

# Lab 10 (PA4)

## Programming Assignment 4

**Released:** 11/15

**Due:** 12/01

In this assignment, you will implement a query optimizer on top of SimpleDB. The main tasks include implementing a selectivity estimation framework and a cost-based optimizer. You have freedom as to exactly what you implement, but we recommend using something similar what was discussed in our lecture.

The remainder of this document describes what is involved in adding optimizer support and provides a basic outline of how you might add this support to your database.

As with the previous assignment, we recommend that you start as early as possible.

## 1. Getting started

You should begin with the code you submitted for PA 3. (If you did not submit code for PA 3, or your solution didn't work properly, contact us to discuss options.)

We have provided you with extra test cases as well as source code files for this assignment that are not in the original code distribution you received. We reiterate that the unit tests we provide are to help guide your implementation along, but they are not intended to be comprehensive or to establish correctness. You will need to add these new test cases to your release. The easiest way to do this is to untar the new code in the same directory as your top-level `simplifiedb` directory, as follows:

- ① Make a backup of your PA 3 solution.
  - Change to the directory that contains your top-level `simplifiedb` code.

- Download the new tests and skeleton code for PA 4 from [CS660-pa4.zip](#):
- Extract the new files for PA 4.

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## 1.1. Implementation hints

We suggest exercises along this document to guide your implementation, but you may find that a different order makes more sense for you. As before, we will grade your assignment by looking at your code and verifying that you have passed the test for the ant targets test and systemtest. See Section 3.4 for a complete discussion of grading and the tests you will need to pass.

Here's a rough outline of one way you might proceed with this assignment. More details on these steps are given in Section 2 below.

- Implement the methods in the TableStats class that allow it to estimate selectivities of filters and cost of scans, using histograms (skeleton provided for the IntHistogram class) or some other form of statistics of your devising.
- Implement the methods in the JoinOptimizer class that allow it to estimate the cost and selectivities of joins.
- Write the orderJoins method in JoinOptimizer. This method must produce an optimal ordering for a series of joins (likely using the Selinger algorithm), given statistics computed in the previous two steps.

## 2. Optimizer outline

Recall that the main idea of a cost-based optimizer is to:

- Estimate "costs" of different query plans. Typically, the cost of a plan is related to the cardinalities of (number of tuples produced by) intermediate joins and selections, as well as the selectivity of filter and join predicates.
- Use these statistics to order joins and selections in an optimal way, and to select the best implementation for join algorithms from amongst several alternatives.

In this assignment, you will implement code to perform both of these functions.

The optimizer will be invoked from simpledb/Parser.java. Briefly, if you have a catalog file catalog.txt describing your tables, you can run the parser by typing:

```
java -jar dist/simpledb.jar parser catalog.txt
```

When the Parser is invoked, it will compute statistics over all of the tables (using statistics code you provide). When a query is issued, the parser will convert the query into a logical plan representation and then call your query optimizer to generate an optimal plan.

### 2.1 Overall Optimizer Structure

The overall control flow of the SimpleDB modules of the parser and optimizer is shown in Figure 1.



