
DBMSBenchmarker

Release 0.1

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```
{include} ../README.md
```


OVERVIEW

This documentation contains

- an example of how to perform a [TPC-H-like Benchmark](#) from a command line
- an illustration of the [concepts](#)
- an illustration of the [evaluations](#)
- a description of the [options and configurations](#)
- more extensive [examples](#) of using the cli tool
- some [use-cases](#) and [test scenarios](#)
- examples of how to use the interactive [inspector](#)
- examples of how to use the interactive [dashboard](#)

EXAMPLE: TPC-H

This example shows how to benchmark 22 reading queries Q1-Q22 derived from TPC-H in MySQL

The query file is derived from the TPC-H and as such is not comparable to published TPC-H results, as the query file results do not comply with the TPC-H Specification.

Official TPC-H benchmark - <http://www.tpc.org/tpch>

Content:

- *Prerequisites*
- *Perform Benchmark*
- *Evaluate Results in Dashboard*
- *Where to go*

2.1 Prerequisites

We need

- a local instance of MySQL
 - having a database database containing the TPC-H data of SF=1
 - access rights for user / password: username/password
- a suitable MySQL JDBC driver jar file
- JDK 8 installed

If necessary, adjust the settings in the file `example/connections.py`:

```
[
{
  'name': "MySQL",
  'alias': "Some DBMS",
  'version': "CE 8.0.13",
  'docker': 'MySQL',
  'docker_alias': "DBMS A",
  'dialect': "MySQL",
  'hostsystem': {'node': 'localhost'},
  'info': "This is an example: MySQL on localhost",
  'active': True,
  'JDBC': {
    'driver': "com.mysql.cj.jdbc.Driver",
```

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```
'url': "jdbc:mysql://localhost:3306/database",
'auth': ["username", "password"],
'jar': "mysql-connector-java-8.0.13.jar"
},
},
]
```

2.2 Perform Benchmark

Run the command:

```
python benchmark.py run -e yes -b -f example/tpch
```

- `-e yes`: This will precompile some evaluations and generate the timer cube.
- `-b`: This will suppress some output
- `-f`: This points to a folder having the configuration files.

For more options, see the [documentation](#)

After benchmarking has been finished will see a message like

```
Experiment <code> has been finished
```

The script has created a result folder in the current directory containing the results. `<code>` is the name of the folder.

2.2.1 Evaluate Results in Dashboard

Run the command:

```
python dashboard.py
```

This will start the evaluation dashboard at `localhost:8050`. Visit the address in a browser and select the experiment `<code>`.

2.3 Where to go

- Use different [DBMS](#)
- Add metadata
- SF
- Use Bexhoma: <https://github.com/Beuth-Erdelt/Benchmark-Experiment-Host-Manager>

3.1 Experiment

An **experiment** is organized in *queries*. A **query** is a statement, that is understood by a Database Management System (DBMS).

3.2 Single Query

A **benchmark** of a query consists of these steps:

1. Establish a **connection** between client and server This uses `jaydebeapi.connect()` (and also creates a cursor - time not measured)
2. Send the query from client to server and
3. **Execute** the query on server These two steps use `execute()` on a cursor of the JDBC connection
4. **Transfer** the result back to client This uses `fetchall()` on a cursor of the JDBC connection
5. Close the connection This uses `close()` on the cursor and the connection

The times needed for steps connection (1.), execution (2. and 3.) and transfer (4.) are measured on the client side. A unit of connect, send, execute and transfer is called a **run**. Connection time will be zero if an existing connection is reused. A sequence of runs between establishing and discarding a connection is called a **session**.

3.3 Basic Parameters

A basic parameter of a query is the **number of runs** (units of send, execute, transfer). To configure sessions it is also possible to adjust

- the **number of runs per connection** (session length, to have several sequential connections) and
- the **number of parallel connections** (to simulate several simultaneous clients)
- a **timeout** (maximum lifespan of a connection)
- a **delay** for throttling (waiting time before each connection or execution)

for the same query.

Parallel clients are simulated using the `pool.apply_async()` method of a `Pool` object of the module `multiprocessing`. Runs and their benchmark times are ordered by numbering.

Moreover we can **randomize** a query, such that each run will look slightly different. This means we exchange a part of the query for a random value.

3.4 Basic Metrics

We have several **timers** to collect timing information:

- **timerConnection** This timer gives the time in ms and per run. It measures the time it takes to establish a JDBC connection. **Note** that if a run reuses an established connection, this timer will be 0 for that run.
- **timerExecution** This timer gives the time in ms and per run. It measures the time between sending a SQL command and receiving a result code via JDBC.
- **timerTransfer** This timer gives the time in ms and per run. **Note** that if a run does not transfer any result set (a writing query or if we suspend the result set), this timer will be 0 for that run.
- **timerRun** This timer gives the time in ms and per run. That is the sum of *timerConnection*, *timerExecution* and *timerTransfer*. **Note** that connection time is 0, if we reuse an established session, and transfer time is 0, if we do not transfer any result set.
- **timerSession** This timer gives the time in ms and per session. It aggregates all runs of a session and sums up their *timerRuns*. A session starts with establishing a connection and ends when the connection is disconnected.

The benchmark times of a query are stored in csv files (optional pickled pandas dataframe): For connection, execution and transfer. The columns represent DBMS and each row contains a run.

We also measure and store the **total time** of the benchmark of the query, since for parallel execution this differs from the **sum of times** based on *timerRun*. Total time means measurement starts before first benchmark run and stops after the last benchmark run has been finished. Thus total time also includes some overhead (for spawning a pool of subprocesses, compute size of result sets and joining results of subprocesses). Thus the sum of times is more of an indicator for performance of the server system, the total time is more of an indicator for the performance the client user receives.

We also compute for each query and DBMS

- **Latency:** Measured Time
- **Throughput:**
 - Number of runs per total time
 - Number of parallel clients per mean time

In the end we have

- Per DBMS: Total time of experiment
- Per DBMS and Query:
 - Time per session
 - Time per run
 - Time per run, split up into: connection / execution / data transfer
 - Latency and Throughputs per run
 - Latency and Throughputs per session

Additionally error messages and timestamps of begin and end of benchmarking a query are stored.

3.5 Comparison

We can specify a dict of DBMS. Each query will be sent to every DBMS in the same number of runs.

