment we have optimized tree, but we can find selection

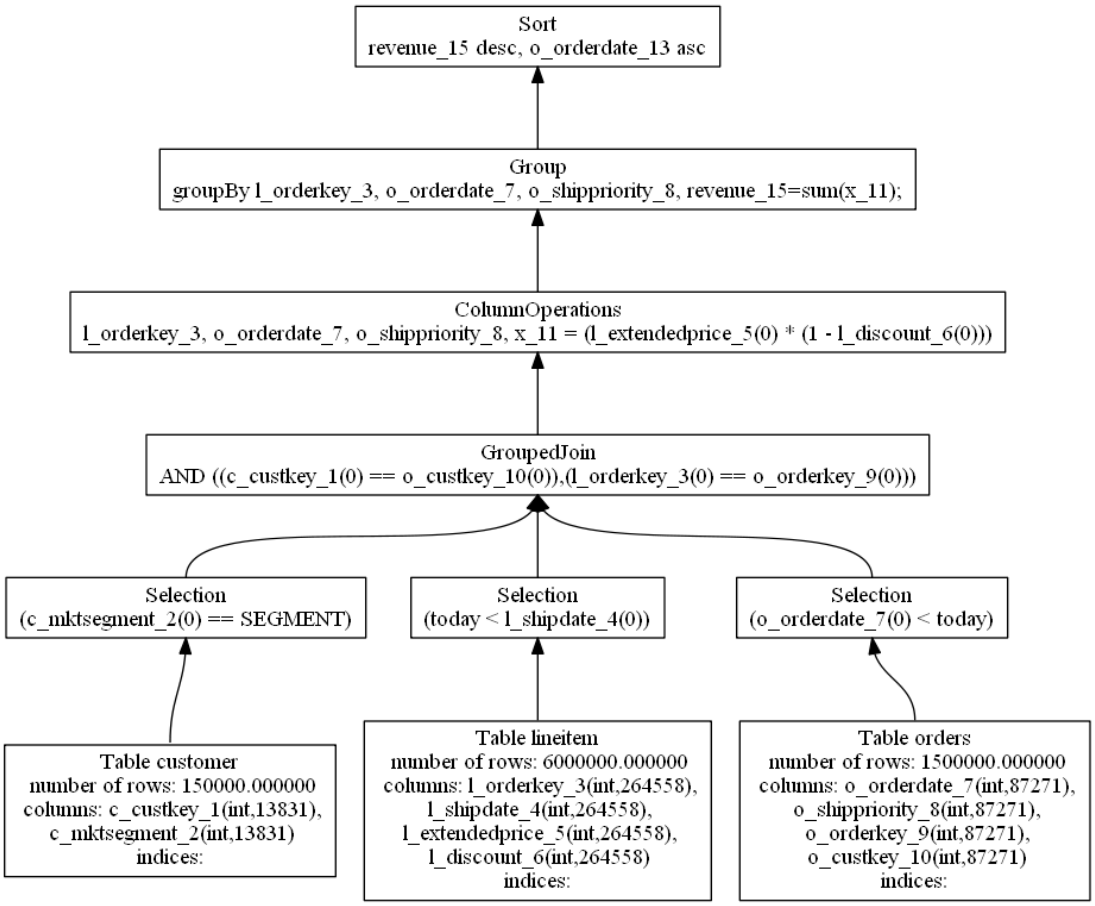

Figure 5.2: Example of optimized algebra tree.

chains in it. To resolve this problem we apply `SelectionFusingVisitor`. This visitor applies following rule to tree:

- $\sigma_A(\sigma_B(R)) = \sigma_{A\ and\ B}(R)$

In figure 5.2 we can see optimizes algebra tree. In comparison figure 5.1, this tree has grouped join with three input relations. Also big selection about joins has been split and moved down the tree. Some part of condition became join condition other were pushed down on of branches of grouped join. Then we can see that new tree has columns with assigned unique identifiers. Because we have this identifiers we don't need to know number of input for each column.

This output is optimized algebra tree. We can of course implement more optimizations to improve logical plan.

5.5 Generating plan

Final logical plan will be processed by `AlgebraCompiler`, which outputs n best plans. n is a constant in `AlgebraCompiler` represented by variable `NUMBER_OF_PLANS`.