Parser.java

TableStats.java

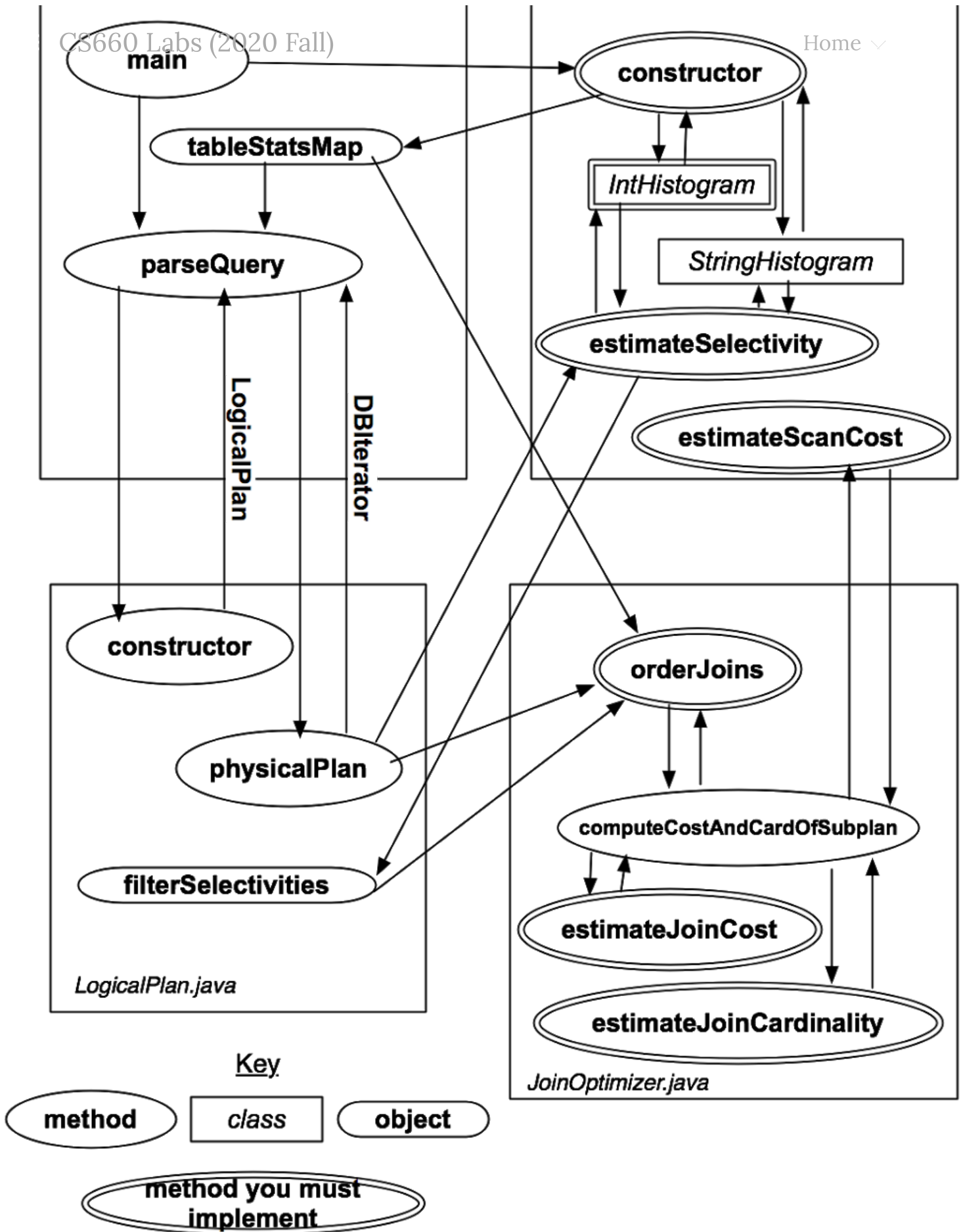


Figure1:Diagram illustrating classes, methods, and objects used in the parser and optimizer.

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The key at the bottom explains the symbols; you will implement the components with double-borders. The classes and methods will be explained in more detail in the text that follows (you may want to refer back to this diagram), but the basic operation is as follows:

1. Parser.java constructs a set of table statistics (stored in the statsMap container) when it is initialized. It then waits for a query to be input, and calls the method `parseQuery` on that query.
2. `parseQuery` first constructs a `LogicalPlan` that represents the parsed query. `parseQuery` then calls the method `physicalPlan` on the `LogicalPlan` instance it has constructed. The `physicalPlan` method returns a `DBIterator` object that can be used to actually run the query.

In the exercises to come, you will implement the methods that help `physicalPlan` devise an optimal plan.

