CS165 Project for Fall 2023

Overview

The goal of the project is to design and build a main-memory optimized column-store.

By the end of the project you will have designed, implemented, and evaluated several key elements of a modern data system and you will have experienced several design tradeoffs in the same way they are experienced in all major data industry labs.

This is a heavy but fun project! We will also point to several open research problems throughout the semester that may be studied on top of the class project and that you may decide to take on as a research project if you like.

The project runs through the whole semester. There are a total of 4 milestones with specific expected software deliverables, which will be accompanied with a design document. The deliverables will be tested using predefined automated tests for functionality and, as extra credit, performance. We will provide these tests before-hand so you can test your system as you develop it.

We will provide you with starting code that implements the basic client-server functionality, i.e., anything that has to do with how a server communicates with the client over a socket. In addition, we will provide a parser for the domain specific language. In this way your focus will be on designing and building the core of the database server, i.e., the essential core data processing algorithms and data structures of a database system. Whenever applicable we will let you know if there are existing libraries that are OK to use.

The project includes work on storage methods such as arrays for plain storage and B-trees for clustered or secondary indexes. It also includes work on access methods such as fast scans that are optimized for modern hardware and can utilize properties such as CPU prefetching and multi-cores. We expect you to provide main-memory optimized designs and implementation for several core operators of a db system: select, fetch, join, aggregations and basic math. In addition, the project includes work on updates and efficient execution of workloads that include multiple concurrent queries using scan sharing.

Putting everything together you will have a data system that gets as input an intermediate language, i.e., a language used by db optimizers to describe a physical query plan. The system will be able to run complete select-project-join queries and it will be at least an order of magnitude faster than traditional row-store database systems in analytical workloads.
Logistics

Implementation language: The implementation language for the project is C. This is because a low-level language is required to design and build efficient systems as we need to have full control of how we utilize memory and computational resources. (Part of our bonus tasks include using alternative languages.)

Why not C++: Due to the complexity of the project, it is feasible to only support a single language. We require C instead of C++ because C is the purest language in terms of its low-level control over memory allocation and processor commands. By removing more advanced language constructs such as virtual function tables, lambda expressions, etc., we code in a way that requires constant thought about how our design is being used physically by the processor and memory subsystems.

Test Machine: All evaluation and formal testing for this class will occur on our lab machine. In particular, credit for assignments is given when your submitted code runs correctly on our lab machine; no credit is given for assignments which run correctly on your local machine but not on the lab machine. The lab machine will run automated tests multiple times per week and you will receive automated email notifications on the status of your code, and so you will be aware of what tests are passing on the lab machine. The correctness tests correspond to the same test generation processes as the test generators in the starter code. For project benchmarking (for performance) the staff will use a held-out private larger workload. The test machine will run Docker Server, using the cs165 Docker image specified in the starter code repository's main Dockerfile. The Docker serves to standardize starting code distribution and execution, please read all setup related documentation including README, and setup notes in the starter code before you start. You can also get help with set-up issues at our daily labs.

Compiler: gcc 7.4.X will be used to compile your code on the test machine before running it. You should not rely on any features or functionality that have been added since this version. gcc is generally backward compatible so if you are using an older version of gcc you should be fine but you should confirm this by running your code on the test machine. You are free to use a different compiler on your own machine but it is your own responsibility to make sure that your code compiles on the Docker execution environment. Compilation using gcc 7.4.X can be easily verified using the Dockerfile provided.

Libraries: Before using any library check with the instructor and the TFs. In general, we will not allow any library that has to do with data structures. The reason is that one of the main objectives of the course is to learn about the trade-offs in designing these data structures/algorithms yourself. By controlling the data structures, you have control over every last bit in your system's data and you can minimize the amount of data your system moves around (which is the primary bottleneck).

IDE: You may use any IDE and development environment that you are familiar with. As long as your project compiles on our machine, everything is OK. We do not support, though, specific IDEs. If you are looking for an IDE, simple yet powerful IDEs include Vim, Emacs, and Sublime Text.

Evaluation: Individual deliverables should pass the automated tests on the test machine. However, you will not be judged only on how well your system works; it should be clear that you have designed and implemented the whole system, i.e., you should be able to perform changes on-the-fly, explain design details, etc.

At the end of the semester each student will have a 1-hour session with the instructor and another 1-hour session with the TFs where they will demonstrate the system and answer design questions about the current design and about supporting alternative functionality. [Tip: From past experience we found that
frequent participation in office hours, brainstorming sessions and sections implies that the instructor and the TFs are very well aware of your system and your progress which makes the final evaluation a mere formality for these cases.]

**Collaboration Policy:** The project is an individual project: the final deliverable should be personal, you must write from scratch all the code of your system and all documentation and reports. Discussing the design and implementation problems with other students is allowed and encouraged! We will do so in the class as well and during office hours, sections and brainstorming sessions.

**Design Document and Feedback:** For every milestone, once you have a basic design that you think you want to try and before you start implementing it, create a 1-2 page PDF with the design and give it to us for feedback. Evaluation and feedback of design documents (and feedback in general) happens during office hours and labs. We have 1 hour of OH every day and 1 hour of labs so you have 10 hours every week to get feedback. Come with your design so we can review it live together. Your design does not have to be perfect; the idea is that we can give you early feedback, help you with your design decisions, and point to possible optimizations.

*Note, that there is hard deadline to deliver a design document for the first 2 milestones as part of the midway check in. After that, the design document is optional for the rest of the milestones but is strongly encouraged in the final report (see template here).*

**Bonus points for extra tasks:** We will regularly assign extra tasks or you can come up with your own extra tasks for the various components of the project. With these extra tasks you gain extra points.

**Leaderboard:** We will have a running competition and an anonymous leaderboard infrastructure so you can continuously test your system against the rest of the class, as well as best projects from previous iterations of the class.