This visitor visits node of algebra tree, the it calls itself on its children. We use generated plans for child nodes to create plans for current node. After that we store best plans in variable `result`, relation size in variable `size` and output columns in variable `outputColumns`.

For every node we generate all possible algorithms. Generated plans are stored in variable `result`. This variables stored a max-heap, where plans are compared by their overall time complexity. This time complexity is computed as sum of time complexity in all physical operators in current plan. This heap has maximal size of n. If there are more than n plans we remove plan in root of the heap.

Both join order algorithms can be found in method `visitGroupedJoin`. If number of join relations is smaller than k we used dynamic programing algorithm to estimate order of join. If we have more relations to join we use greedy algorithm. Constant k is represented in variable `LIMIT_FOR_GREEDY_JOIN_ORDER_ALGORITHM`. Both join algorithm call method `join`. This method combines plans and generates all possible plans.

Physical plan is represented as polymorphic tree.

In figure 5.3 we can see best generated physical plan for query presented on the beginning of this chapter. Every operator contains estimated size and time. Below that we can see output columns with their unique identifiers and estimated number of unique values for each column. Since read tables doesn't contain any indexes, we have to read all the tables and filter results. After that we can only use hash join, because sorting relations for merge join would be to expressive and nested loop join is not supported by runtime or compiler. From the result