## 2.2. Statistics Estimation

Accurately estimating plan cost is quite tricky. In this assignment, we will focus only on the cost of sequences of joins and base table accesses. We won't worry about access method selection (since we only have one access method, table scans) or the costs of additional operators (like aggregates). You are only required to consider left-deep plans for this assignment.

### 2.2.1 Overall Plan Cost

We will write join plans of the form `p=t1 join t2 join ... tn`, which signifies a left deep join where `t1` is the left-most join (deepest in the tree). Given a plan like `p`, its cost can be expressed as:

```
scancost(t1) + scancost(t2) + joincost(t1 join t2) +
scancost(t3) + joincost((t1 join t2) join t3) +
...
```

Here, `scancost(t1)` is the I/O cost of scanning table `t1`, `joincost(t1, t2)` is the CPU cost to join `t1` to `t2`. To make I/O and CPU cost comparable, typically a constant scaling factor is used, e.g.:

```
cost(predicate application) = 1
```

```
cost(pageScan) = SCALING_FACTOR x cost(predicate application)
```

For this assignment, you can ignore the effects of caching (e.g., assume that every access to a table incurs the full cost of a scan). Therefore, `scancost(t1)` is simply the number of pages in `t1`  $\times$  `SCALING_FACTOR`.

### 2.2.2 Join Cost

When using nested loops joins, recall that the cost of a join between two tables `t1` and `t2` (where `t1` is the outer) is

simply:

```
joincost(t1 join t2) = scancost(t1) * runtime(t1) * scancost(t2) // IO cost
```

$$\text{JoinCost}(t_1 \text{ join } t_2) = \text{ScanCost}(t_1) + \text{ntups}(t_1) \times \text{ScanCost}(t_2) // 10 \text{ cost}$$

$$+ \text{ntups}(t_1) \times \text{ntups}(t_2) // \text{CPU cost}$$

Here,  $\text{ntups}(t_1)$  is the number of tuples in table  $t_1$ .

### 2.2.3 Filter Selectivity

$\text{ntups}$  can be directly computed for a base table by scanning that table. Estimating  $\text{ntups}$  for a table with one or more selection predicates over it can be trickier -- this is the *filter/selection selectivity estimation* problem. Here's one approach that you might use, based on computing a histogram over the values in the table:

- Compute the minimum and maximum values for every attribute in the table (by scanning it once).
- Construct a histogram for every attribute in the table. A simple approach is to use a fixed number of buckets  $\text{NumB}$ , with each bucket representing the number of records in a fixed range of the domain of the attribute of the histogram. For example, if a field  $f$  ranges from 1 to 100, and there are 10 buckets, then bucket 1 might contain the count of the number of records between 1 and 10, bucket 2 a count of the number of records between 11 and 20, and so on. Note that this is simply the equi-width histogram we have discussed in class.
- Scan the table again, selecting out all of fields of all of the tuples and using them to populate the counts of the buckets in each histogram.
- To estimate the selectivity of an equality expression,  $f = \text{const}$ , compute the bucket that contains value  $\text{const}$ . Suppose the width (range of values) of the bucket is  $w$ , the height (number of tuples) is  $h$ , and the number of tuples in the table is  $\text{ntups}$ . Then, assuming values are uniformly distributed throughout the bucket, the selectivity of the expression is roughly  $(h/w) / \text{ntups}$ , since  $(h/w)$  represents the expected number of tuples in the bin with value  $\text{const}$ .
- To estimate the selectivity of a range expression  $f > \text{const}$ , compute the bucket  $b$  that  $\text{const}$  is in, with width  $w_b$  and height  $h_b$ . Then,  $b$  contains a fraction  $b_f = h_b / \text{ntups}$  of the total tuples. Assuming tuples are uniformly distributed throughout  $b$ , the fraction  $b_{\text{part}}$  of  $b$  that is  $> \text{const}$  is  $(b_{\text{right}} - \text{const}) / w_b$ , where  $b_{\text{right}}$  is the right endpoint of  $b$ 's bucket. Thus, bucket  $b$  contributes  $(b_f \times b_{\text{part}})$  selectivity to the predicate. In addition, buckets  $b+1 \dots \text{NumB}-1$  contribute all of their selectivity (which can be computed using a formula similar to  $b_f$  above). Summing the selectivity contributions of all the buckets will yield the overall selectivity of the expression. Figure 2 illustrates this process.
- Selectivity of expressions involving *less than* can be performed similar to the greater than case, looking at buckets down to 0.