This also respects randomization, i.e. every DBMS receives exactly the same versions of the query in the same order. We assume all DBMS will give us the same result sets. Without randomization, each run should yield the same result set. This tool can check these assumptions automatically by **comparison**. The resulting data table is handled as a list of lists and treated by this:

```
# restrict precision
data = [[round(float(item), int(query.restrict_precision)) if tools.
↳convertToFloat(item) == float else item for item in sublist] for sublist in data]
# sort by all columns
data = sorted(data, key=itemgetter(*list(range(0, len(data[0])))))
# size of result
size = int(df.memory_usage(index=True).sum())
# hash of result
columnnames = [[i[0].upper() for i in connection.cursor.description]]
hashed = columnnames + [[hashlib.sha224(pickle.dumps(data)).hexdigest()]]
```

Result sets of different runs (not randomized) and different DBMS can be compared by their sorted table (small data sets) or their hash value or size (bigger data sets). In order to do so, result sets (or their hash value or size) are stored as lists of lists and additionally can be saved as csv files or pickled pandas dataframes.

3.6 Monitoring Hardware Metrics

To make hardware metrics available, we must [provide](#) an API URL for a Prometheus Server. The tool collects metrics from the Prometheus server with a step size of 1 second.

The requested interval matches the interval a specific DBMS is queried. To increase expressiveness, it is possible to extend the scraping interval by n seconds at both ends. In the end we have a list of per second values for each query and DBMS. We may define the metrics in terms of promql. Metrics can be defined per connection.

Example:

```
'title': 'CPU Memory [MB]'
'query': 'container_memory_working_set_bytes'

'title': 'CPU Memory Cached [MB]'
'query': 'container_memory_usage_bytes'

'title': 'CPU Util [%]'
'query': 'sum(irate(container_cpu_usage_seconds_total[1m]))'

'title': 'CPU Throttle [%]'
'query': 'sum(irate(container_cpu_cfs_throttled_seconds_total[1m]))'

'title': 'CPU Util Others [%]'
'query': 'sum(irate(container_cpu_usage_seconds_total{id!="/" }[1m]))'

'title': 'Net Rx [b]'
'query': 'sum(container_network_receive_bytes_total)'

'title': 'Net Tx [b]'
'query': 'sum(container_network_transmit_bytes_total)'
```

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```
'title': 'FS Read [b]'
'query': 'sum(container_fs_reads_bytes_total)'

'title': 'FS Write [b]'
'query': 'sum(container_fs_writes_bytes_total)'

'title': 'GPU Util [%]'
'query': 'DCGM_FI_DEV_GPU_UTIL{UUID=~"GPU-4d1c2617-649d-40f1-9430-2c9ab3297b79"}'

'title': 'GPU Power Usage [W]'
'query': 'DCGM_FI_DEV_POWER_USAGE{UUID=~"GPU-4d1c2617-"}'

'title': 'GPU Memory [MiB]'
'query': 'DCGM_FI_DEV_FB_USED{UUID=~"GPU-4d1c2617-"}'
```

Note this expects monitoring to be installed properly and naming to be appropriate. See <https://github.com/Beuth-Erdelt/Benchmark-Experiment-Host-Manager> for a working example and more details.

Note this has limited validity, since metrics are typically scraped only on a basis of several seconds. It works best with a high repetition of the same query.

3.7 Evaluation

As a result we obtain measured times in milliseconds for the query processing parts: connection, execution, data transfer.

These are described in three dimensions: number of run, number of query and configuration. The configuration dimension can consist of various nominal attributes like DBMS, selected processor, assigned cluster node, number of clients and execution order. We also can have various hardware metrics like CPU and GPU utilization, CPU throttling, memory caching and working set. These are also described in three dimensions: Second of query execution time, number of query and number of configuration.

All these metrics can be sliced or diced, rolled-up or drilled-down into the various dimensions using several aggregation functions for evaluation.

3.7.1 Aggregation Functions

Currently the following statistics may be computed per dimension:

- Sensitive to outliers
 - Arithmetic mean
 - Standard deviation
 - Coefficient of variation
- Insensitive to outliers
 - Median - percentile 50 (Q2)
 - Interquartile range - Q3-Q1
 - Quartile coefficient of dispersion
- First

- Last
- Minimum
- Maximum
- Range (Maximum - Minimum)
- Sum
- Geometric Mean
- percentile 25 (Q1)
- percentile 75 (Q3)
- percentile 90 - leave out highest 10%
- percentile 95 - leave out highest 5%

In the complex configuration dimension it can be interesting to aggregate to groups like same DBMS or CPU type.

USE CASES

Use Cases may be

- *Benchmark 1 Query in 1 DBMS*
- *Compare 2 Queries in 1 DBMS*
- *Compare 2 Databases in 1 DBMS*
- *Compare 1 Query in 2 DBMS* and combinations like compare n queries in m DBMS.
- *Benchmarking DBMS Configurations*

Scenarios may be

- *Many Users / Few, Complex Queries*
- *Few Users / Several simple Queries*
- *Updated Database*

4.1 Benchmark 1 Query in 1 DBMS

We want to measure how long it takes to run one query in a DBMS.

The following performs a counting query 10 times against one DBMS. The script benchmarks the execution of the query and also the transfer of data. The result (the number of rows in table test) is stored and should be the same for each run.

connections.config:

```
[
  {
    'name': "MySQL",
    'version': "CE 8.0.13",
    'info': "This uses engine innodb",
    'active': True,
    'JDBC': {
      'driver': "com.mysql.cj.jdbc.Driver",
      'url': "jdbc:mysql://localhost:3306/database",
      'auth': ["username", "password"],
      'jar': "mysql-connector-java-8.0.13.jar"
    },
  },
]
```

queries.config:

```

{
  'name': 'A counting query',
  'queries':
  [
    {
      'title': "Count all rows in test",
      'query': "SELECT COUNT(*) FROM test",
      'numRun': 10,
      'timer':
      {
        'datatransfer':
        {
          'active': True,
          'compare': 'result'
        },
      }
    },
  ]
}

```

4.2 Compare 2 Queries in 1 DBMS

We want to compare run times of two queries in a DBMS.

The following performs a query 10 times against two DBMS each. This helps comparing the relevance of position of ordering in the execution plan in this case. The script benchmarks the execution of the query and also the transfer of data. The result (some rows of table test in a certain order) is stored and should be the same for each run. **Beware** that storing result may take a lot of RAM and disk space!

connections.config:

```

[
  {
    'name': "MySQL-1",
    'version': "CE 8.0.13",
    'info': "This uses engine innodb",
    'active': True,
    'JDBC': {
      'driver': "com.mysql.cj.jdbc.Driver",
      'url': "jdbc:mysql://localhost:3306/database",
      'auth': ["username", "password"],
      'jar': "mysql-connector-java-8.0.13.jar"
    },
  },
  {
    'name': "MySQL-2",
    'version': "CE 8.0.13",
    'info': "This uses engine innodb",
    'active': True,
    'JDBC': {
      'driver': "com.mysql.cj.jdbc.Driver",
      'url': "jdbc:mysql://localhost:3306/database",
      'auth': ["username", "password"],
      'jar': "mysql-connector-java-8.0.13.jar"
    },
  },
]

```

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```

    },
  ]

```

queries.config:

```

{
  'name': 'An ordering query',
  'queries':
  [
    {
      'title': "Retrieve rows in test in a certain order",
      'DBMS': {
        'MySQL-1': "SELECT * FROM (SELECT * FROM test WHERE a IS TRUE) tmp ORDER BY b
↪",
        'MySQL-2': "SELECT * FROM (SELECT * FROM test ORDER BY b) tmp WHERE a IS TRUE
↪",
      },
      'numRun': 10,
      'timer':
      {
        'datatransfer':
        {
          'active': True,
          'compare': 'result'
        },
      },
    },
  ],
}

```

4.3 Compare 2 Databases in 1 DBMS

We want to compare run times of two databases in a DBMS. An application may be having the same tables with different indices and data types to measure influence.