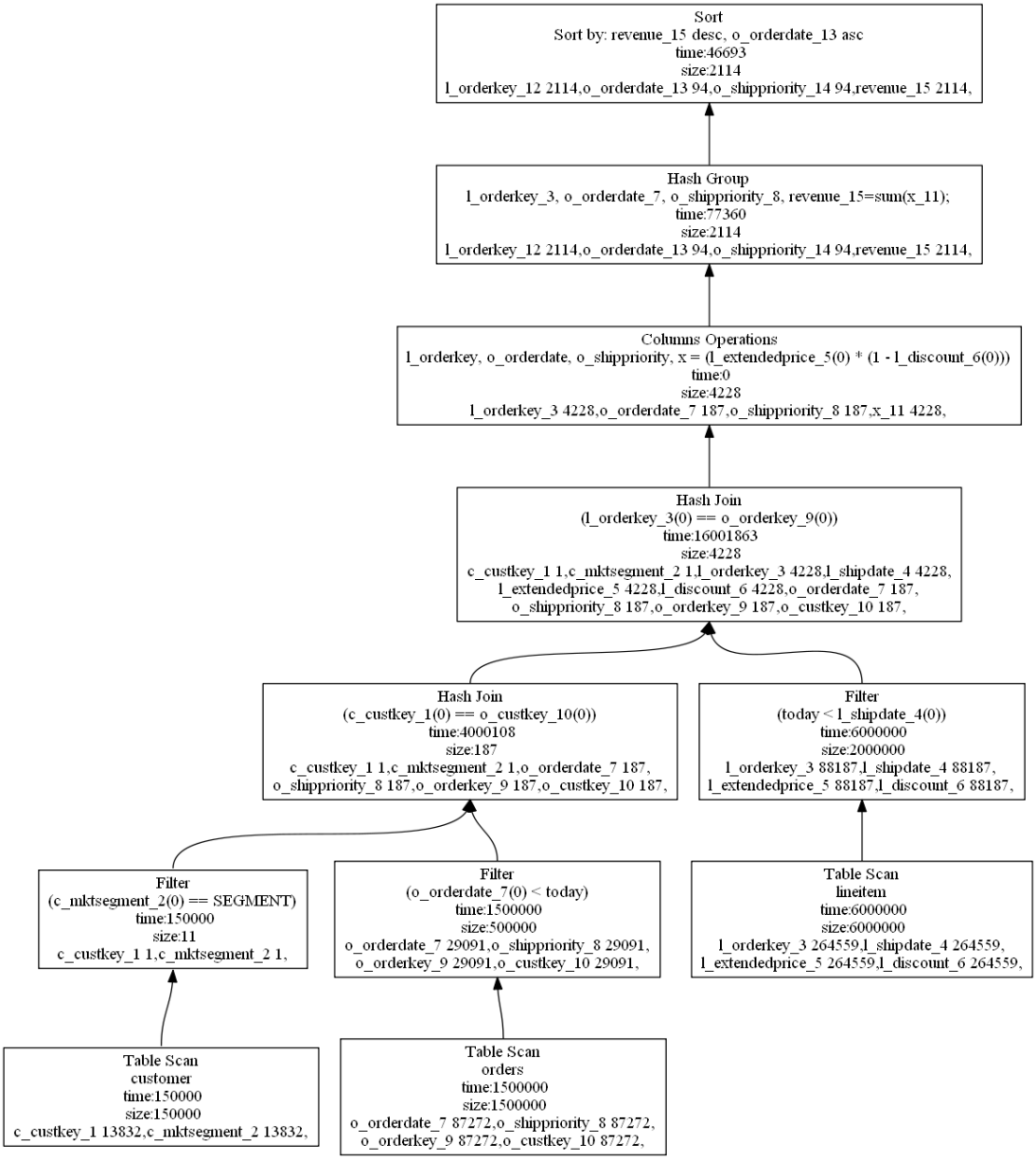

Figure 5.3: Example of physical plan.

we compute new columns and use hash group algorithm. We didn't use sorted group, because input is not sorted and output has to be sorted by other than group column.

Physical operators are chosen based on their estimated time complexity. It is computed from estimated size. In class `TimeComplexity` we have static functions which compute time complexity for each operation. It also contains constants used in this functions. We assume, that this constants or whole functions need to be improved. This improvement can be done base on testing and measuring evaluation queries in Bobox. At the time of submitting thesis runtime environment is not fully functional.

5.6 Resolving sort parameters

Sort parameters structure 4.5 is represented by class `PossibleSortParameters`. Every columns group is stored in class `SortParameters`. Class `SortParameter` is used to store column name, sort direction.

We take generated plans from class `AlgebraCompiler`. Sort parameters of sort nodes need to be resolved. Two plans also can contain same physical operator. That's why need to clone plans, to assure that no algorithm representing object are used in two or more plans.

For cloning we used `CloningPhysicalOperatorVisitor`. Than we resolve generated plans in `SortResolvingPhysicalOperatorVisitor`. In figure 5.4 we can see physical plan with unresolved sort parameters.

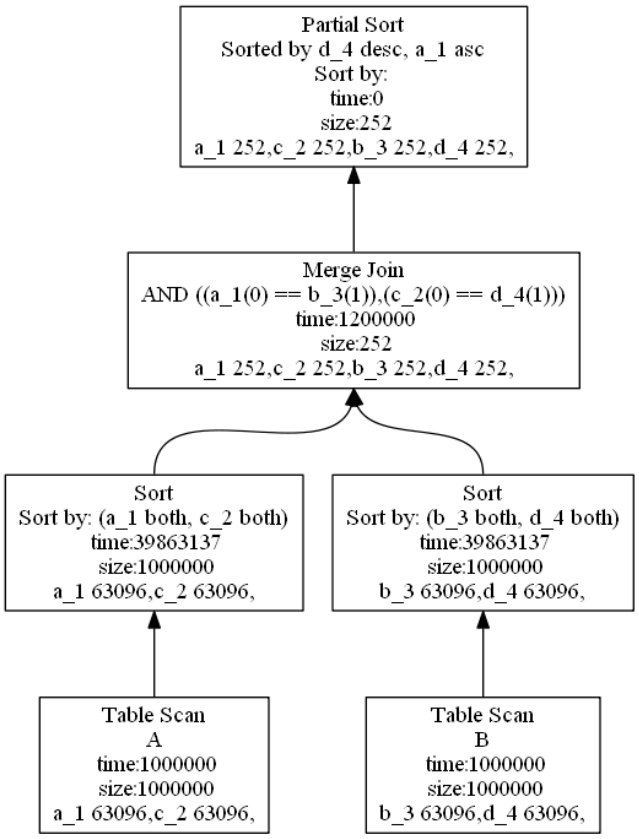

Figure 5.4: Example of physical plan.

It contains two sort algorithms. Left one has following possible parameters:

- $a : both, c : both$
- $c : both, a : both$

Right sort algorithm has sort parameters:

- $b : both, d : both$

- $d : both, b : both$

At the time of generating this algorithm, we didn't know that order was the best to choose. After merge join plan has to be sorted by $d : desc, a : asc$. At the top of the tree we generated partial sort. It doesn't do anything because relation is already sorted. It only indicates, that from all sort parameter possibilities we chose $d : desc, a : asc$ and we don't have to do any additional sorting.