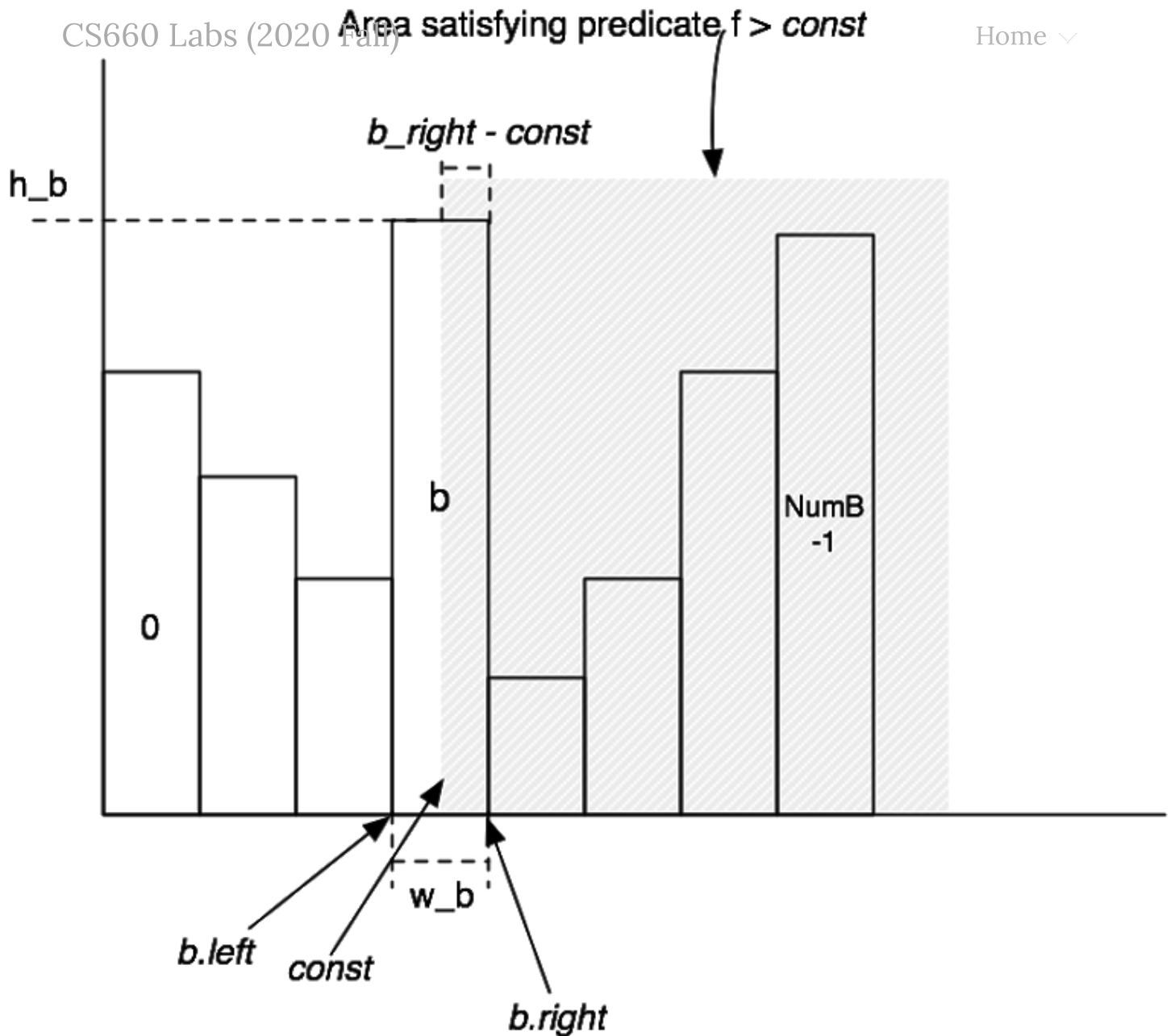


Figure 2: Diagram illustrating the histograms you will implement in PA 4.

In the next two exercises, you will code to perform selectivity estimation of joins and filters.

### Exercise 1: IntHistogram.java

You will need to implement some way to record table statistics for selectivity estimation. We have provided a skeleton class, IntHistogram that will do this. Our intent is that you calculate histograms using the bucket-based method described above, but you are free to use some other method so long as it provides reasonable selectivity estimates.

We have provided a class StringHistogram that uses IntHistogram to compute selectivities for String predicates. You may modify StringHistogram if you want to implement a better estimator, though you should not need to in order to complete this assignment.

After completing this exercise, you should be able to pass the IntHistogramTest unit test.

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### Exercise 2: TableStats.java

The class TableStats contains methods that compute the number of tuples and pages in a table and that estimate the selectivity of predicates over the fields of that table. The query parser we have created creates one instance of TableStats per table, and passes these structures into your query optimizer (which you will need in later exercises).

You should fill in the following methods and classes in TableStats:

- Implement the TableStats constructor: Once you have implemented a method for tracking statistics such as histograms, you should implement the TableStats constructor, adding code to scan the table (possibly multiple times) to build the statistics you need. **(UPDATE: Constructor already provided, so you don't need to implement this function)**
- Implement estimateSelectivity(int field, Predicate.Op op, Field constant): Using your statistics (e.g., an IntHistogram or StringHistogram depending on the type of the field), estimate the selectivity of predicate field op constant on the table.