**Grading:** The project counts for the 60% of the class grade. Out of the 60%, 30% is passing the 37 automated tests spread over the four milestones, 12% is the final report and presentation, 8% is the final code evaluation, 5% is midway check-in tests, and 3% is midway check-in document. Furthermore, there are three bonus tasks per each milestone, where each of the bonus tasks counts for an extra 0.25% of the total class grade. Furthermore, there is a final milestone 5, which counts for another extra of 5% of the total class grade. Furthermore, the top 3 projects in every leaderboard milestone will get 1% of the class grade as another bonus (there are total 8 leaderboard milestones).
Starting Code and API

We have created a repository with handout code that you can use to get started on your project. The goal of providing this code is twofold. First, in this repository we provide the parts of your system that are not directly related to data systems (such as client/server communication). Second, we give you a starting implementation of various parts of the database system that can help you with your own design. You are free to build upon the given code or to start over with your own architecture.

We will notify you if/when the base code changes (bug fixes or added functionality), but you may also want to pull from the master periodically.

To add the repository, do the following:

1. Login to code.harvard.edu. Add the ssh key of your computer to your code.harvard.edu account.
2. Create a bare clone of the repository. (This is temporary and will be removed so just do it wherever.):
   
   ```
   git clone --bare git@code.harvard.edu:sap835/cs165-2021-starter-code.git
   ```

3. Create a new private repository on your Github (code.harvard.edu) and name it say "cs165-project".
4. Mirror-push your bare clone to your new 'cs165-project' repository. Replace <your_username> with your actual code.harvard.edu username in the url below.
   
   ```
   cd cs165-2021-starter-code.git
   git push --mirror git@code.harvard.edu:<your_username>/cs165-project.git
   ```

5. Remove the temporary local repository you created in Step 3.
   
   ```
   cd ..
   rm -rf cs165-2021-starter-code.git
   ```

6. You can now clone your cs165-project repository on your machine (in our case in the 'code' folder).
   
   ```
   cd ~/code
   git clone git@code.harvard.edu:<your_username>/cs165-project.git
   ```

7. Add the original repo as remote to fetch (potential) future changes. Make sure you also disable push on the remote (as you are not allowed to push to it anyway).
   
   ```
   cd cs165-project
   git remote add upstream git@code.harvard.edu:sap835/cs165-2021-starter-code.git
   git remote set-url --push upstream DISABLE
   ```

8. You can list all your remotes with
   
   ```
   git remove -v
   ```
You should see:

```
origin  git@code.harvard.edu:<your_username>/cs165-project.git
(fetch)
origin  git@code.harvard.edu:<your_username>/cs165-project.git
(push)
upstream  git@code.harvard.edu:sap835/cs165-2021-starter-code.git (fetch)
upstream  DISABLE (push)
```

9. When you push, do so on origin with `git push origin`. When you want to pull changes from upstream you can just fetch the remote and rebase on top of your work.

```
git fetch upstream
git rebase upstream/master
```

And solve the conflicts if any.
**Milestones**

**MILESTONE 1: BASIC COLUMN-STORE - SUGGESTED COMPLETION DATE: FIRST WEEK OF OCTOBER**

In this milestone, the goal is to design and implement the basic functionality of a column-store with the ability to run single-table queries. The first part of this milestone is about the storage and organization of relational data in the form of columns, one per attribute. This requires the creation and persistence of a database catalog containing metadata about the tables in your database as well as the creation and maintenance of files to store the data contained in these tables. While the data in your database should be persistent, it does not need to be fault tolerant (you may assume power is never interrupted, disks don’t fail, etc). Your system should support storing integer data.

The next step is to implement a series of scan-based operators on top of the columns to support queries with select, project, aggregation and math operators. Then using these operators you will synthesize single-table query plans such as `SELECT max(A) FROM R where B< 20 and C > 30` that work with a bulk processing data flow. It should be noted that even when columns store only integer data, the results of aggregation statements (such as AVG) may produce non-integer results.

** Desired Functionality:**

After implementing this milestone we expect that your system will be able to support loading and retrieving data from a simple column-store. In particular, after **Milestone 1**, the system should be able to create a database, load files, insert new rows, select data from a column, fetch data from a column, and calculate aggregates (max, min, avg, sum, add, sub). For example, after creating a database, a table, and the corresponding columns:

- `create(db,"awesomebase")` -- create db with name "awesomebase"
- `create(tbl,"grades",awesomebase,6)` -- create table "grades" with 6 columns in the "awesomebase"
- `create(col,"project",awesomebase.grades)` -- create column 1 with name "project"
- `create(col,"midterm1",awesomebase.grades)` -- create column 2 with name "midterm1"
- `create(col,"midterm2",awesomebase.grades)` -- create column 3 with name "midterm2"
- `create(col,"class",awesomebase.grades)` -- create column 4 with name "class"
- `create(col,"quizzes",awesomebase.grades)` -- create column 5 with name "quizzes"
- `create(col,"student_id",awesomebase.grades)` -- create column 6 with name "student_id"
The system should be able to insert a few values:

relational_insert(awesomebase.grades,107,80,75,95,93,1)
relational_insert(awesomebase.grades,92,75,82,90,85,2)
relational_insert(awesomebase.grades,110,95,90,100,95,3)
relational_insert(awesomebase.grades,88,70,75,85,95,4)

In order to eventually, be able to select and fetch to implement a very simple query:

a_plus=select(awesomebase.grades.project,90,100) -- Find the students (rows) with project grade between 90 and 100

ids_of_students_with_top_project=fetch(awesomebase.grades.student_id,a_plus) -- Find the student id of the students

Finally, the database should shut down gracefully, storing the databases, tables, and columns in the database:

shutdown -- close the server and store all data to disk

**Suggested Guidance (How To Proceed, But Not Binding!):**

a) To complete this milestone your database will need to implement a variable pool and database catalog. The variable pool is transient and keeps track of the state of client-server communication. This includes keeping track of named intermediate results. For instance, “a_plus” in the previous example is an intermediate result specific to the client that executed the query. These variables are not persistent and should be released on client shutdown. In contrast, the database catalog is a persistent structure that tells your database how to locate tables, columns, and their metadata. This information must be persisted on shutdown and recreated when the database starts up again.

b) To store intermediate results during predicate evaluation, there are two popular alternatives: position lists and bit vectors. Position lists keep track of qualifying tuples by storing their positions. Bit vectors keep track of qualifying positions by setting the corresponding bit to 1 in a bit array with size equal to the column being scanned. We encourage you to think about the pros and cons of using each of these alternatives.

c) For persisting data, we encourage you to use memory-mapped files, which allow you to map any file into the memory space. The system call `mmap()` creates a mapping between the virtual memory space and the space within physical hardware. It allows you to conveniently read from and write to disk-resident files. Unlike `read()` or `write()`, you can selectively load regions of a file that you would want to access. This particularly speeds up I/O performance on large files. `mmap()` is also useful when multiple processes need read/write access to the same file. When you’re done, you can simply use `munmap()` to unmap the file from memory. Please look into the `man pages` for more information.
**Bonus Tasks:**

1. Add support for variable length data.
2. Implement vectorized processing plans and provide a performance comparison with the bulk processing ones.
3. Implement this milestone in an alternative language of your choice and provide a performance comparison and analysis against the C implementation. We propose you use Go.