The following performs a query 10 times against two databases in a DBMS each. This helps comparing the relevance of table structure in this case. Suppose we have a table test in database database and in database2 resp. The script benchmarks the execution of the query and also the transfer of data. The result (the number of rows in table test) is stored and should be the same for each run.

connections.config:

```

[
  {
    'name': "MySQL",
    'version': "CE 8.0.13",
    'info': "This uses engine innodb",
    'active': True,
    'JDBC': {
      'driver': "com.mysql.cj.jdbc.Driver",
      'url': "jdbc:mysql://localhost:3306/database",
      'auth': ["username", "password"],
      'jar': "mysql-connector-java-8.0.13.jar"
    },
  },

```

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```

},
{
  'name': "MySQL-2",
  'version': "CE 8.0.13",
  'info': "This uses engine myisam",
  'active': True,
  'JDBC': {
    'driver': "com.mysql.cj.jdbc.Driver",
    'url': "jdbc:mysql://localhost:3306/database2",
    'auth': ["username", "password"],
    'jar': "mysql-connector-java-8.0.13.jar"
  },
},
]

```

queries.config:

```

{
  'name': 'A counting query',
  'queries':
  [
    {
      'title': "Count all rows in test",
      'query': "SELECT COUNT(*) FROM test",
      'numRun': 10,
      'timer':
      {
        'datatransfer':
        {
          'active': True,
          'compare': 'result'
        },
      },
    },
  ],
}

```

4.4 Compare 1 Query in 2 DBMS

We want to compare run times of two DBMS. An application may be having the same tables in different DBMS and want to find out which one is faster.

The following performs a query 10 times against two DBMS each. This helps comparing the power of the two DBMS, MySQL and PostgreSQL in this case. Suppose we have a table test in both DBMS. The script benchmarks the execution of the query and also the transfer of data. The result (the number of rows in table test) is stored and should be the same for each run.

connections.config:

```

[
  {
    'name': "MySQL",
    'version': "CE 8.0.13",
    'info': "This uses engine innodb",

```

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```

'active': True,
'JDBC': {
  'driver': "com.mysql.cj.jdbc.Driver",
  'url': "jdbc:mysql://localhost:3306/database",
  'auth': ["username", "password"],
  'jar': "mysql-connector-java-8.0.13.jar"
},
},
{
  'name': "PostgreSQL",
  'version': "v11",
  'info': "This uses standard config"
  'active': True,
  'JDBC': {
    'driver': "org.postgresql.Driver",
    'url': "jdbc:postgresql://localhost:5432/database",
    'auth': ["username", "password"],
    'jar': "postgresql-42.2.5.jar"
  },
},
],
]

```

queries.config:

```

{
  'name': 'A counting query',
  'queries':
  [
    {
      'title': "Count all rows in test",
      'query': "SELECT COUNT(*) FROM test",
      'numRun': 10,
      'timer':
      {
        'datatransfer':
        {
          'active': True,
          'compare': 'result'
        },
      },
    },
  ],
}

```


SCENARIOS

5.1 Many Users / Few, Complex Queries

Excerpt from `connections.config`:

```
'connectionmanagement': {  
  'timeout': 600,  
  'numProcesses': 20,  
  'runsPerConnection': 1  
},
```

That is we allow 20 parallel clients, which connect to the DBMS host to run 1 single query each. Note the host of the benchmarking tool must be capable of 20 parallel processes.

Excerpt from `queries.config`:

```
{  
  'title': "Pricing Summary Report (TPC-H Q1)",  
  'query': ""select  
    l_returnflag,  
    l_linestatus,  
    cast(sum(l_quantity) as int) as sum_qty,  
    sum(l_extendedprice) as sum_base_price,  
    sum(l_extendedprice*(1-l_discount)) as sum_disc_price,  
    sum(l_extendedprice*(1-l_discount)*(1+l_tax)) as sum_charge,  
    avg(l_quantity) as avg_qty,  
    avg(l_extendedprice) as avg_price,  
    avg(l_discount) as avg_disc,  
    count(*) as count_order  
  from  
    lineitem  
  where  
    l_shipdate <= date '1998-12-01' - interval '{DELTA}' day  
  group by  
    l_returnflag,  
    l_linestatus  
  order by  
    l_returnflag,  
    l_linestatus  
  limit 10000000""",  
  'parameter': {  
    'DELTA': {  
      'type': "integer",  
      'range': [60,99]  
    }  
  }  
}
```

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```

    },
  },
  'active': True,
  'numRun': 20,
  'timer':
  {
    'datatransfer':
    {
      'active': True,
      'sorted': True,
      'compare': 'hash',
      'store': 'dataframe',
      'precision': 0,
    },
    'connection':
    {
      'active': True,
    }
  }
},

```

That is each simulated user runs the (randomized) TPC-H query number 1. The result sets will be truncated to no decimals, sorted and compared by their hash values. The result set of the first run will be stored to disk as a pickled pandas dataframe. The time for connection, execution and data transfer will be measured.

5.2 Few Users / Several simple Queries

Excerpt from `connections.config`:

```

'connectionmanagement': {
  'timeout': 600,
  'numProcesses': 1,
  'runsPerConnection': 5
},

```

That is we allow only one client at a time, which connects to the DBMS host to run 5 single queries.

Excerpt from `queries.config`:

```

{
  'title': "Count rows in nation",
  'query': "SELECT COUNT(*) c FROM nation",
  'active': True,
  'numRun': 20,
  'timer':
  {
    'datatransfer':
    {
      'active': True,
      'sorted': True,
      'compare': 'result',
      'store': 'dataframe',
      'precision': 4,
    },
    'connection':

```

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```

    {
      'active': True,
    }
  }
},

```

That is each simulated user counts the number of rows in table nations (five times per connection). We want to have 20 counts in total, so the simulated user (re)connects four times one after the other. The result sets will be truncated to 4 decimals, sorted and compared. The result set of the first run will be stored to disk as a pickled pandas dataframe. The time for connection, execution and data transfer will be measured.