- Implement estimateScanCost(): This method estimates the cost of sequentially scanning the file, given that the cost to read a page is costPerPageIO. You can assume that there are no seeks and that no pages are in the buffer pool. This method may use costs or sizes you computed in the constructor.
- Implement estimateTableCardinality(double selectivityFactor): This method returns the number of tuples in the relation, given that a predicate with selectivity selectivityFactor is applied. This method may use costs or sizes you computed in the constructor.

You may wish to modify the constructor of TableStats.java to, for example, compute histograms over the fields as described above for purposes of selectivity estimation.

After completing these tasks you should be able to pass the unit tests in TableStatsTest.

### 2.2.4 Join Cardinality

Finally, observe that the cost for the join plan  $p$  above includes expressions of the form  $\text{joincost}((t_1 \text{ join } t_2) \text{ join } t_3)$ . To evaluate this expression, you need some way to estimate the size (ntups) of  $t_1 \text{ join } t_2$ . This *join cardinality estimation* problem is harder than the filter selectivity estimation problem. In this assignment, you aren't required to do anything fancy for this, though it is possible to do a histogram-based method for join selectivity estimation, but this is not required.

While implementing, you should keep in mind the following:

- For equality joins, when one of the attributes is a primary key, the number of tuples produced by the join cannot be larger than the cardinality of the non-primary key attribute.
- For equality joins when there is no primary key, it's hard to say much about what the size of the output is -- it
  - ① **i**ld be the size of the product of the cardinalities of the tables (if both tables have the same value for all tuples) -- or it could be 0. It's fine to make up a simple heuristic (say, the size of the larger of the two tables).