**MILESTONE 2: FAST SCANS: SCAN SHARING & MULTI-CORES - SUGGESTED COMPLETION DATE:**

**THIRD WEEK OF OCTOBER**

The second milestone is about making your scans fast. You will be adding support for scan sharing to minimize data movement and making scans use multiple cores to fully utilize parallelization opportunities of modern CPUs.

Your system should be able to run N>>1 queries in parallel by reading data only once for the different queries’ select operators. The end goal is to be able to run simple single-table queries (as in the first milestone) but use the new select operators that are capable of scan sharing.

To introduce more opportunities and enable shared scans, we introduce batching operators. The client can declare a batch of queries to execute and then tell the server to execute them all at once. The server then must coordinate with the client when it is done with this batch. During this batching operation, it can be assumed that no print commands will be executed.

The end result of this milestone should be a linear scale up with the number of concurrent queries and number of cores. Your final deliverable should include a performance report (graphs and discussion) to demonstrate that you can achieve such a performance boost. This report should discuss your results with respect to the various parameters that affect shared scan performance such as the number of queries and the number of cores.

We also expect you to answer the following question: How many concurrent queries can your shared scan handle? Is there an upper limit? If yes, why?

**Desired Functionality:**

After **Milestone 2**, the main effort is in optimizing scanning and fetching, hence, the relevant calls should be much faster. The following call should run now much faster.

```python
batch_queries()

a_plus=select(awesomebase.grades.project,90,100) -- Find the students (rows) with project grade between 90 and 100

a=select(awesomebase.grades.project,80,90) -- Find the students (rows) with project grade between 80 and 90

super_awesome_peeps=select(awesomebase.grades.project,95,105)

ids_of_students_with_top_project=fetch(awesomebase.grades.student_id,a_plus) -- Find the student id of the a_plus students
```
batch_execute() -- The three selects should run as a shared scan

**Suggested Guidance (How To Proceed, But Not Binding!):**

a) Creating a fixed thread pool can help in reducing overheads due to thread calls and coordination as opposed to spawning and destroying multiple threads as and when needed. Consider thinking on this decision.

b) Consider deciding if the job of a single scan should be shared across cores (for very large range size) or separate scan jobs shared across cores e.g. 1 scan/core (for low/moderate range size).

c) For cases where’s queries to be batched is greater than number of available physical cores, think about the rationale of which queries map to which cores. For instance, if 2 or more queries scan overlapping data on a given column, they may be mapped to the same core to take advantage of locality of query access patterns and prevent unnecessary cache eviction.

**Bonus Tasks:**

1. Utilize sharing for queries from multiple clients
2. Utilize sharing for additional operators (like fetch).
3. Implement this milestone in an alternative language of your choice and provide a performance comparison and analysis against the C implementation. We propose you use Go.

**MILESTONE 3: INDEXING - SUGGESTED COMPLETION DATE: FIRST WEEK OF NOVEMBER**

The goal is to add indexing support to boost select operators. Your column-store should support memory-optimized B-tree indexes and sorted columns in both clustered and unclustered form. In the first case, all columns of a table follow the sort order of a leading column(s). We expect query plans to differentiate between the two cases and properly exploit their physical layout properties. The end goal is to be able to run single-table queries (as in the first milestone) but use the new index-based select operators instead. Your column-store should support multiple clustered indices as well as multiple unclustered indices. To support multiple clustered indices, your database must organize and keep track of several copies of your base data. To make the creation of these clustered indices easier, we place several restrictions on them:

1. All clustered indices will be declared before the insertion of data to a table.
2. Every clustered index has a copy of base data, which is sorted based on the values in the column to be indexed.
3. The first declared clustered index will be the principal copy of the data. Only this copy of the data will support primary indices.

**TIP**  You should consider the case where a column has duplicate data and therefore your index should be able to handle duplicate keys.

In addition, in this milestone we expect that you implement a very basic query optimizer. In particular, we expect your system to decide between using an index or using a scan for the select operator. This will require the keeping of very basic statistics such as a rough histogram of the data distribution for each column and will allow you to demonstrate the performance gains from your Milestone 3 index design.
Desired Functionality:

After the third milestone, the system should be able to create columns organized using a B-Tree or in sorted form. For example, we may want an index for column 6 of the example in Milestone 1 in order to locate easily each student based on their id. In this case, we should be able to give:

```
create(idx, awesomebase.grades.student_id, btree, clustered)
```

**TIP**| Be careful of random access during tuple reconstruction after an unclustered index-based select.

Suggested Guidance (How To Proceed, But Not Binding!):

a) We expect your B-tree to be tuned for main-memory, i.e., to minimize cache misses by properly tuning design parameters such as the fan-out of the tree based on the underlying hardware as well as any other design parameter that may affect performance.

b) Consider changing various design decisions for internal vs. leaf nodes in the B-Tree, and then as well consider optimizations that can be made for clustered vs. unclustered indices. A common example of an optimization that deviates away from the standard B-tree is making leaf nodes contain more elements than internal nodes. In order to optimize performance, you are allowed to move away from the basic B-tree design.

Your final deliverable should include a performance analysis (i.e., graphs and discussion) that shows the performance difference between your various select methods (alternative tree designs, scans, and binary search) based on various parameters that affect performance such as selectivity and number of tuples.