5.3 Updated Database

We want to compute a sum, update some value and compute the sum again. This will take place 10 times as a sequence one after the other.

Excerpt from `queries.config`:

```

{
  'title': "Sum of facts",
  'query': "SELECT SUM(fact) s FROM facts",
  'active': False,
  'numRun': 1,
},
{
  'title': "Update Facts",
  'query': "UPDATE facts SET fact={FACT} WHERE id={ID}",
  'active': False,
  'numRun': 10,
  'parameter': {
    'FACT': {
      'type': "float",
      'range': [0.05, 20.00]
    },
    'ID': {
      'type': "integer",
      'range': [1,1000]
    }
  },
},
{
  'title': "Sequence of compute/update/compute",
  'queryList': [1,2,1]
  'active': True,
  'numRun': 30,
  'connectionmanagement': {
    'timeout': 600,
    'numProcesses': 1,
    'runsPerConnection': 3
  }
}

```


EXAMPLE RUNS

6.1 Run benchmarks

`python3 benchmark.py run -f test` generates a folder containing result files: csv of benchmarks per query. The example uses `test/connections.config` and `test/queries.config` as config files.

Example: This produces a folder containing

```
connections.config
queries.config
protocol.json
query_1_connection.csv
query_1_execution.csv
query_1_transfer.csv
query_2_connection.csv
query_2_execution.csv
query_2_transfer.csv
query_3_connection.csv
query_3_execution.csv
query_3_transfer.csv
```

where

- `connections.config` is a copy of the input file
- `queries.config` is a copy of the input file
- `protocol.json`: JSON file containing error messages (up to one per query and connection), durations (per query) and retried data (per query)
- `query_n_connection.csv`: CSV containing times (columns) for each dbms (rows) for query n - duration of establishing JDBC connection
- `query_n_execution.csv`: CSV containing times (columns) for each dbms (rows) for query n - duration of execution
- `query_n_transfer.csv`: CSV containing times (columns) for each dbms (rows) for query n - duration of data transfer

6.2 Run benchmarks and generate evaluations

`python3 benchmark.py run -e yes -f test` is the same as above, and additionally generates evaluation cube files.

```
evaluation.dict
evaluation.json
```

These can be inspected comfortably using the dashboard or the Python API.

6.3 Read stored benchmarks

`python3 benchmark.py read -r 12345` reads files from folder 12345 containing result files and shows summaries of the results.

6.4 Generate evaluation of stored benchmarks

`python3 benchmark.py read -r 12345 -e yes` reads files from folder 12345 containing result files, and generates evaluation cubes. The example uses `12345/connections.config` and `12345/queries.config` as config files.

6.5 Continue benchmarks

`python3 benchmark.py continue -r 12345 -e yes` reads files from folder 12345 containing result files, continues to perform possibly missing benchmarks and generates evaluation cubes. This is useful if a run had to be stopped. It continues automatically at the first missing query. It can be restricted to specific queries or connections using `-q` and `c` resp. The example uses `12345/connections.config` and `12345/queries.config` as config files.

6.5.1 Continue benchmarks for more queries

You would go to a result folder, say 12345, and add queries to the query file. `python3 benchmark.py continue -r 12345 -g yes` then reads files from folder 12345 and continue benchmarking the new (missing) queries.

Do not remove existing queries, since results are mapped to queries via their number (position). Use ``active`` instead.

6.5.2 Continue benchmarks for more connections

You would go to a result folder, say 12345, and add connections to the connection file. `python3 benchmark.py continue -r 12345 -g yes` then reads files from folder 12345 and continue benchmarking the new (missing) connections.

Do not remove existing connections, since their results would not make any sense anymore. Use ``active`` instead.

6.6 Rerun benchmarks

`python3 benchmark.py run -r 12345 -e yes` reads files from folder 12345 containing result files, performs benchmarks again and generates evaluation cubes. It also performs benchmarks of missing queries. It can be restricted to specific queries or connections using `-q` and `c` resp. The example uses `12345/connections.config` and `12345/queries.config` as config files.

6.6.1 Rerun benchmarks for one query

`python3 benchmark.py run -r 12345 -e yes -q 5` reads files from folder 12345 containing result files, performs benchmarks again and generates evaluation cubes. The example uses `12345/connections.config` and `12345/queries.config` as config files. In this example, query number 5 is benchmarked (again) in any case.

6.6.2 Rerun benchmarks for one connection

`python3 benchmark.py run -r 12345 -g yes -c MySQL` reads files from folder 12345 containing result files, performs benchmarks again and generates evaluation cubes. The example uses `12345/connections.config` and `12345/queries.config` as config files. In this example, the connection named MySQL is benchmarked (again) in any case.

7.1 Featured Parameters

The lists of *DBMS* and *queries* are given in config files in dict format.

Benchmarks can be *parametrized* by

- number of benchmark runs: *Is performance stable across time?*
- number of benchmark runs per connection: *How does reusing a connection affect performance?*
- number of warmup and cooldown runs, if any: *How does (re)establishing a connection affect performance?*
- number of parallel clients: *How do multiple user scenarios affect performance?*
- optional list of timers (currently: connection, execution, data transfer, run and session): *Where does my time go?*
- *sequences* of queries: *How does sequencing influence performance?*
- optional *comparison* of result sets: *Do I always receive the same results sets?*

Benchmarks can be *randomized* (optionally with specified *seeds* for reproducible results) to avoid caching side effects and to increase variety of queries by taking samples of arbitrary size from a

- list of elements
- dict of elements (one-to-many relations)
- range of integers
- range of floats
- range of days
- range of (first of) months
- range of years

This is inspired by TPC-H and TPC-DS - Decision Support Benchmarks.