`SortResolvingPhysicalOperatorVisitor` works down tree. It uses variable `sortParameters`. We store there information how the input has been sorted before input of visited node. Using this variable we adjust sort parameters of sort algorithm. Adjusted plan is in figure 5.5.

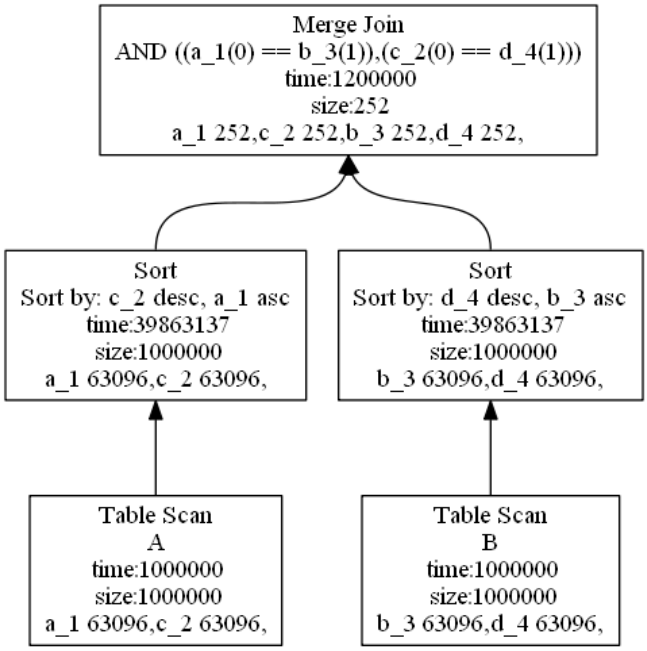

Figure 5.5: Example of final physical plan.

Output od the query has to be sorted by $d : desc, a : asc$. Visitor sets that input of partial sort has to be sorted by $d : desc, a : asc$. After that we resolve in merge join that left input has to be sorted by and right input has to be sorted by $c : desc, a : asc\ d : desc, b : asc$. Using this information we choose correct sort parameters in sort algorithms.

There can be situations where we use sort based algorithm but output doesn't been sorted, we can choose arbitrary order of sort parameters.

5.7 Output

Output in Bobolang is generated by `BoboxPlanWritingPhysicalOperatorVisitor`. We can also generate output from algebra tree. Visitor `GraphDrawingVisitor`

can generate output in dot language. Physical plan's output can be generated in dot language using `PhysicalOperatorDrawingVisitor`. `PhysicalOperatorDrawingVisitorWithouSorts` provides dot output without partial sorts with empty sort by parameters. In following chapters we text output generated by implemented compiler.

5.7.1 Filters

Example:

```
Filter(double,double,int)->(double,double,int)
f(condition="OP_LOWER(OP_double_CONSTANT(4.8),1)");
```

Input and output columns are same. Both are numbered from 0. This operator takes input of two double streams and integer stream and it filters by condition $4.8 <$ (*column number* 1). Columns 0 and 1 are streams of doubles and column 2 is stream of ints. We have also another version of this operator, which guaranteers that input and output are sorted the same way. To use it we write *FilterKeepingOrder* instead of *Filter* in operator declaration.

5.7.2 Group

Example:

```
HashGroup(string,string,int)->(string,int,int)
g(groupBy="1",functions="count(),max(2)");
```

Input columns are numbered from 0. Output columns consists from grouped columns and computed aggregate functions in the same order as in parameters. This example groups by column number 1 and computes aggregate function $COUNT$ and MAX. MAX has as parameter column number 2.

We have also sorted version of this operator. It assumes that input is sorted by group columns. To use it we write *SortedGroup* instead of *HashGroup* in declaration.

5.7.3 Column operations

Example:

```
ColumnsOperations(int,int,int,int,int)->(int,int,int,double)
c(out="0,3,4,OP_TIMES(2,OP_MINUS(OP_double_CONSTANT(1),2))");
```

Input columns are numbered from 0. Output is specified in parameter *out*. If it contains number operator, it copies input to output, otherwise it computes new

column. This example copies columns number $0, 3, 4$ to output and computes new column with expression: $2 * (1 - (column\ number\ 2))$.