**Bonus Tasks:**

1. Add support for zone-maps and provide performance comparison with scans and indexes.
2. Utilize multi-cores for the B-tree index.
3. Implement this milestone in an alternative language of your choice and provide a performance comparison and analysis against the C implementation. We propose you use Go.
MILESTONE 4: JOINS - SUGGESTED COMPLETION DATE: THIRD WEEK OF NOVEMBER

For the fourth milestone you will be adding join support to your system. We expect you to support cache-conscious hash joins and nested-loop join that utilize all cores of the underlying hardware.

In addition you need to support query plans that use these new join operators, e.g.:

```
SELECT max(R.d), min(S.g)
FROM R, S
WHERE
    R.a = S.a
AND R.c >= 1
AND R.c <= 9
AND S.f >= 31
AND S.f <= 99
```

Your plans should use late materialization and bulk processing.

TIP: Make sure you minimize random access during fetch operators after a join.

The final deliverable for this milestone includes a performance report of nested loops vs hash joins, and a comparison of a grace-hash join vs. a one-pass hash join for large data sizes.

Desired Functionality:

Milestone 4 introduces joins, a key relational operation. The result would be that the system would support joins, and be able to join two tables. For example, after creating two tables and populating them with tuples, the user should be able to join them:

```
positions1=select(awesomebase.cs165.project_score,100,null) -- select positions where project score >= 100 in cs165

positions2=select(awesomebase.cs265.project_score,100,null) -- select positions where project score >= 100 in cs265

values1=fetch(awesomebase.cs165.student_id,positions1)

values2=fetch(awesomebase.cs265.student_id,positions2)

r1,r2=join(positions1,values1,positions2,values2,hash) -- positions of students who have project score >= 100 in both classes
```

Suggested Guidance (How To Proceed, But Not Binding!):

a) Implement single core versions of the three join types (nested loop, hash, grace hash). Nested loop is a good sanity check for correct logic as it has very simple code.

b) Consider parallelization opportunities for each join type. For each consider which tasks are embarrassingly parallel and which require coordination.
c) Measure the cost of coordination for tasks. For those with high cost of coordination, find ways to reduce the costs or argue that single core is about as well as can be done.

**Bonus Tasks:**

1. Add support for sort-merge joins and provide a performance comparison with hash joins.
2. Download an open-source row-store DBMS such as PostgreSQL and an open-source column-store DBMS such as MonetDB and provide a comparison with your system on this milestone’s tests.
3. Implement this milestone in an alternative language of your choice and provide a performance comparison and analysis against the C implementation. We propose you use Go.

**MILESTONE 5 (BONUS MILESTONE): UPDATES - SUGGESTED COMPLETION DATE: FIRST WEEK OF DECEMBER**

For the final milestone we will be adding update support. We expect you to support inserts, deletes, and updates on relational tables. Any changes to data should be persistent, i.e., they should not get lost if we restart the server.

The goal is to add update support, maintaining the correctness of the various indexes on the base data. In this milestone you should be able to run workloads where read queries interleave with updates (inserts, deletes or actual updates). As a bonus task, you can add parallelism to updates, allowing multiple queries to work in parallel, updating/reading the same data but this is not mandatory for the main deliverable.

An update requires changing each copy of the data. This means keeping metadata around in some form such that updates made on one copy of the data get propagated to the other copies of the data! Come to office hours and labs early and often on this front if unsure about the best way to achieve this. One suggested way is to keep a table which maps row numbers in your primary copy to each of the other copies. Then given positions for one copy of the data, the other positions can be found using a join on this table.

**Desired Functionality:**

In the final milestone general updates should be supported. In addition to inserts, relational deletes and relational updates should be implemented.

```sql
low_project = select(awesomebase.grades.project,0,10) -- Find the rows with project less than 10

relational_delete(awesomebase.grades,low_project) -- clearly this is a mistake!!

-- or update

update(awesomebase.grades.project,low_project,85) -- change value of column project of table grades
```

**Suggested Guidance (How To Proceed, But Not Binding!):**
a) First try updates without multiple copies of the data and eagerly applied. This might be slow but is the easiest to see that logic works correctly.

b) Add an extra copy of the data. Here consider the interplay between a mapping between tables (i.e. row 2 in copy 1 is row 5 in copy 2) and several of the topics discussed in class. In particular, things like primary keys, joins, and indexes all are helpful in creating potential solutions.

**Bonus Tasks:**

1. Add support for concurrent updates in batched queries, making sure to guarantee correctness as well as performance improvements.
2. Implement this milestone in an alternative language of your choice and provide a performance comparison and analysis against the C implementation. We propose you use Go.

**MIDWAY EVALUATION:** October 25

**EVALUATION:** Before mid-December – exact date TBA (Hard Deadline)
CS165 Domain Specific Language

Here you can find the syntax of the CS165 Domain Specific Language (165L). In a full system design, this language would be used by the optimizer to pass instructions (i.e., query plans) to the execution engine after parsing and optimizing incoming SQL queries. In this project you only work at the lower level, i.e., the storage and execution engine, and you will use 165L to write query plans to test your engine. As 165L is the interface between your data system and our test files, supporting the exact 165L syntax is mandatory.

A few details about things you will encounter in the rest of the language description:

1. Keywords are unqualified text and symbols. For example: create, tbl, col etc. (These are static words that you can use to parse the instructions. They will appear in the same order and location in the string).
2. Items that appear in brackets are required but indicate good opportunities for extensions, or relate to one of the extra features found in the project description. For example, 'create(idx,<col_name>,[btree])' means that you must support creating at least B-tree indexes, but you may want to also support additional indexes like zone maps or hash maps.
3. Variables appear in-between angle brackets. They are strings that appear in 165L and are either identifiers like the name of a table or are labels that the system must carry through the execution of the commands (this will become more clear through the examples).
4. End of line indicates next instruction (but your design can buffer or parse multiple lines at a time as you see fit).
5. Comments are marked with '--' and continue until the end of the line.

CREATING NEW DATABASE OBJECTS

create(<object_type>,<object_name>,<parameter1>,<parameter2>,...)