8.1 Command Line Options and Configuration

How to configure the benchmarker can be illustrated best by looking at the source code of the command line tool `benchmark.py`, which will be described in the following.

```
python3 benchmark.py -h
```

```
usage: dbmsbenchmarker [-h] [-d] [-b] [-qf QUERY_FILE] [-cf CONNECTION_FILE] [-q
↳ QUERY] [-c CONNECTION] [-ca CONNECTION_ALIAS] [-f CONFIG_FOLDER] [-r RESULT_FOLDER]
↳ [-e {no,yes}] [-w {query,connection}] [-p NUMPROCESSES] [-s SEED]
      [-cs] [-ms MAX_SUBFOLDERS] [-sl SLEEP] [-st START_TIME] [-sf
↳ SUBFOLDER] [-vq] [-vs] [-vr] [-vp] [-pn NUM_RUN] [-m] [-mps]
      {run,read,continue}
```

A benchmark tool **for** RDBMS. It connects to a given **list** of RDBMS via JDBC **and** runs a **list** of benchmark queries. Optionally some reports are generated.

positional arguments:

```
{run,read,continue}  run benchmarks and save results, or just read benchmark
↳ results from folder, or continue with missing benchmarks only
```

optional arguments:

```
-h, --help          show this help message and exit
-d, --debug        dump debug informations
-b, --batch        batch mode (more protocol-like output), automatically on for
↳ debug mode
-qf QUERY_FILE, --query-file QUERY_FILE
                    name of query config file
-cf CONNECTION_FILE, --connection-file CONNECTION_FILE
                    name of connection config file
-q QUERY, --query QUERY
                    number of query to benchmark
-c CONNECTION, --connection CONNECTION
                    name of connection to benchmark
-ca CONNECTION_ALIAS, --connection-alias CONNECTION_ALIAS
                    alias of connection to benchmark
-f CONFIG_FOLDER, --config-folder CONFIG_FOLDER
                    folder containing query and connection config files. If set,
↳ the names connections.config and queries.config are assumed automatically.
-r RESULT_FOLDER, --result-folder RESULT_FOLDER
                    folder for storing benchmark result files, default is given
↳ by timestamp
-e {no,yes}, --generate-evaluation {no,yes}
```

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```

                                generate new evaluation file
-w {query,connection}, --working {query,connection}
                                working per query or connection
-p NUMPROCESSES, --numProcesses NUMPROCESSES
                                Number of parallel client processes. Global setting, can be
↳overwritten by connection. If None given, half of all available processes is taken
-s SEED, --seed SEED            random seed
-cs, --copy-subfolder
                                copy subfolder of result folder
-ms MAX_SUBFOLDERS, --max-subfolders MAX_SUBFOLDERS
                                maximum number of subfolders of result folder
-sl SLEEP, --sleep SLEEP
                                sleep SLEEP seconds before going to work
-st START_TIME, --start-time START_TIME
                                sleep until START-TIME before beginning benchmarking
-sf SUBFOLDER, --subfolder SUBFOLDER
                                stores results in a SUBFOLDER of the result folder
-vq, --verbose-queries
                                print every query that is sent
-vs, --verbose-statistics
                                print statistics about query that have been sent
-vr, --verbose-results
                                print result sets of every query that have been sent
-vp, --verbose-process
                                print result sets of every query that have been sent
-pn NUM_RUN, --num-run NUM_RUN
                                Parameter: Number of executions per query
-m, --metrics
                                collect hardware metrics per query
-mps, --metrics-per-stream
                                collect hardware metrics per stream

```

8.1.1 Result folder

This optional argument is the name of a folder.

If this folder contains results, results saved inside can be read or benchmarks saved there can be continued. Example: `-r /tmp/dbmsresults/1234/` contains benchmarks of code 1234.

If this folder does not contain results, a new subfolder is generated. Its name is set automatically to some number derived from current timestamp. Results and reports are stored there. Input files for connections and queries are copied to this folder. Example: `-r /tmp/dbmsresults/`, and a subfolder, say 1234, will be generated containing results.

8.1.2 Config folder

Name of folder containing query and connection config files. If set, the names `connections.config` and `queries.config` are assumed automatically.

8.1.3 Monitoring

The parameter `--metrics` can be used to activate fetching metrics from a Prometheus server. In the `connection.config` we may insert a section per connection about where to fetch these metrics from and which metrics we want to obtain.

More information about monitoring and metrics can be found here: <https://github.com/Beuth-Erdelt/Benchmark-Experiment-Host-Manager/blob/master/docs/Monitoring.html>

The parameter `--metrics-per-stream` does the same, but collects the metrics per stream - not per query. This is useful when queries are very fast.

8.1.4 Query

This parameter sets reading or running benchmarks to one fixed query. For `mode=run` this means the fixed query is benchmarked (again), no matter if benchmarks already exist for this query. For `mode=continue` this means missing benchmarks are performed for this fixed query only. Queries are numbered starting at 1.

8.1.5 Connection

This parameter sets running benchmarks to one fixed DBMS (connection). For `mode=run` this means the fixed DBMS is benchmarked (again), no matter if benchmarks already exist for it. For `mode=continue` this means missing benchmarks are performed for this fixed DBMS only. Connections are called by name.

8.1.6 Generate evaluation

If set to yes, an evaluation file is generated. This is a JSON file containing most of the `evaluations`. It can be accessed most easily using the inspection class or the interactive dashboard.

8.1.7 Debug

This flag activates output of debug infos.

8.1.8 Sleep

Time in seconds to wait before starting to operate. This is handy when we want to wait for other systems (e.g. a DBMS) to startup completely.

8.1.9 Batch

This flag changes the output slightly and should be used for logging if script runs in background. This also means reports are generated only at the end of processing. Batch mode is automatically turned on if debug mode is used.

8.1.10 Verbosity Level

Using the flags `-vq` means each query that is sent is dumped to stdout. Using the flags `-vr` means each result set that is received is dumped to stdout. Using the flags `-vp` means more information about the process and connections are dumped to stdout. Using the flags `-vs` means after each query that has been finished, some statistics are dumped to stdout.

8.1.11 Working querywise or connectionwise

This options sets if benchmarks are performed per query (one after the other is completed) or per connection (one after the other is completed).

This means processing `-w query` is

- loop over queries `q`
 - loop over connections `c`
 - * making `n` benchmarks for `q` and `c`
 - * compute statistics
 - * save results
 - * generate reports

and processing `-w connection` is

- loop over connections `c`
 - loop over queries `q`
 - * making `n` benchmarks for `q` and `c`
 - * compute statistics
 - * save results
 - * generate reports

8.1.12 Client processes

This tool simulates parallel queries from several clients. The option `-p` can be used to change the global setting for the number of parallel processes. Moreover each connection can have a local values for this parameter. If nothing is specified, the default value is used, which is half of the number of processors.

8.1.13 Random Seed

The option `-s` can be used to specify a random seed. This should guarantee reproducible results for randomized queries.

8.1.14 Subfolders

If the flag `--copy-subfolder` is set, connection and query configuration will be copied from an existing result folder to a subfolder. The name of the subfolder can be set via `--subfolder`. These flags can be used to allow parallel quering of independent dbmsbenchmark: Each will write in an own subfolder. These partial results can be merged using the `merge.py` command line tool. The normal behaviour is: If we run the same connection twice, the results of the first run will be overwritten. Since we might query the same connection in these instances, the subfolders will be numbered automatically. Using `MAX_SUBFOLDERS` we can limit the number of subfolders that are allowed. Example: `-r /tmp/dbmsresults/1234/ -cs -sf MySQL` will continue the benchmarks of folder `/tmp/dbmsresults/1234/` by creating a folder `/tmp/dbmsresults/1234/MySQL-1`. If that folder already exists, `/tmp/dbmsresults/1234/MySQL-2` will be used etc.

This is in particular used by <https://github.com/Beuth-Erdelt/Benchmark-Experiment-Host-Manager> for jobs of parallel benchmarker.

8.1.15 Delay start

The parameter `--sleep` can be used to set a start time. DBMSBenchmark will wait until the given time is reached.

This is in particular used by <https://github.com/Beuth-Erdelt/Benchmark-Experiment-Host-Manager> for synching jobs of parallel benchmarker.

8.2 Query File

Contains the queries to benchmark.

Example for `QUERY_FILE`:

