SQL QUERY EVALUATION

CS121: Introduction to Relational Database Systems

Fall 2016 – Lecture 12

Query Evaluation

- Last time:
  - Began looking at database implementation details
  - How data is stored and accessed by the database
  - Using indexes to dramatically speed up certain kinds of lookups
- Today: What happens when we issue a query?
  - …and how can we make it faster?
- To optimize database queries, must understand what the database does to compute a result

Query Evaluation (2)

- Today:
  - Will look at higher-level query evaluation details
  - How relational algebra operations are implemented
    - Common-case optimizations employed in implementations
  - More details on how the database uses these details to plan and optimize your queries
- There are always exceptions…
  - e.g. MySQL's join processor is very different from others
  - Every DBMS has documentation about query evaluation and query optimization, for that specific database

SQL Query Processing

- Databases go through three basic steps:
  - Parse SQL into an internal representation of a plan
  - Transform this into an optimized execution plan
  - Evaluate the optimized execution plan
- Execution plans are generally based on the extended relational algebra
  - Includes generalized projection, grouping, etc.
  - Also some other features, like sorting results, nested queries, LIMIT/OFFSET, etc.

Query Evaluation Example

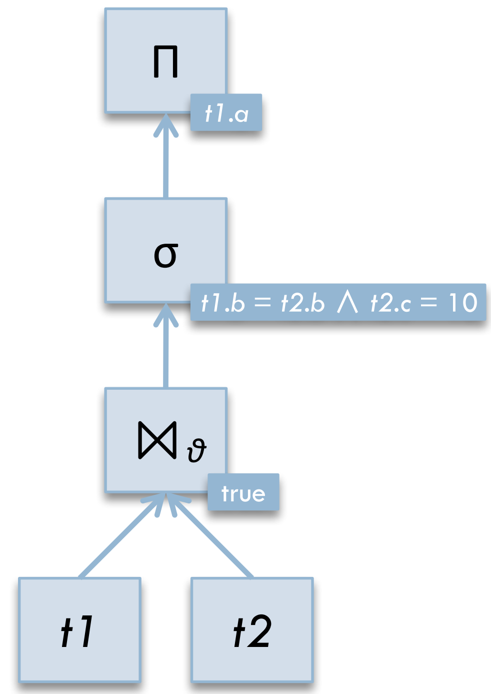
- A simple query:

```
SELECT t1.a FROM t1, t2
WHERE t1.b = t2.b AND t2.c = 10;
```

- Translating directly into the relational algebra:

  $\Pi_{t1.a}(\sigma_{t1.b = t2.b \wedge t2.c = 10}(t1 \times t2))$

- Database might create this structure:
  - DBs usually implement common join operations with theta-join plan nodes
  - Can be evaluated using a push- or a pull-based approach
  - Evaluation loop retrieves results from top-level Π operation



Query Optimization

- Are there alternate formulations of our query?

  $$\Pi_{t1.a}(\sigma_{t1.b\,=\,t2.b\ \wedge\ t2.c\,=\,10}(t1 \times t2))$$

  $$\Pi_{t1.a}(t1 \bowtie_{t1.b\,=\,t2.b} (\sigma_{t2.c\,=\,10}(t2)))$$

  $$\Pi_{t1.a}(\sigma_{t2.c\,=\,10}(t1 \bowtie_{t1.b\,=\,t2.b} t2))$$

  - *Which one is fastest?*
- The query optimizer generates many equivalent plans using a set of equivalence rules
  - <u>Cost-based optimizers</u> assign each plan a cost, and then the lowest-cost plan is chosen for execution
  - <u>Heuristic optimizers</u> just follow a set of rules for optimizing a query plan

Query Evaluation Costs

- A variety of costs in query evaluation
- Primary expense is reading data from disk
  - Usually, data being processed won't fit entirely into memory
  - Try to minimize disk seeks, reads and writes!
- CPU and memory requirements are secondary
  - Some ways of computing a result require more CPU and memory resources than others
  - Becomes especially important in concurrent usage scenarios
- Can be other costs as well
  - In distributed database systems, network bandwidth must be managed by query optimizer

Query Optimization (2)

- Several questions the optimizer has to consider:
  - How is a relation's data stored on the disk?
    - …and what access paths are available to the data?
  - What implementations of the relational algebra operations are available to use?
    - Will one implementation of a particular operation be much better or worse than another?
  - How does the database decide which query execution plan is best?
- Given the answers to these questions, what can <u>we</u> do to make the database go faster?