5.7.4 Cross join

Example:

```
CrossJoin(string,int),(int,string)->(string,string)
c(left="0,1",right="2,3",out="0,3");
```

left parameter specifies how are columns from first input numbered. *right* parameter specifies numbering columns from second input. Join outputs only columns given in *out* argument.

5.7.5 Hash join

Example:

```
HashJoin(int,int),(int,int,int,int)->(int,int,int,int,int,int)
h(left="0,1",right="2,3,4,5",out="0,1,2,3,4,5",
leftPartOfCondition="0,1","rightPartOfCondition="5,2");
```

Numbering columns from first input is specified in *left* parameter and numbering columns from second input is specified in *right* parameter. Join outputs only columns given in *out* argument. This operators works only with equal condition, which is given in parameters *leftPartOfCondition* and *rightPartOfCondition*. Relation in first input should be stored in hash table, because it's estimated size is smaller. This example computes join with condition:
$(column\ 0 = column\ 5)\ and\ (column\ 1 = column\ 2)$.

5.7.6 Merge equijoin

Example:

```
MergeEquiJoin(int),(int)->(int,int))
m(left="0",right="1",out="0,1",leftPartOfCondition="0:D",
rightPartOfCondition="1:D");
```

Numbering columns from first input is specified in *left* parameter and numbering columns from second input is specified in *right* parameter. Join outputs only columns given in *out* argument. Condition is given in parameters *leftPartOfCondition* and *rightPartOfCondition*, and they also contain information how are inputs sorted. This example computes join with condition $(0 == 1)$. First input is sorted by column number 0 descending and the second input is sorted by column 1 descending.

5.7.7 Merge non equijoin

Example:

```
MergeNonEquiJoin(date,date),(date)->(date,date,date)
m(left="0,1",right="2",out="0,1,2",
leftInputSortedBy = "0:A,1:A",rightInputSortedBy = "2:A",
condition="OP_AND(OP_LOWER_OR_EQUAL(0,2)
,OP_LOWER_OR_EQUAL(2,1))");
```

This operator joins sorted relations. Numbering from left(first) and right(second) input is specified in parameters *left* and *right*. Parameters *leftInputSortedBy* and *rightInputSortedBy* store information about how are input relations sorted. Join condition is in parameter *condition*. Operator in this example joins by condition *column* 0 $\leq$ *column* 2 $\leq$ *column* 1. First input is sorted by column 0 ascending and column 1 ascending and second input is sorted by column 2 ascending.

5.7.8 Hash anti join

Example:

```
HashAntiJoin(int),(int)->(int)
h(left="0",right="1",out="0",leftPartOfCondition="0",
rightPartOfCondition="1");
```

Column number from first input is specified in *left* parameter and columns numbers from second input is specified in *right* parameter. Join outputs only columns given in *out* argument. Parameter *out* can only contains columns from first input. Condition is given in parameters *leftPartOfCondition* and *rightPartOfCondition*. Relation in first input should be stored in hash table, because it's estimated size is smaller. This example computes anti join with condition (*column* 0 == *column* 1).

5.7.9 Merge anti join

Example:

```
$MergeAntiJoin(int),(int)->(int)
$m(left="0",right="1",out="0",leftPartOfCondition="0:D",
rightPartOfCondition="1:D");
```

Numbering columns from first input is specified in *left* parameter and numbering columns from second input is specified in *right* parameter. Join outputs only columns given in *out* argument. Operator copies to output only rows from first

input for which doesn't exist row in second input satisfying given condition. Condition is given in parameters *leftPartOfCondition* and *rightPartOfCondition* and they also contain information how are inputs sorted. This example computes join with condition (*column* 0 == *column* 1). First input is sorted by column number 0 descending and the second input is sorted by 1 descending.

5.7.10 Table scan

Example:

```
TableScan()->(int,int,int,int)
t(name="lineitem",
columns="l_orderkey,l_shipdate,l_extendedprice,l_discount");
```

This operator scans table specified in parameter *name* and reads only columns given in parameter *columns*.

5.7.11 Scan And Sort By Index

Example:

```
ScanAndSortByIndexScan()->(string,string,int)
s(name="people",index="index",
columns="user_name,country,parameter");
```

Operator reads whole table given in *name* using *index* and reads columns specified in attribute *columns*.