```
{
  'name': 'Some simple queries',
  'intro': 'Some describing text about this benchmark test setup',
  'info': 'It runs on a P100 GPU',
  'factor': 'mean',
  'queries':
  [
    {
      'title': "Count all rows in test",
      'query': "SELECT COUNT(*) FROM test",
      'delay': 0,
      'numRun': 10,
    },
  ]
}
```

- `name`: Name of the list of queries
- `intro`: Introductional text for reports
- `info`: Short info about the current experiment
- `factor`: Determines the measure for comparing performances (optional). Can be set to mean or median or relative. Default is mean.
- `query`: SQL query string
- `title`: Title of the query

- delay: Number of seconds to wait before each execution statement. This is for throttling. Default is 0.
- numRun: Number of runs of this query for benchmarking

Such a query will be executed 10 times and the time of execution will be measured each time.

8.2.1 Extended Query File

Extended example for QUERY_FILE:

```
{
  'name': 'Some simple queries',
  'intro': 'This is an example workload',
  'info': 'It runs on a P100 GPU',
  'connectionmanagement': {
    'timeout': 600,           # in seconds
    'numProcesses': 4,      # number of parallel client processes
    'runsPerConnection': 5, # number of runs performed before connection is closed
    'singleConnection': False # if connection should be used for the complete stream
  },
  'queries':
  [
    {
      'title': "Count all rows in test",
      'query': "SELECT COUNT(*) c FROM test",
      'DBMS': {
        'MySQL': "SELECT COUNT(*) AS c FROM test"
      }
      'delay': 1,
      'numRun': 10,
      'connectionmanagement': {
        'timeout': 100,
        'numProcesses': 1,
        'runsPerConnection': None
      },
      'timer':
      {
        'connection':
        {
          'active': True,
          'delay': 0
        },
        'datatransfer':
        {
          'active': True,
          'sorted': True,
          'compare': 'result',
          'store': 'dataframe',
          'precision': 4,
        }
      }
    },
  ],
}
```


8.2.1.1 SQL Dialects

The `DBMS` key allows to specify SQL dialects. All connections starting with the key in this dict will use the specified alternative query. In the example above, for instance a connection `'MySQL-InnoDB'` will use the alternative. Optionally at the definition of the connections an attribute `dialect` can be used. For example MemSQL may use the dialect MySQL.

8.2.1.2 Connection Management

The first `connectionmanagement` options set global values valid for all DBMS. This can be overwritten by the settings in the `connection config`. The second `connectionmanagement` is fixed valid for this particular query and cannot be overwritten.

- `timeout`: Maximum lifespan of a connection. Default is None, i.e. no limit.
- `numProcesses`: Number of parallel client processes. Default is 1.
- `runsPerConnection`: Number of runs performed before connection is closed. Default is None, i.e. no limit.
- `singleConnection`: This indicates if the connection should be used for the complete stream of queries. Default is True. Switch this off, if you want to have reconnects during the stream, for example to inspect the effect of reconnection of execution times.

8.2.1.3 Connection Latency

The `connection` timer will also measure the time for establishing a connection. It is possible to force sleeping before each establishment by using `delay` (in seconds). Default is 0.

8.2.1.4 Results and Comparison

The `datatransfer` timer will also measure the time for data transfer. The tool can store retrieved data to compare different queries and dbms. This helps to be sure different approaches yield the same results. For example the query above should always return the same number of rows in table `test`.

`compare` can be used to compare result sets obtained from different runs and dbms. `compare` is optional and can be

- `result`: Compare complete result set. Every cell is trimmed. Floats can be rounded to a given `precision` (decimal places). This is important for example for comparing CPU and GPU based DBMS.
- `hash`: Compare hash value of result set.
- `size`: Compare size of result set.

If comparison detects any difference in result sets, a warning is generated.

The result set can optionally be sorted by each column before comparison by using `sorted`. This helps avoid mismatch due to different orderings in the received sets.

Note that comparing result sets necessarily means they have to be stored, so `result` should only be used for small data sets. The parameter `store` commands the tool to keep the result set and is automatically set to `True` if any of the above is used. It can be set to `False` to command the tool to fetch the result set and immediately forget it. This helps measuring the time for data transfer without having to store all result sets, which in particular for large result sets and numbers of runs can exhaust the RAM. Setting `store` can also yield the result sets to be stored in extra files. Possible values are: `'store': ['dataframe', 'csv']`

8.2.2 Randomized Query File

Example for QUERY_FILE with randomized parameters:

```
{
  'name': 'Some simple queries',
  'defaultParameters': {'SF': '10'},
  'queries':
  [
    {
      'title': "Count rows in test",
      'query': "SELECT COUNT(*) FROM test WHERE name = {NAME}",
      'parameter': {
        'NAME': {
          'type': "list",
          'size': 1,
          'range': ["AUTOMOBILE", "BUILDING", "FURNITURE", "MACHINERY", "HOUSEHOLD"]
        }
      },
      'numWarmup': 5,
      'numRun': 10,
    },
  ]
}
```

A parameter contain of a name NAME, a range (list), a size(optional, default 1) and a type, which can be

- list: list of values - random element
- integer: 2 integers - random value in between
- float: 2 floats - random value in between
- date: 2 dates in format 'YYYY-mm-dd' - random date in between
- firstofmonth: 2 dates in format 'YYYY-mm-dd' - first of random month in between
- year: 2 years as integers - random year in between
- hexcode: 2 integers - random value in between as hexcode

For each benchmark run, {NAME} is replaced by a (uniformly) randomly chosen value in the range and type given above. By size we can specify the size of the sample (without replacement). If set, each generated value will receive a {NAME} concatenated with the number of the sample. Python3's `format()` is used for replacement. The values are generated once per query. This means if a query is rerun or run for different dbms, the same list of values is used.

Example:

```
'NAME': {
  'type': "integer",
  'range': [1,100]
},
```

in a query with `numWarmup=5` and `numRun=10` will generate a random list of 10 integers between 1 and 100. Each time the benchmark for this query is done, the same 10 numbers are used.