Select Operation

- How to implement σ_P operation?
- Easy solution from last time: scan the entire data file
  - Called a file scan
  - Test selection predicate against each tuple in the data file
  - Will be slow, since every disk block must be read
- This is a *general* solution, but not a *fast* one.
- What is the selection predicate P?
  - Depending on the characteristics of P, might be able to choose a more optimal evaluation strategy
  - If we can't, just stick with the file scan

Select Operation (2)

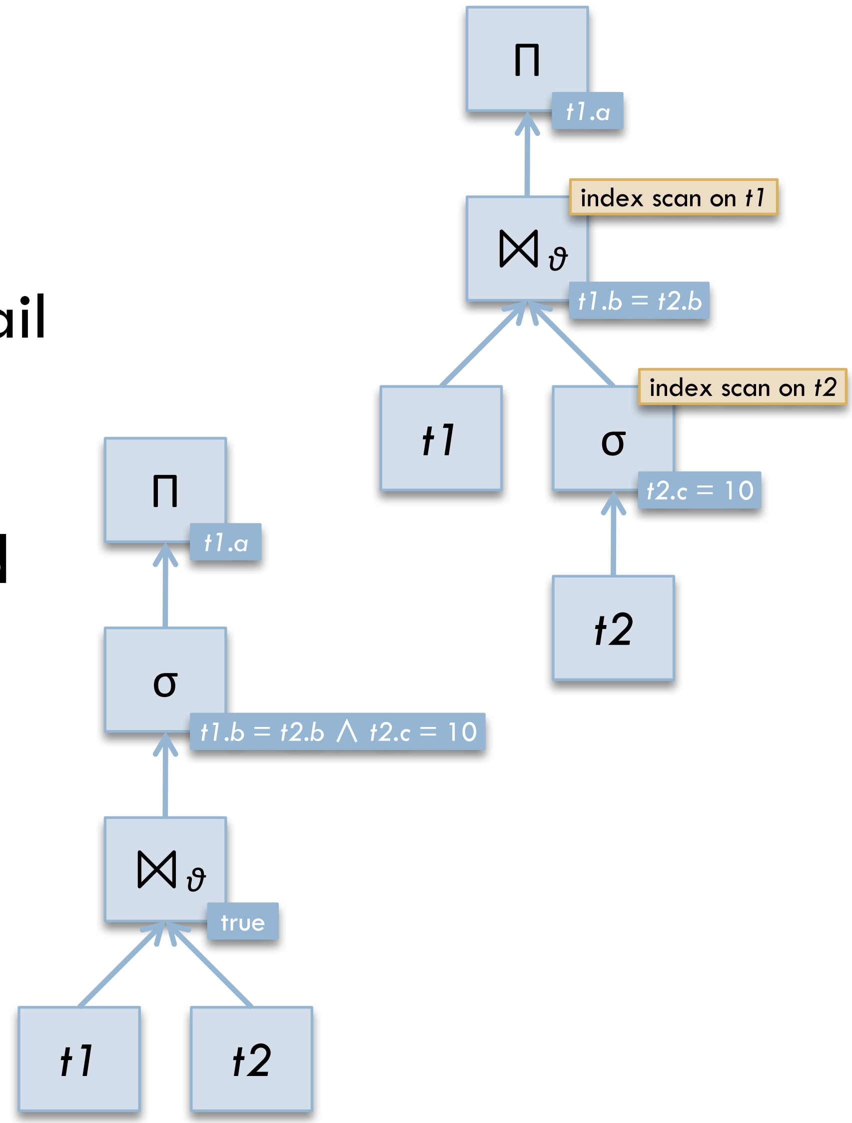
- Most select predicates involve a binary comparison
  - "Is an attribute equal to some value?"
  - "Is an attribute less than some value?"
- If data file was ordered, could use a binary search…
  - Would substantially reduce number of blocks read
  - Maintaining the logical record ordering becomes very costly if data changes frequently
- Solution:
  - Continue using heap file organization for table data
  - For important attributes, build <u>indexes</u> against the data file
    - Index provides a faster way to find specific values in the data file

Select Operation

- Query planner/optimizer looks at all access paths available for a given attribute
- For select operations:
  - If select predicate is an equality test and an index is available for that attribute, can use an index scan
  - Can also use index scan for comparison/range tests if an ordered index is available for the attribute
- For more complicated tests, or if no index is available for attributes being used:
  - Use the simple file scan approach

Query Optimization Using Indexes

- Database query optimizer looks for available indexes
  - If a select/lookup operation can use an index, execution plan is annotated with this detail
  - Overall plan cost is computed including these optimizations
- Indexes can only be exploited in certain circumstances
  - Typically, only by plan nodes that directly access the table
  - e.g. original plan can't really exploit indexes at all ☹



Project Operation

- Project operation is simple to implement
  - For each input tuple, create a new tuple with only the specified attributes
  - May also involve computed values
- Which would be faster, in general?