- For range scans, it is similarly hard to say anything accurate about sizes. The size of the output should be proportional to the sizes of the inputs. It is fine to assume that a fixed fraction of the cross-product is emitted by range scans (say, 30%). In general, the cost of a range join should be larger than the cost of a non-primary key equality join of two tables of the same size.

### Exercise 3: Join Cost Estimation

The class `JoinOptimizer.java` includes all of the methods for ordering and computing costs of joins. In this exercise, you will write the methods for estimating the selectivity and cost of a join, specifically:

- Implement `estimateJoinCost(LogicalJoinNode j, int card1, int card2, double cost1, double cost2)`: This method estimates the cost of join `j`, given that the left input is of cardinality `card1`, the right input of cardinality `card2`, that the cost to scan the left input is `cost1`, and that the cost to access the right input is `card2`. You can assume the join is an NL join, and apply the formula mentioned earlier.
- Implement `estimateJoinCardinality(LogicalJoinNode j, int card1, int card2, boolean t1pkey, boolean t2pkey)`: This method estimates the number of tuples output by join `j`, given that the left input is size `card1`, the right input is size `card2`, and the flags `t1pkey` and `t2pkey` that indicate whether the left and right (respectively) field is unique (a primary key).

After implementing these methods, you should be able to pass the unit tests in `JoinOptimizerTest.java`.

## 2.3 Join Ordering

Now that you have implemented methods for estimating costs, you will implement the query optimizer. For these methods, joins are expressed as a list of join nodes (e.g., predicates over two tables) as opposed to a list of relations to join as described in class.

Translating the algorithm from our class to the join node list form mentioned above, an outline in pseudocode would be:

```

1. j = set of join nodes
2. for (i in 1...|j|):
3.     for s in {all length i subsets of j}
4.         bestPlan = {}
5.         for s' in {all length i-1 subsets of s}
6.             subplan = optjoin(s')
7.             plan = best way to join (s-s') to subplan
8.             if (cost(plan) < cost(bestPlan))
9.                 bestPlan = plan

```



```

10.     optjoin(s) = bestPlan
11. return optjoin(j)

```

To help you implement this algorithm, we have provided several classes and methods to assist you. First, the method `enumerateSubsets(Vector v, int size)` in `JoinOptimizer.java` will return a set of all of the subsets of `v` of size `size`. This method is not particularly efficient; you can try to implement a more efficient enumerator, but this is not required.

Second, we have provided the method:

```

private CostCard computeCostAndCardOfSubplan(HashMap<String, TableStats>
stats,

    HashMap<String, Double> filterSelectivities,

    LogicalJoinNode joinToRemove,

    Set<LogicalJoinNode> joinSet,

    double bestCostSoFar,

    PlanCache pc)

```

Given a subset of joins (`joinSet`), and a join to remove from this set (`joinToRemove`), this method computes the best way to join `joinToRemove` to `joinSet - {joinToRemove}`. It returns this best method in a `CostCard` object, which includes the cost, cardinality, and best join ordering (as a vector). `computeCostAndCardOfSubplan` may return null, if no plan can be found (because, for example, there is no left-deep join that is possible), or if the cost of all plans is greater than the `bestCostSoFar` argument. The method uses a cache of previous joins called `pc` (`optjoin` in the psuedocode above) to quickly lookup the fastest way to join `joinSet - {joinToRemove}`. The other arguments (`stats` and `filterSelectivities`) are passed into the `orderJoins` method that you must implement as a part of Exercise 4, and are explained below. This method essentially performs lines 6--8 of the psuedocode described earlier.

Third, we have provided the method:

```

private void printJoins(Vector<LogicalJoinNode> js,

    PlanCache pc,

    HashMap<String, TableStats> stats,

    HashMap<String, Double> selectivities)

```

This method can be used to display a graphical representation of a join plan (when the "explain" flag is set via the "-explain" option to the optimizer, for example).

Fourth, we have provided a class `PlanCache` that can be used to cache the best way to join a subset of the joins considered so far in your implementation of Selinger (an instance of this class is needed to use `computeCostAndCardOfSubplan`).