```
'NAME': {
  'type': "integer",
  'size': 2,
  'range': [1,100]
},
```

in a query with `numWarmup=5` and `numRun=10` will generate a random list of 10 pairs of integers between 1 and 100. These pairs will replace `{NAME1}` and `{NAME2}` in the query. Both elements of each pair will be different from each other. Each time the benchmark for this query is done, the same 10 pairs are used.

`defaultParameters` can be used to set parameters that hold for the complete workload.

8.2.3 Query List

Example for `QUERY_FILE` with a query that is a sequence:

```
{
  'name': 'Some simple queries',
  'queries':
  [
    {
      'title': "Sequence",
      'queryList': [2,3,4,5],
      'connectionmanagement': {
        'timeout': 600,
        'numProcesses': 1,
        'runsPerConnection': 4
      },
      'numRun': 12,
    },
  ],
}
```

This query does not have a `query` attribute, but an attribute `queryList`. It is a list of other queries, here number 2, 3, 4 and 5. The 12 benchmark runs are done by running these four queries one after the other, three times in total. Here, we reconnect each time the sequence is through (`runsPerConnection = 4`) and we simulate one parallel client (`numProcesses = 1`).

This also respects randomization, i.e. every DBMS receives exactly the same versions of the queries in the same order.

8.3 Connection File

Contains infos about JDBC connections.

Example for `CONNECTION_FILE`:

```
[
  {
    'name': "MySQL",
    'version': "CE 8.0.13",
    'info': "This uses engine innodb",
    'active': True,
    'alias': "DBMS A",
    'docker': "MySQL",
    'docker_alias': "DBMS A",
    'dialect': "MySQL",
    'timeload': 100,
    'priceperhourdollar': 1.0,
    'JDBC': {
      'driver': "com.mysql.cj.jdbc.Driver",
      'url': "jdbc:mysql://localhost:3306/database",
```

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```

    'auth': ["username", "password"],
    'jar': "mysql-connector-java-8.0.13.jar"
  },
  'connectionmanagement': {
    'timeout': 600,
    'numProcesses': 4,
    'runsPerConnection': 5
  },
  'hostsystem': {
    'RAM': 61.0,
    'CPU': 'Intel(R) Xeon(R) CPU E5-2686 v4 @ 2.30GHz\n',
    'Cores': '8\n',
    'host': '4.4.0-1075-aws\n',
    'disk': '82G\n',
    'CUDA': ' NVIDIA-SMI 410.79          Driver Version: 410.79          CUDA Version: 10.
↪0',
    'instance': 'p3.2xlarge'
  },
  'monitoring': {
    'shift': 0,
    'extend': 20,
    'prometheus_url': 'http://127.0.0.1:9090/api/v1/',
    'metrics': {
      'total_cpu_memory': {
        'query': 'container_memory_working_set_bytes{job="monitor-node"}/1024/1024',
        'title': 'CPU Memory [MiB]'
      }
    }
  }
},
]

```

- **name:** References the connection
- **version and info:** Just info texts for implementation in reports
- **active:** Use this connection in benchmarking and reporting (optional, default True)
- **alias:** Alias for anonymized reports (optional, default is a random name)
- **docker:** Name of the docker image. This helps aggregating connections using the same docker image.
- **docker_alias:** Anonymized name of the docker image. This helps aggregating connections using the same docker image in anonymized reports.
- **alias:** Alias for anonymized reports (optional default is a random name)
- **dialect:** Key for (optional) alternative SQL statements in the query file
- **driver, url, auth, jar:** JDBC data
- **Additional information useful for reporting and also used for computations**
 - **timeload:** Time for ingest (in milliseconds), because not part of the benchmark
 - **priceperhourdollar:** Used to compute total cost based on total time (optional)
- **connectionmanagement:** Parameter for connection management. This overwrites general settings made in the *query config* and can be overwritten by query-wise settings made there.
 - **timeout:** Maximum lifespan of a connection. Default is None, i.e. no limit.

- numProcesses: Number of parallel client processes. Default is 1.
- runsPerConnection: Number of runs performed before connection is closed. Default is None, i.e. no limit.
- singleConnection: This indicates if the connection should be used for the complete stream of queries. Default is True. Switch this off, if you want to have reconnects during the stream, for example to inspect the effect of reconnection of execution times.
- hostsystem: Describing information for report in particular about the host system. This can be written automatically by <https://github.com/Beuth-Erdelt/Benchmark-Experiment-Host-Manager>
- monitoring: We might also add information about fetching *monitoring* metrics.
 - prometheus_url: URL to API of Prometheus instance monitoring the system under test
 - shift: Shifts the fetched interval by n seconds to the future.
 - extend: Extends the fetched interval by n seconds at both ends.

In the following we list some minimal connection information that have been used in the past to connect to DBMS successfully.

Make sure to adjust the

- URL of the server `localhost`
- port of the server, when necessary
- name of the database `database` (and / or schema)
- username and password `user/password`
- path of the (locally existing) JDBC jar file - **you will have to download the jar file from the website of the vendor**

9.1 Citus Data

<https://www.citusdata.com/>

JDBC driver: <https://jdbc.postgresql.org/>

```
[
  {
    'name': 'Citus',
    'info': 'This is a demo of Citus',
    'active': True,
    'JDBC': {
      'driver': 'org.postgresql.Driver',
      'url': 'jdbc:postgresql://localhost:5432/database',
      'auth': ['user', 'password'],
      'jar': 'jars/postgresql-42.2.5.jar'
    }
  },
]
```

9.2 Clickhouse

<https://clickhouse.com/>

JDBC driver: <https://github.com/ClickHouse/clickhouse-jdbc>

```
[
  {
    'name': 'Clickhouse',
    'info': 'This is a demo of Clickhouse',
    'active': True,
    'JDBC': {
      'driver': 'ru.yandex.clickhouse.ClickHouseDriver',
      'url': 'jdbc:clickhouse://localhost:8123/database',
      'auth': ['user', 'password'],
      'jar': ['clickhouse-jdbc-0.2.4.jar', 'commons-codec-1.9.jar', 'commons-
↪ logging-1.2.jar', 'guava-19.0.jar', 'httpclient-4.5.2.jar', 'httpcore-4.4.4.jar',
↪ 'httpmime-4.5.2.jar', 'jackson-annotations-2.7.0.jar', 'jackson-core-2.7.3.jar',
↪ 'jackson-databind-2.7.3.jar', 'jaxb-api-2.3.0.jar', 'lz4-1.3.0.jar', 'slf4j-api-1.7.
↪ 21.jar'],
    }
  },
]
```