  $\Pi_{balance}(\sigma_{balance\ <\ 2500}(account))$

  $\sigma_{balance\ <\ 2500}(\Pi_{balance}(account))$

  - Want to project as few rows as possible, to minimize CPU and memory usage
    - Do select first: $\Pi_{balance}(\sigma_{balance\ <\ 2500}(account))$
  - Good heuristic example: "Do projects as late as possible."

Sorting

- SQL allows results to be ordered
- Databases must provide sorting capabilities in execution plans
  - Data being sorted may be much larger than memory!
- For tables that fit in memory, traditional sorting techniques are used (e.g. quick-sort)
- For tables that are larger than memory, must use an <u>external-memory sorting</u> technique
  - Table is divided into <u>runs</u> to be sorted in memory
  - Each run is sorted, then written to a temporary file
  - All runs are merged using an N-way merge sort

Sorting (2)

- In general, sorting should be applied as late as possible
  - Ideally, rows being sorted will fit into memory
- Some other operations can also use sorted inputs to improve performance
  - Join operations
  - Grouping and aggregation
  - Usually occurs when sorted results are already available
- Could also perform sorting with an ordered index
  - Scan index, and retrieve each tuple from table file in order
  - With magnetic disks, seek-time usually makes this prohibitive
    - (solid-state disks don't have this issue!)

Join Operations

- Join operations are *very* common in SQL queries
  - …especially when using normalized schemas
- Could also potentially be a very costly operation!
  - $r \bowtie s$ defined as $\sigma_{r.A\,=\,s.A}(r \times s)$
- A simple strategy for $r \bowtie_\theta s$:

for each tuple t_r **in** r **do begin**
    for each tuple t_s **in** s **do begin**
        if t_r , t_s satisfy condition θ **then**
            add $t_r \cdot t_s$ to result
    end
end

- $t_r \cdot t_s$ denotes the concatenation of t_r with t_s

Nested-Loop Join

- Called the <u>nested-loop join</u> algorithm:

  for each tuple t_r **in** r **do begin**
      for each tuple t_s **in** s **do begin**
          if t_r , t_s satisfy condition θ **then**
              add $t_r \cdot t_s$ to result
      end
  end

- A very slow join implementation
  - Scans r once, and s once for each row in r !
  - Not so horrible if s fits entirely in memory
- But, it can handle arbitrary conditions
  - For some queries, the only option is a nested-loop join!

Indexed Nested-Loop Join

- Most join conditions involve equalities
  - Called equijoins
- Indexes can speed up table lookups…
- Modify nested-loop join to use indexes in inner loop:

  for each tuple t_r **in** r **do begin**
      use index on s to retrieve tuple t_s
      if t_r **,** t_s satisfy condition θ **then**
          add $t_r \cdot t_s$ to result
  end

- Only an option for equijoins, where an index exists for the join attributes

MySQL Join Processor

- MySQL join processor is based on nested-loop join algorithm
  - Instead of joining two tables, can join N tables at once

```
for each tuple t_r in r do begin
    for each tuple t_s in s do begin
        for each tuple t_t in t do begin
            if t_r , t_s , t_t , … satisfy condition θ then
                add t_r · t_s · t_t · … to result
        end
    end
end
```

- Employs <u>many</u> optimizations
  - When possible, outer table is processed in blocks, to reduce number of iterations over inner tables
  - Indexes are exploited *heavily* for finding tuples in inner tables.
  - If a subquery can be resolved into a constant, it is.