The create function creates new structures in the system. The possible structures are databases, tables, columns, and indexes. It does not return anything. Below you can see all possible instances.

create(db,<db_name>)
create(tbl,<t_name>,<db_name>,<col_cnt>)
create(col,<col_name>,<tbl_var>)
create(idx,<col_name>,[btree, sorted], [clustered, unclustered])

Usage

create(db,"awesomebase") -- create db with name "awesomebase"
create(tbl,"grades",awesomebase,6) -- create table "grades" with 6 columns in the "awesomebase"
create(col, "project", awesomebase.grades, unsorted) -- create column 1 with name "project"

create(col, "midterm1", awesomebase.grades, unsorted) -- create column 2 with name "midterm1"

create(col, "midterm2", awesomebase.grades, unsorted) -- create column 3 with name "midterm2"

create(col, "class", awesomebase.grades, unsorted) -- create column 4 with name "class"

create(col, "quizzes", awesomebase.grades, unsorted) -- create column 5 with name "quizzes"

create(col, "student_id", awesomebase.grades, unsorted) -- create column 6 with name "student_id"

**SQL Example**

CREATE DATABASE awesomebase

CREATE TABLE grades (grades int, project int, midterm1 int, midterm2 int, class int, quizzes int, student_id int)

In the create table statement, the first value of a parameter is the column name and the second parameter is its type. VARCHAR(n), BINARY(n), BIGINT, and TIMESTAMP are examples of other SQL data types.

**LOADING**

load(<filename>)

This function loads values from a file. Both absolute and relative paths should be supported. The columns within the file are assigned names that correspond to already created database objects. This filename should be a file on the client's side and the client should pass the data in this file to the server for loading. IMPORTANT: The server does not directly open the file.

**Parameters**

<filename>: The name of the file to load the database from.

**Return Value**

None.
Usage

load("/path/to/myfile.txt")

-- or relative path
load("./data/myfile.txt")

File Format

Input data will be provided as ASCII-encoded CSV files. For example:

foo.t1.a,foo.t1.b
10,-23
-22,910

This file would insert two rows into columns 'a' and 'b' of table 't1' in database 'foo'.

SQL Example

There is no direct correlate in SQL to the load command. That being said, almost all vendors have commands to load a file into a table. The MySQL version would be:

LOAD DATA INFILE myfile.txt

INSERTING ROWS INTO A TABLE

The system will support relational, that is, row-wise (one row at a time) inserts:

relational_insert(<tbl_var>,[INT1],[INT2],...)

Parameters

<col_var>: A fully qualified column name.
<tbl_var>: A fully qualified table name.
INT/INTk: The value to be inserted (32 bit signed).

Return Value

None.
Usage

relational_insert(awesomebase.grades,107,80,75,95,93,1)

SQL Example

There are two different insert statements in SQL. In the first statement below, the column names are omitted and the values are inserted into the columns of the table in the order those columns were declared in table creation. In the second statement, column names are included and the values in the insert statement are put in the corresponding given column. The two statements below perform the same action.

INSERT INTO grades VALUES (107,80,75,95,93,1)

INSERT INTO grades (midterm1, project, midterm2, class, quizzes, student_id) VALUES (80,107,75,95,93,1)

SELECTING VALUES

There are two kinds of select commands.

Select from within a column:

<vec_pos>=select(<col_var>,<low>,<high>)

Parameters

<col_name>: A fully qualified column name or an intermediate vector of values
<low>: The lowest qualifying value in the range.
<high>: The exclusive upper bound.
null: specifies an infinite upper or lower bound.

Select from pre-selected positions of a vector of values:

<vec_pos>=select(<posn_vec>,<col_var>,<low>,<high>)

Parameters

<posn_vec>: A vector of positions
<col_var>: A vector of values.
<low>: The lowest qualifying value in the range.
<high>: The exclusive upper bound.
null: specifies an infinite upper or lower bound.
Return Value

<vec_pos>: A vector of qualifying positions.

Usage

-- select

pos_1=select(awesomebase.grades.project,90,100) -- Find the rows with project score between 90 and 99

pos_2=select(awesomebase.grades.project,90,null) -- Find the rows with project greater --or equal to 90

SQL Example

SELECT student_id FROM grades WHERE midterm1 > 90 AND midterm2 > 90

In the statement above, we might select on midterm1 using the first select, then select on midterm2 using the second type of select.

FETCHING VALUES

This function collects the values from a column at given positions.

<vec_val>=fetch(<col_var>,<vec_pos>)

Parameters

<col_var>: A fully qualified column name.
<vec_pos>: A vector of positions that qualify (as returned by select or join).

Return Value

<vec_val>: A vector of qualifying values.

Usage

a_plus=select(awesomebase.grades.project,100,null) -- Find the rows with project greater or equal to 100

ids_of_top_students=fetch(awesomebase.grades.student_id,a_plus) -- Return column 6 (student id) of the said rows (students)
**SQL Example**

The fetch command would be an internal operation at the end of a SQL query. For example, using our last query:

```sql
SELECT student_id FROM grades WHERE midterm1 > 90 AND midterm2 > 90
```

The last part of this query after the two WHERE clauses had been evaluated would use a fetch on column student_id.

**DELETING ROWS**

Row deletions happen using the relational_delete operation. It will internally issue multiple separate column deletes.

```sql
relational_delete(<tbl_var>,<vec_pos>)
```

**Parameters**

- `<tbl_var>`: A fully qualified table name.
- `<vec_pos>`: A vector of positions.

**Return Value**

None.

**Usage**

```sql
low_project=select(awesomebase.grades.project,0,10) -- Find the rows with project less than 10
relational_delete(awesomebase.grades,low_project) -- Clearly this is a mistake!!
```

**SQL Example**

```sql
DELETE FROM grades WHERE midterm1 < 40 AND midterm2 < 40
```

**JOINING COLUMNS**

This function performs a join between two inputs, given both the values and respective positions of each input. We expect at least a hash and nested-loop join to be implemented, but implementing others (such as sort-merge) is a possibility.
<vec_pos_1_out>,<vec_pos_2_out>=join(<vec_val_1>,<vec_pos_1>,<vec_val_2>,<vec_pos_2>, [hash,nested-loop,...])