### Exercise 4: Join Ordering

In `JoinOptimizer.java`, implement the method:

```
Vector orderJoins(HashMap<String, TableStats> stats,  
                  HashMap<String, Double> filterSelectivities,  
                  boolean explain)
```

This method should operate on the `joins` class member, returning a new `Vector` that specifies the order in which joins should be done. Item 0 of this vector indicates the left-most, bottom-most join in a left-deep plan. Adjacent joins in the returned vector should share at least one field to ensure the plan is left-deep. Here `stats` is an object that lets you find the `TableStats` for a given table name that appears in the `FROM` list of the query. `filterSelectivities` allows you to find the selectivity of any predicates over a table; it is guaranteed to have one entry per table name in the `FROM` list. Finally, `explain` specifies that you should output a representation of the join order for informational purposes.

You may wish to use the helper methods and classes described above to assist in your implementation. Roughly, your implementation should loop through subset sizes, subsets, and sub-plans of subsets, calling `computeCostAndCardOfSubplan` and building a `PlanCache` object that stores the minimal-cost way to perform each subset join.

After implementing this method, you should be able to pass system test `QueryTest`.

## 3. Logistics

You must submit your code (see below) as well as a short (2 pages, maximum) writeup describing your approach. This writeup should:

- Describe any design decisions you made, including methods for selectivity estimation, join ordering.
- Discuss and justify any changes you made to the API.
- Describe any missing or incomplete elements of your code.
- Describe how long you spent on the assignment, and whether there was anything you found particularly difficult or confusing.

### 3.1. Collaboration

Please indicate clearly who you worked with (if anyone) and the division of the work on your writeup. Remember to use group submission and include your group member in gradescope.

### 3.2. Submitting your assignment

Please follow the same submission procedure as before. If applicable, please indicate your partner in your writeup.

Please submit your writeup as a PDF or plain text file only (no .rtf/.doc/.docx/.odf formats please). Don't forget to run `ant clean` and remove hidden directories (e.g. `.git/`) before you zip your codes.

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### 3.3. Submitting a bug

SimpleDB is a relatively complex piece of code. It is very possible you are going to find bugs, inconsistencies, and bad, outdated, or incorrect documentation, etc.

We ask you, therefore, to do this assignment with an adventurous mindset. Don't get mad if something is not clear, or even wrong; rather, try to figure it out yourself or send us a friendly email. Please submit (friendly!) bug reports to either TAs or the instructor. When you do, please try to include:

- A description of the bug.
- A `.java` file we can drop in the `test/simplydb` directory, compile, and run.
- A `.txt` file with the data that reproduces the bug. We should be able to convert it to a `.dat` file using `HeapFileEncoder`.

You can also post on the class page on Piazza if you feel you have run into a bug.

### 3.4 Grading

**85%** of your grade will be based on whether or not your code passes the test suite we will run over it. These tests will be a superset of the tests we have provided. Before handing in your code, you should make sure it produces no errors (passes all of the tests) from both `ant test` and `ant systemtest`.

**Important:** before testing, we will replace your `build.xml`, `HeapFileEncoder.java`, and the entire contents of the `test/` directory with our version of these files! This means you cannot change the format of `.dat` files! You should therefore be careful changing our APIs. This also means you need to test whether your code compiles with our test programs. In other words, we will untar your tarball, replace the files mentioned above, compile it, and then grade it. It will look roughly like this:

```
[replace build.xml, HeapFileEncoder.java, and test]
```

```
$ ant test
```

```
$ ant systemtest
```

```
[additional tests]
```

If any of these commands fail, we'll be unhappy, and, therefore, so will your grade.

**15%** of your grade will be based on the quality of your writeup and our subjective evaluation of your code.

We've had a lot of fun designing this assignment, and we hope you enjoy hacking on it!