MySQL Join Processor (2)

- Since MySQL join processor relies so heavily on indexes, what kinds of queries is it bad at?
  - Queries against tables without indexes… (duh)
  - **Queries involving joins against derived relations (ugh!)**
  - MySQL isn't smart enough to save the derived relation into a temporary table, then build an index against it
    - A common technique for optimizing complex queries in MySQL
- For more sophisticated queries, really would like more advanced join algorithms…
  - Most DBs include several other very powerful join algorithms
  - (Can't add to MySQL easily, since it doesn't use relational algebra as a query-plan representation…)

Sort-Merge Join

- If tables are already ordered by join attributes, can use a merge-sort technique
  - Must be an equijoin!
- Simple high-level description:
  - Two pointers to traverse tables in order:
    - p_r starts at first tuple in r
    - p_s starts at first tuple in s
  - If one pointer's tuple has join-attribute values less than the other pointer, advance that pointer
  - When pointers have the same value of the join attribute, generate joins using those rows
    - If p_r or p_s points to a run of records with the same value, must include all of these records in the join result

Sort-Merge Join (2)

- Much better performance than nested-loop join
  - Dramatically reduces disk accesses
  - Unfortunately, relations aren't usually ordered
- Can also enhance sort-merge joins when at least one relation has an index on the join attributes
  - e.g. one relation is sorted, and the unsorted relation has an index on the join attributes
  - Traverse unsorted relation's index in order
  - When rows match, use index to pull those tuples from disk
  - Disk seek cost must be managed carefully with this technique
    - e.g. can sort record pointers before reading the tuples from disk, to minimize the overall seek time

Hash Join

- Another join technique for equijoins
- For tables r and s :
  - Use a hash function on the join attributes to divide rows of r and s into partitions
    - Use same hash function on both r and s, of course
    - Partitions are saved to disk as they are generated
    - Aim for each partition to fit in memory
    - r partitions: $H_{r1}, H_{r2}, \ldots, H_{rn}$
    - s partitions: $H_{s1}, H_{s2}, \ldots, H_{sn}$
  - Rows in H_{ri} will only join with rows in H_{si}

Hash Join (2)

- After partitioning:

```
for i = 1 to n do
    build a hash index on H_si                    (using a second hash function!)
    for each row t_r in H_ri
        probe hash index for matching rows in H_si
        for each matching tuple t_s in H_si
            add t_r · t_s to result
        end
    end
end
```

- Very fast and efficient equijoin strategy
  - Very good for joining against derived relations!
  - Can perform badly when rows can't be hashed into partitions that fit into memory

Outer Joins

- Join algorithms can be modified to generate left outer joins reasonably efficiently
  - Right outer join can be restated as left outer join
  - Will still impact overall query performance if many rows are generated
- Full outer joins can be significantly harder to implement
  - Sort-merge join can compute full outer join easily
  - Nested loop and hash join are much harder to extend
  - Full outer joins can also impact query performance heavily

Other Operations

- Set operations require duplicate elimination
  - Duplicate elimination can be performed with sorting or with hashing
- Grouping and aggregation can be implemented in several ways
  - Can sort results on the grouping attributes, then compute aggregates over the sorted values
    - All rows in a given group are adjacent to each other, so uses memory very efficiently (at least, after the sorting step…)
    - MySQL uses this approach by default
  - Can also use hashing to perform grouping and aggregation
    - Hash tuples on the grouping attributes, and compute each group's aggregate values incrementally

Optimizing Query Performance

- To improve query performance, you must know how the database actually runs your query
- Discussed the "explain" statement last time
  - Runs planner and optimizer on your query, then outputs the plan and corresponding cost estimates
- Using this information, you can:
  - Create indexes on tables, where appropriate
  - Restate the query to help the DB pick a better plan
- Harder cases may require multiple steps:
  - Generate intermediate results more well-suited for the desired query
  - Then, use intermediate results to generate final results

Query Execution Example

- For each assignment, finds the average size of the last submission from students for that assignment:

```
SELECT shortname,
       AVG(last_submission_size) AS
           avg_last_submission_size
FROM assignment NATURAL JOIN
     submission NATURAL JOIN
     (SELECT sub_id,
             total_size AS last_submission_size
      FROM fileset NATURAL JOIN
           (SELECT sub_id, MAX(sub_date) AS sub_date
            FROM fileset GROUP BY sub_id
           ) AS last_sub_dates
     ) AS last_sub_sizes
GROUP BY shortname;
```

Find the date of the last fileset submitted for each student's submission. Name the result columns to allow a natural join against the fileset table.

Query Execution Example (2)

- For each assignment, finds the average size of the last submission from students for that assignment:

```
SELECT shortname,
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FROM assignment NATURAL JOIN
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      FROM fileset NATURAL JOIN
           (SELECT sub_id, MAX(sub_date) AS sub_date
            FROM fileset GROUP BY sub_id
           ) AS last_sub_dates
     ) AS last_sub_sizes
GROUP BY shortname;
```

Join the derived result against fileset so we can retrieve the total size of the submitted files.