**Parameters**

<vec_val_1>: The vector of values 1.
<vec_pos_1>: The vector of positions 1.
<vec_val_2>: The vector of values 2.
<vec_pos_2>: The vector of positions 2.
<type>: The type of join to execute. An example of type is hash or nested loop.

**NOTE:** There is no explicit indication which is the smaller relation. Why this matters will become apparent when we discuss joins.

**Return Value**

<vec_pos_1_out>,<vec_pos_2_out>: The concatenation of the positions in each input table of the resulting join.

**Usage**

positions1=select(awesomebase.cs165.project_score,100,null) -- select positions where project score >= 100 in cs165
positions2=select(awesomebase.cs265.project_score,100,null) -- select positions where project score >= 100 in cs265
values1=fetch(awesomebase.cs165.student_id,positions1)
values2=fetch(awesomebase.cs265.student_id,positions2)
r1,r2=join(positions1,values1,positions2,values2, hash) -- positions of students who have project score >= 100 in both classes
student_ids=fetch(awesomebase.cs165.student_id, r1)
print(student_ids)

**SQL Example**

```sql
SELECT student_id FROM cs165_grades JOIN cs265_grades
WHERE cs165_grades.project > 100
AND cs165_grades.project > 100
AND cs165_grades.student_id = cs265_grades.student_id
```
MIN AGGREGATE

There are two kinds of min aggregate commands.

\(<\text{min\_val}> = \text{min}(\langle\text{vec\_val}\rangle)\)

The first min aggregation signature returns the minimum value of the values held in \(<\text{vec\_val}>\).

**Parameters**

\(<\text{vec\_val}>\): A vector of values to search for the min OR a fully qualified name.

**Return Value**

\(<\text{min\_val}>\): The minimum value of the input \(<\text{vec\_val}>\).

\(<\text{min\_pos}>, \text{min\_val}> = \text{min}(\langle\text{vec\_pos}\rangle, \langle\text{vec\_val}\rangle)\)

The second min aggregation signature returns the minimum value and the corresponding position(s) (as held in \(<\text{vec\_pos}>\)) from the values in \(<\text{vec\_val}>\).

**Parameters**

\(<\text{vec\_pos}>\): A vector of positions corresponding to the values in \(<\text{vec\_val}>\).
\(<\text{vec\_val}>\): A vector of values to search for the min OR a fully qualified name.

Note: When null is specified as the first input of the function, it returns the position of the min from the \(<\text{vec\_val}>\) array.

**Return Value**

\(<\text{min\_pos}>\): The position (as defined in \(<\text{vec\_pos}>\)) of the min.
\(<\text{min\_val}>\): The minimum value of the input \(<\text{vec\_val}>\).

**Usage**

\begin{verbatim}
positions1=select(awesomebase.grades.project,100,null) -- select students with project more than or equal to 100
values1=fetch(awesomebase.grades.midterm1,positions1)
-- used here
min=min(values1) -- the lowest midterm1 grade for students who got 100 or more in their project
\end{verbatim}
SQL Example

SELECT min(midterm1) FROM grades WHERE project >= 100

MAX AGGREGATE

There are two kinds of max aggregate commands.

\(<\text{max\_val}>=\text{max}(\text{vec\_val})\)

The first max aggregation signature returns the maximum value of the values held in \text{vec\_val}.

Parameters

\text{<vec\_val>: A vector of values to search for the max OR a fully qualified name.}

Return Value

\text{<max\_val>: The maximum value of the input <vec\_val>.}

The second max aggregation signature returns the maximum value and the corresponding position(s) (as held in \text{vec\_pos}) from the values in \text{vec\_val}.

\(<\text{max\_pos},\text{max\_vals}=\text{max}(\text{vec\_pos},\text{vec\_val})\)

Parameters

\text{<vec\_pos>: A vector of positions corresponding to the values in <vec\_val>.}
\text{<vec\_val>: A vector of values to search for the max OR a fully qualified name.}

Note: When null is specified as the first input of the function, it returns the position of the max from the \text{<vec\_val> array.}

Return Value

\text{<max\_pos>: The position (as defined in <vec\_pos>) of the max.}
\text{<max\_val>: The maximum value of the input <vec\_val>.}

Usage

positions1=select(awesomebase.grades.midterm1,null,90) -- select students with midterm less than 90

values1=fetch(awesomebase.grades.project,positions1)

-- used here
max1=max(values1)  -- get the maximum project grade for students with midterm less than 90

SQL Example

```
SELECT max(project) FROM grades WHERE midterm1 < 90
```

SUM AGGREGATE

```
<scl_val>=avg(<vec_val>)
```

This is the aggregation function sum. It returns the sum of the values in <vec_val>.

Parameters

<vec_val>: A vector of values.

Return Value

<scl_val>: The scalar value of the sum.

Usage

```
positions1=select(awesomebase.grades.project,100,null)  -- select students with project more than or equal to 100
values1=fetch(awesomebase.grades.quizzes,positions1)
-- used here
sum_quizzes=sum(values1)  -- get the sum of the quizzes grade for students with project more than or equal to 100
```

SQL Example

```
SELECT SUM(quizzes) FROM grades WHERE project >= 100
```

AVERAGE AGGREGATE

```
<scl_val>=avg(<vec_val>)
```

This is the aggregation function average. It returns the arithmetic mean of the values in <vec_val>. 
Parameters

<vec_val>: A vector of values.

Return Value

<scl_val>: The scalar value of the average. For the average operator, in staff automated grading we expect your system to provide 2 places of decimal precision (e.g. 0.00).

Usage

positions1=select(awesomebase.grades.project,100,null) -- select students with project more than or equal to 100

values1=fetch(awesomebase.grades.quizzes,positions1) -- used here

avg_quizzes=avg(values1) -- get the average quizzes grade for students with project more than or equal to 100

SQL Example

SELECT AVG(quizzes) FROM grades WHERE project >= 100

ADDING TWO VECTORS

<vec_val>=add(<vec_val1>,<vec_val2>)

This function adds two vectors of values.

Parameters

<vec_val1>: The vector of values 1.
<vec_val2>: The vector of values 2.