5.7.12 Index Scan

Example:

```
IndexScan()->(int,int)
i(name="customer",index="index2",columns="c_custkey,c_mktsegment",
condition="OP_EQUALS(1,OP_string_CONSTANT(SEGMENT))");
```

Operator reads part of table given in *name* using *index* and reads columns specified in attribute *columns*. Operator reads only rows satisfying condition given in attribute *condtion*.

5.7.13 Sort

Example:

```
SortOperator(int,int)->(int,int)
s(sortedBy="0",sortBy="1:D");
```

Input and output columns are the same and they are numbered from 0. Parameter *sortedBy* specifies by which columns is table sorted and parameter *sortBy* specifies by which columns should table be sorted. Example is already sorted by *colum* 0 and will be sorted by *column* 1 descending.

5.7.14 Union

Example:

```
Union(int,string)(string,int)->(int,string)
u(left="0,1",right="1,0",out="0,1");
```

Numbering columns from the first input is given in the *left* parameter. Second input uses same number of columns like first output. This information is specified in parameter *right*. Operator appends columns from input 1 to columns from input 0. Order of output columns is specified in parameter *out*. Operator unites columns with same numbers.

6. Conclusions

We described Bobox architecture and Bobolang language in Chapter 2. Chapter 3 contains theory used to implement the query transformer. Chapter Analysis 4 deals with description of used algorithms and important data structures used in the implemented tool. Final chapter 5 presents some implementation details of created program.

The aim of this thesis was to implement part of the SQL compiler. Created program reads input relational algebra which is optimized. We implemented very effective optimization of logical plan: pushing selections down the tree. Possible physical plans were enumerated using Selinger–Style Optimization method. In this phase, we replaced algebra operators with physical plan. We implemented two different algorithms for choosing the order of joins. Asymptotically slower algorithm based on dynamic programming is used for estimated order of joins on smaller amount of relations. A faster greedy algorithm, which can generate less optimal join tree is provide for larger amount of joined relations. While choosing order of joins, we assigned physical algorithms. Merging of the assignment of physical algorithms and chose of join order can result in faster physical plan, in case we do not have information about sizes of input relations. Physical plan is written to output in the Bobolang language. Implemented compiler provides possibility to write algebra tree and physical plan to language Dot for debugging purposes.

Created software is a first part of planned SQL compiler. Front end, which transforms text query to the relational algebra, has not yet been implemented. At the time of submitting this thesis, compiler was successfully connected to Bobox. However not all of the physical operators have been implemented. Therefore we were not able to evaluate any queries to prove that generated plans are correct.

We tested software by transforming some simple queries and queries from TPC benchmark [5] to physical plans. We are able to check generated plans by looking at generated debug outputs. Based on this results we onclude that generated plans are correct and also optimal.

Implemented tool can be improved by adding more logical plan optimizations. After queries are run and their run time is measured, compiler time estimations, used for selection of physical algorithms, can be improved. We can also add support for more physical algorithms like nested loop joins.

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Attachments

Attachment on CD

The genereted documentation can be found in the folder `RelationalQueryEvaluator/Doxygen/html/html`. THe folder `Thesis` contains text of this thesis.

Software was developed in Visual studio and its solution can be found in the folder `RelationalQueryEvaluator`. Recommended tool for compiling source codes is Visual Studio 2013. We used external library $XercesC++$ version 3.1.1 which is located in the folder `RelationalQueryEvaluator/externals`.

Test queries can be found in folder `RelationalQueryEvaluator/RelationalQueryEvaluator/data`. Files with the suffix .xml contain test queries. Compiler generates the following outputs for every processed file (for example named `query.xml`) containing query:

1. `query.xml._1.txt` – Dot representation of the input algebra tree.
2. `query.xml._2.txt` – Dot representation of the input algebra tree after semantic analysis and grouping phase.
3. `query.xml._3.txt` – Dot representation of the optimized algebra tree.
4. `query.xml._4.txt` – Dot representation of the best physical plans with unresolved sort parameters.
5. `query.xml._5.txt` – Dot representation of the best final physical plans.
6. `query.xml._6.bbx` – Bobolang representation of the best physical plan.

The generated PNG images from outputs of queries can be found in the folder with test queries. Description of image output can be found in Chapter 5. Provided Windows binaries are located in the folder `Binaries`.

Program usage:

- `RelationalQueryEvaluator.exe inputfile`

Every line of the input file should contain the name of the file with relational query.