Query Execution Example (3)

- For each assignment, finds the average size of the last submission from students for that assignment:

```
SELECT shortname,
       AVG(last_submission_size) AS
           avg_last_submission_size
FROM assignment NATURAL JOIN
     submission NATURAL JOIN
     (SELECT sub_id,
             total_size AS last_submission_size
      FROM fileset NATURAL JOIN
           (SELECT sub_id, MAX(sub_date) AS sub_date
            FROM fileset GROUP BY sub_id
           ) AS last_sub_dates
     ) AS last_sub_sizes
GROUP BY shortname;
```

Outermost query finds the averages of these last submissions, and also incorporates the short-name of each assignment.

MySQL Execution and Analysis

- MySQL executes this query rather slowly*
  - About 3 sec on a server with 8GB RAM, RAID1 mirroring
  - Intuitively makes sense…
    - Joins against derived relations, non-index columns, etc.
    - All the stuff that MySQL isn't so good at handling
- **`EXPLAIN`** output:

id	select_type	table	type	possible_keys	key	key_len	ref	rows	Extra
1	PRIMARY	<derived2>	ALL	NULL	NULL	NULL	NULL	1506	Using temporary; Using filesort
1	PRIMARY	submission	eq_ref	PRIMARY	PRIMARY	4	last_sub_sizes.sub_id	1	
1	PRIMARY	assignment	eq_ref	PRIMARY	PRIMARY	4	donnie_db.submission.asn_id	1	
2	DERIVED	<derived3>	ALL	NULL	NULL	NULL	NULL	1506	
2	DERIVED	fileset	ALL	NULL	NULL	NULL	NULL	2799	Using where; Using join buffer
2	DERIVED	submission	eq_ref	PRIMARY	PRIMARY	4	last_sub_dates.sub_id	1	Using index
3	DERIVED	fileset	ALL	NULL	NULL	NULL	NULL	2799	Using temporary; Using filesort

- Confirms our suspicions
- Can optimize by storing innermost results in a temp table, and creating indexes on (sub_id, sub_date)

* Test was performed with MySQL 5.1; MariaDB 5.5 executes this query extremely quickly.

PostgreSQL Execution/Analysis (1)

- Postgres executes this query instantaneously. On a laptop.
  - Fundamental difference: more sophisticated join algorithms
    - Specifically hash join, which is very good at joining relations on non-indexed attributes
- **EXPLAIN** output:

```
HashAggregate  (cost=221.38..221.39 rows=1 width=8)
  ->  Nested Loop  (cost=144.28..221.37 rows=1 width=8)
        ->  Nested Loop  (cost=144.28..213.09 rows=1 width=20)
              ->  Nested Loop  (cost=144.28..212.81 rows=1 width=20)
                    ->  Hash Join  (cost=144.28..204.53 rows=1 width=12)
                          Hash Cond: ((fileset.sub_id = fileset.sub_id) AND ((max(fileset.sub_date)) = fileset.sub_date))
                          ->  HashAggregate  (cost=58.35..77.18 rows=1506 width=12)
                                ->  Seq Scan on fileset  (cost=0.00..44.57 rows=2757 width=12)
                          ->  Hash  (cost=44.57..44.57 rows=2757 width=16)
                                ->  Seq Scan on fileset  (cost=0.00..44.57 rows=2757 width=16)
                    ->  Index Scan using submission_pkey on submission  (cost=0.00..8.27 rows=1 width=8)
                          Index Cond: (submission.sub_id = fileset.sub_id)
              ->  Index Scan using assignment_pkey on assignment  (cost=0.00..0.27 rows=1 width=8)
                    Index Cond: (assignment.asn_id = submission.asn_id)
        ->  Index Scan using submission_pkey on submission  (cost=0.00..8.27 rows=1 width=4)
              Index Cond: (submission.sub_id = fileset.sub_id)
```

- As expected, Postgres uses a hash join to join the derived relation against **fileset** table on non-index columns

PostgreSQL Execution/Analysis (2)