Return Value

<vec_val>: A vector of values equal to the component-wise addition of the two inputs.

Usage
midterms=add(awesomebase.grades.midterm1, awesomebase.grades.midterm2)

**SQL Example**

```sql
SELECT midterm1 + midterm2 FROM grades
```

**SUBTRACTING TWO VECTORS**

```sql
<vec_val>=sub(<vec_val1>,<vec_val2>)
```

This function subtracts two vectors of values.

**Parameters**

- `<vec_val1>`: The vector of values 1.
- `<vec_val2>`: The vector of values 2.

**Return Value**

- `<vec_val>`: A vector of values equal to the component-wise addition of the two inputs.

**Usage**

```sql
-- used here
score=sub(awesomebase.grades.project, awesomebase.grades.penalty)
```

**SQL Example**

```sql
SELECT AVG(project - penalty) FROM grades
```

**UPDATING VALUES**

This function updates values from a column at given positions with a given value.

```sql
update(<col_var>,<vec_pos>,[INT])
```

**Parameters**

- `<col_var>`: A variable that indicates the column to update.
- `<vec_pos>`: A vector of positions.
Return Value

None.

Usage

project_to_update=select(awesomebase.grades.project,0,100) -- ...it should obviously be over 100!

-- used here

update(awesomebase.grades.project,project_to_update,113)

SQL Example

UPDATE grades SET midterm1 = 100 WHERE midterm2 = 100

PRINTING RESULTS

print(<vec_val1>,...)

The print command prints one or more vector in a tabular format.

Note: Do not worry about optimizing the print operator.

Parameters

<vec_val1>: One or more vectors of values to be combined and printed.

Return Value

None.

Usage

-- used here

print(awesomebase.grades.project,awesomebase.grades.quizzes) -- print project grades and quiz grades

--OR--

pos_high_project=select(awesomebase.grades.project,80,null) -- select project more than or equal to 80
val_project=fetch(awesomebase.grades.project,pos1) -- fetch project grades

val_studentid=fetch(awesomebase.grades.student_id,pos1) -- fetch student id

val_quizzes=fetch(awesomebase.grades.quizzes,pos1) -- fetch quiz grades

print(val_studentid,val_project,val_quizzes) -- print student_id, project grades and quiz grades for projects more than or equal to 80

Then, the result should be:

1,107,93
2,92,85
3,110,95
4,88,95

**SQL Example**

This instruction is used to print out the results of a query. As such, this command is used in every query in a database which returns values.

**Batching Commands**

Batching consists of two commands. The first command, batch_queries, tells the server to hold the execution of the subsequent requests. The second command, batch_execute, then tells the server to execute these queries.

batch_queries()

batch_execute()

**Return Value**

batch_queries: none.

batch_execute: No explicit return value, but the server must work out with the client when it is done sending results of the batched queries.

**Usage**

batch_queries()
a_plus=select(awesomebase.grades.project,90,100) -- Find the students (rows) with project grade between 90 and 100

a=select(awesomebase.grades.project,80,90) -- Find the students (rows) with project grade between 80 and 90

super_awesome_peeps=select(awesomebase.grades.project,95,105)

ids_of_students_with_top_project=fetch(awesomebase.grades.student_id, a_plus) -- Find the student id of the a_plus students

batch_execute() -- The three selects should run as a shared scan

**SQL Example**

There is no batching command in the SQL syntax. However, almost all commercial databases have a command to submit a batch of queries.

**SHUTTING DOWN**

This command shuts down the server.

*shutdown*

**Return Value**

None.

**Usage**

shutdown
Project Testing

We provide tests for each milestone in the project repo under the “project_tests” directory. There are a total of 41 tests divided between different milestones as follows:

Milestone 1: test01 through test09
Milestone 2: test10 through test17
Milestone 3: test18 through test29
Milestone 4: test30 through test35
Milestone 5: test36 through test41

In addition to the dsl files (testX.dsl), we provide all required data sets (dataX.csv) as well as the expected outputs (testX.exp) so that you can run and verify the tests on your machine.

Running Tests:

To run the tests on your machine, you can pass dsl files directly to your client. The following command passes test00.dsl file to the client executable and stores the output in test00.out:

```
./client < test00.dsl > test00.out
```

After successful execution of the above command, you can see the difference between test00.out and test00.exp using the following command:

```
./diff -B -w test00.out test00.exp
```

More information about format of the output generated by the command above can be found [here](#).

Automated Testing:

Starting from the fourth week of class, we will automatically pull your project code and run tests on it. We will email you a detailed report containing running times, logs, errors, etc. We will run automated tests three times a week. We will increase the frequency of automated testing as we approach midway check-in and final submission deadlines.

To participate in automated testing:

1. Sign up for automated testing using [this form](#). Note that your git URL should resemble a format like this: “git@code.harvard.edu:~john_doe/cs165-20XX-base/john_doe.cs165-20XX-base.git”.
2. Make sure “cs165-staff” has read access to your project and your repository. To do this you will need to add user ‘sap835’ as a collaborator for your repository.
3. Tag your code so that we know which version of your code to pull and what tests to run on it. In particular, use the tag ”milestone1-submit” for M1, "milestone2-submit" for M2, "milestone3-submit" for M3, "milestone4-submit" for M4, and "milestone5-submit" for M5. During automated testing, we will pull your project code and look for the highest milestone you tagged and run all tests up to that milestone. To tag your code, use the command `git tag`
 milestonex-submit -f and then push the tags using git push --tags -f. More information on managing git tags can be found here.

Interpreting Automated Reports:

For every test, the automated report contains information about whether the test passes and how long it takes to execute. Further, to make it easy for you to debug we include three files per test in the report: (a) testX.out, containing the output of your code to stdout, (b) testX.err, containing the output of your code to stderr, and (c) testX.diff, containing the difference between the output of your code and the expected output. To generate this diff file, we use the diff -B -w testX.out testX.exp command. More information about format of the output generated by this command can be found here.

Adding Your Tests:

You can also provide your own tests to execute on the server machine. To do this, include the command to run your tests under the test target in your Makefile. We will execute these tests and send you the execution time and output. Please make sure you commit all files needed to run your tests to your project repository. Here is an example of how you can include tests in your Makefile:

test:
  ./client < mytest1.dsl
  ./client < mytest2.dsl

Typical Errors When Tested On Server

1. Mac includes libraries by default that Linux doesn’t. Please make sure that functions which are called on your machine have the necessary libraries included for running on Linux. See https://www.kernel.org/doc/man-pages/ to see what libraries need to be included and linked for each function call.
2. Please define necessary feature test macros. As an example, the default client file includes _XOPEN_SOURCE. The linux manual pages, posted above, will tell you what needs to be defined to call various functions. Note that not all features are compatible with each other.
3. Please close all file descriptors. Certain operating systems (both Linux based and Mac OS X) will cover for you if you do not close file descriptors when you are done writing data, however data is not guaranteed to be flushed to disk if a file descriptor is not closed correctly. This leads to nondeterministic behavior, missing data, and varying behavior across machines, making debugging hard.
4. Be careful to send and receive exactly the same number of bytes. Often times off by one errors can accumulate and lead to programs crashing at weird times or both sides of a socket waiting for the other (which is observed as a "hang"). This behavior is also very hard to debug.
5. Memory errors can be validated using Valgrind. As a helpful hint, whenever segfaults are occurring or you aren't sure why errors are happening, try using Valgrind to see if you are touching unallocated memory.
6. Remember with C you are responsible for your own memory management. Where do you allocate memory for your structs? When are you done with using them and can free memory? Do you need any special treatment for allocating and freeing nested structures?
7. When casting values between different primitive types, what direction are you casting (e.g. are you creating potential for a value overflow error)? Are you clear on your function's argument passing and return convention? Are you passing arguments in by value or by reference? Are you
returning by value or by reference? When might you use one convention instead of the other? This can vary with OS.

8. When you begin to use synchronization primitives, do you introduce any code paths with potential for synchronization issues (e.g. deadlock or race condition)?
What is a Successful Project?

A successful project passes all the predefined tests we provide and the students successfully pass the final face-to-face evaluation.

A successful final evaluation is one where the student is able:

1. to fully explain every detail of the design, and
2. to propose efficient designs for new functionality on the spot.

A project will get extra points for going the extra mile to provide solutions that are efficient and are elegantly implemented and designed. Efficiency is judged by comparing against other systems. Elegance is judged by the course staff. Participating in office hours and extra sessions guarantees that you get feedback about your design often.

A project also gets extra points for doing some of the bonus tasks we provide or bonus tasks that the student comes up with.
Project Dos and Don’ts

Do's

1. do start early. Starting early will mean that you keep up with the class better and will prevent you from failing to complete all milestones.
2. do get a Linux test environment. This means even if you code regularly on your MacBook, you should test on a virtual machine that you download.
3. do all coding on a Unix environment (i.e., not Windows). The system calls are incompatible and all work using Windows system calls will be wasted.
4. do make sure you address all compiler warnings.
5. do ensure that your code repo is private with access to “cs165-staff” for automated testing.
6. do ensure that after pulling your repo and compiling your project we get a fresh system with a clean database (no data and no metadata).
7. do make sure that main returns 0 on success (for example, when your client terminates without an error it should do so with "return 0;").
8. do compile with warnings enabled (-Wall -Wextra -Werror).
9. do use valgrind to avoid memory leaks.
10. do ensure that your project includes a working Makefile (if you are using cmake, please generate and include a GNU Makefile in your repo).
11. do add a "make distclean" option in your makefile that deletes all metadata your system creates (e.g., your data directory and your socket files).
12. do ensure that all necessary files are committed and pushed to code.seas (double check any new source and header files you have added).
13. do make sure your code compiles in a linux environment (even if it compiles successfully in a Mac OS X system).
14. do consider adding a debug target in your Makefile.
15. do consider creating a "data" directory to store any files you create for you catalog and data.
16. do make sure that all output of the client, other than the actual values, is prepended by -- (two dashes).
17. do save your data in binary files (and not ascii).
18. The lab TFs will keep an up-to-date list of common bugs and errors. Please do check these before coming into lab whenever you have a problem.
19. do come to lab! Lab is not just about solving bugs and errors, you can also come to discuss design decisions or how to most efficiently implement various operators in the database. Also we are loving people.

Don’ts

1. do not commit binaries (executables and object files) in your repo (do use .gitignore).
2. do not commit your database or your catalog (in general any file you create during the system’s operation in your repo (do use .gitignore).
3. do not access the input data file from the server directly, rather parse it from the client and send the data through the socket (for example, the file “data1.csv” should not be opened by the server process).
4. do not use the logging mechanism for printing out the results of execution (for example, use plain printf or another printing mechanism that is always on when printing the result of “print”).
5. do not use outside libraries (c packages outside the Berkeley BSD). This is against the spirit of the project and will adversely effect your grade.
**Practicing SQL and Column-store Plan**

A great way to practice your SQL skills is to go to the state-of-the-art benchmark for analytical workloads (TPCH) and study the queries. TPCH is a very popular ad-hoc decision support benchmark used both by academia and industry to test data systems.

You can install any db system you prefer (e.g., MonetDB, MySQL, PostgreSQL or a combination of them).

And use the database generator (dbgen) of the TPCH data in order to create raw files which you can then bulk load.

In the specification of the TPCH you can find:

1. the TPCH schema in page 13
2. all 22 TPCH queries in English and SQL starting from page 29 (subsections 2.4.1.1, 2.4.2.1, 2.4.3.1, ... , 2.4.22.1 have the English description and 2.4.1.1, 2.4.2.2, 2.4.3.2, ... , 2.4.22.2 have the SQL of them).

You can use these queries, which are typically an excellent and challenging exercise for thinking how to "convert" English to SQL as well as formulate more queries of your own on top of this schema.

In addition, it is a good idea to practice with column-store plans so that you can get a better understanding of concepts such as late tuple reconstructions and how data flows as queries get more complex. This will help you a lot with your project. Use MonetDB and prefix your SQL queries with the keyword “explain”. What you will see then is the column-store plan (equivalent of our DSL language). (Use MonetDB in read-only mode to get a simpler plan that does not consider on-the-fly merging of pending updates.)