- Can disable various join algorithms in Postgres ☺
  - **`SET enable_hashjoin = off;`**
- **`EXPLAIN`** output:

```
HashAggregate  (cost=422.68..422.69 rows=1 width=8)
  -> Nested Loop  (cost=373.85..422.67 rows=1 width=8)
        -> Nested Loop  (cost=373.85..414.39 rows=1 width=20)
              -> Nested Loop  (cost=373.85..414.11 rows=1 width=20)
                    -> Merge Join  (cost=373.85..405.83 rows=1 width=12)
                          Merge Cond: ((fileset.sub_id = fileset.sub_id) AND (fileset.sub_date = (max(fileset.sub_date))))
                          -> Sort  (cost=202.12..209.01 rows=2757 width=16)
                                Sort Key: fileset.sub_id, fileset.sub_date
                                -> Seq Scan on fileset  (cost=0.00..44.57 rows=2757 width=16)
                          -> Sort  (cost=171.73..175.50 rows=1506 width=12)
                                Sort Key: fileset.sub_id, (max(fileset.sub_date))
                                -> HashAggregate  (cost=58.35..77.18 rows=1506 width=12)
                                      -> Seq Scan on fileset  (cost=0.00..44.57 rows=2757 width=12)
                    -> Index Scan using submission_pkey on submission  (cost=0.00..8.27 rows=1 width=8)
                          Index Cond: (submission.sub_id = fileset.sub_id)
              -> Index Scan using assignment_pkey on assignment  (cost=0.00..0.27 rows=1 width=8)
                    Index Cond: (assignment.asn_id = submission.asn_id)
        -> Index Scan using submission_pkey on submission  (cost=0.00..8.27 rows=1 width=4)
              Index Cond: (submission.sub_id = fileset.sub_id)
```

- Sort + sort-merge join is still faster than nested loops!!

PostgreSQL Execution/Analysis (3)

- Now, disable sort-merge joins too:
  - **`SET enable_mergejoin = off;`**
- Finally, Postgres performance is closer to MySQL
- **`EXPLAIN`** output:

```
HashAggregate  (cost=103956.21..103956.23 rows=1 width=8)
  ->  Nested Loop  (cost=93.75..103956.21 rows=1 width=8)
        ->  Nested Loop  (cost=93.75..103947.93 rows=1 width=20)
              ->  Nested Loop  (cost=93.75..103947.65 rows=1 width=20)
                    ->  Nested Loop  (cost=93.75..103939.37 rows=1 width=12)
                          Join Filter: ((fileset.sub_id = fileset.sub_id) AND (fileset.sub_date = (max(fileset.sub_date))))
                          ->  Seq Scan on fileset  (cost=0.00..44.57 rows=2757 width=16)
                          ->  Materialize  (cost=93.75..108.81 rows=1506 width=12)
                                ->  HashAggregate  (cost=58.35..77.18 rows=1506 width=12)
                                      ->  Seq Scan on fileset  (cost=0.00..44.57 rows=2757 width=12)
                    ->  Index Scan using submission_pkey on submission  (cost=0.00..8.27 rows=1 width=8)
                          Index Cond: (submission.sub_id = fileset.sub_id)
              ->  Index Scan using assignment_pkey on assignment  (cost=0.00..0.27 rows=1 width=8)
                    Index Cond: (assignment.asn_id = submission.asn_id)
        ->  Index Scan using submission_pkey on submission  (cost=0.00..8.27 rows=1 width=4)
              Index Cond: (submission.sub_id = fileset.sub_id)
```

Query Estimates

- Query planner/optimizer must make *estimates* about the cost of each stage
- Database maintains statistics for each table, to facilitate planning and optimization
- Different levels of detail:
  - Some DBs only track min/max/count of values in each column. Estimates are very basic.
  - Some DBs generate and store histograms of values in important columns. Estimates are much more accurate.
- Different levels of accuracy:
  - Statistics are expensive to maintain! Databases update these statistics relatively infrequently.
  - If a table's contents change substantially, must recompute statistics

Table Statistics Analysis

- Databases also frequently provide a command to compute table statistics
- MySQL command:

```
ANALYZE TABLE assignment, submission, fileset;
```

- PostgreSQL command:

```
VACUUM ANALYZE;
```

  - for all tables in database

```
VACUUM ANALYZE tablename;
```

  - for a specific table
- These commands are expensive!
  - Perform a full table-scan
  - Also, typically lock the table(s) for exclusive access

Review

- Discussed general details of how most databases evaluate SQL queries
- Some relational algebra operations have several ways to evaluate them
  - Optimizations for very common special cases, e.g. equijoins
- Can give the database some guidance
  - Create indexes on tables where appropriate
  - Rewrite queries to be more efficient
  - Make sure statistics are up-to-date, so that planner has best chance of generating a good plan