9.3 Exasol

<https://www.exasol.com/de/>

JDBC driver: https://docs.exasol.com/db/latest/connect_exasol/drivers/jdbc.htm

```
[
  {
    'name': 'Exasol',
    'info': 'This is a demo of Exasol',
    'active': True,
    'JDBC': {
      'driver': 'com.exasol.jdbc.EXADriver',
      'url': 'jdbc:exa:localhost:8888;schema=schema',
      'auth': ['user', 'password'],
      'jar': 'jars/exajdbc.jar'
    }
  },
]
```

9.4 HEAVY.AI

9.4.1 OmniSci

<https://www.heavy.ai/>

JDBC driver: <https://search.maven.org/artifact/com.omnisci/omnisci-jdbc/5.10.0/jar>


```
[
  {
    'name': 'OmniSci',
    'info': 'This is a demo of OmniSci',
    'active': True,
    'JDBC': {
      'driver': 'com.omnisci.jdbc.OmniSciDriver',
      'url': 'jdbc:omnisci:localhost:6274:omnisci',
      'auth': ['user', 'password'],
      'jar': ['omnisci-jdbc-5.5.0.jar', 'libthrift-0.13.0.jar', 'commons-codec-
→1.9.jar', 'commons-logging-1.2.jar', 'guava-19.0.jar', 'httpclient-4.5.2.jar',
→'httpcore-4.4.4.jar', 'httpmime-4.5.2.jar', 'jackson-annotations-2.7.0.jar',
→'jackson-core-2.7.3.jar', 'jackson-databind-2.7.3.jar', 'jaxb-api-2.3.0.jar', 'lz4-
→1.3.0.jar', 'slf4j-api-1.7.21.jar']
    }
  },
]
```

9.5 IBM DB2

<https://www.ibm.com/products/db2-database>

JDBC driver: <https://www.ibm.com/support/pages/db2-jdbc-driver-versions-and-downloads>

```
[
  {
    'name': 'DB2',
    'info': 'This is a demo of DB2',
    'active': True,
    'JDBC': {
      'driver': 'com.ibm.db2.jcc.DB2Driver',
      'url': 'jdbc:db2://localhost:50000/database:currentSchema=schema',
      'auth': ['user', 'password'],
      'jar': 'jars/db2jcc4.jar'
    }
  },
]
```

9.6 MariaDB

<https://mariadb.com/>

JDBC driver: <https://mariadb.com/kb/en/about-mariadb-connector-j/>

```
[
  {
    'name': 'MariaDB',
    'info': 'This is a demo of MariaDB',
    'active': True,
    'JDBC': {
      'driver': 'org.mariadb.jdbc.Driver',
      'url': 'jdbc:mariadb://localhost:3306/database',
      'auth': ['user', 'password'],

```

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```
        'jar': 'jars/mariadb-java-client-2.4.0.jar'
    },
],
```

9.7 MariaDB Columnstore

<https://mariadb.com/kb/en/mariadb-columnstore/>

JDBC driver: <https://mariadb.com/kb/en/about-mariadb-connector-j/>

```
[
  {
    'name': 'MariaDB Columnstore',
    'info': 'This is a demo of MariaDB Columnstore',
    'active': True,
    'JDBC': {
      'driver': 'org.mariadb.jdbc.Driver',
      'url': 'jdbc:mariadb://localhost:3306/database',
      'auth': ['user', 'password'],
      'jar': 'jars/mariadb-java-client-2.4.0.jar'
    }
  },
]
```

9.8 MonetDB

<https://www.monetdb.org/>

JDBC driver: <https://www.monetdb.org/downloads/Java/>

```
[
  {
    'name': 'MonetDB',
    'info': 'This is a demo of MonetDB',
    'active': True,
    'JDBC': {
      'driver': 'nl.cwi.monetdb.jdbc.MonetDriver',
      'url': 'jdbc:monetdb://localhost:50000/database?so_timeout=10000',
      'auth': ['user', 'password'],
      'jar': 'jars/monetdb-jdbc-2.29.jar',
    }
  },
]
```

9.9 MS SQL Server

<https://www.microsoft.com/en-us/sql-server>

JDBC driver: <https://github.com/microsoft/mssql-jdbc>

```
[
  {
    'name': 'MS SQL Server',
    'info': 'This is a demo of MS SQL Server',
    'active': True,
    'JDBC': {
      'driver': 'com.microsoft.sqlserver.jdbc.SQLServerDriver',
      'url': 'jdbc:sqlserver://localhost:1433;databaseName=database',
      'auth': ['user', 'password'],
      'jar': 'mssql-jdbc-8.2.2.jre8.jar'
    }
  },
]
```

9.10 MySQL

<https://www.mysql.com/>

JDBC driver: <https://dev.mysql.com/downloads/connector/j/>

```
[
  {
    'name': 'MySQL',
    'info': 'This is a demo of MySQL',
    'active': True,
    'JDBC': {
      'driver': 'com.mysql.cj.jdbc.Driver',
      'url': 'jdbc:mysql://localhost:3306/database?serverTimezone=Europe/Berlin',
      'auth': ['user', 'password'],
      'jar': 'jars/mysql-connector-java-8.0.13.jar'
    }
  },
]
```

9.11 Oracle DB

<https://www.oracle.com/database/technologies/>

JDBC driver: <https://www.oracle.com/database/technologies/appdev/jdbc.html>

```
[
  {
    'name': 'Oracle DB',
    'info': 'This is a demo of Oracle DB',
    'active': True,
    'JDBC': {
```

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```
        'driver': 'oracle.jdbc.driver.OracleDriver',
        'url': 'jdbc:oracle:thin:@{localhost:1521}',
        'auth': ['user', 'password'],
        'jar': 'ojdbc8.jar'
    },
],
```

9.12 PostgreSQL

<https://www.postgresql.org/>

JDBC driver: <https://jdbc.postgresql.org/>

```
[
  {
    'name': 'PostgreSQL',
    'info': 'This is a demo of PostgreSQL',
    'active': True,
    'JDBC': {
      'driver': 'org.postgresql.Driver',
      'url': 'jdbc:postgresql://localhost:5432/database',
      'auth': ['user', 'password'],
      'jar': 'jars/postgresql-42.2.5.jar'
    }
  },
]
```

9.13 SAP HANA

<https://www.sap.com/products/hana.html>

JDBC driver: <https://mvnrepository.com/artifact/com.sap.cloud.db.jdbc/ngdbc>

```
[
  {
    'name': 'SAP HANA',
    'info': 'This is a demo of SAP HANA',
    'active': True,
    'JDBC': {
      'driver': 'com.sap.db.jdbc.Driver',
      'url': 'jdbc:sap://localhost:39041/HXE?currentSchema=schema',
      'auth': ['user', 'password'],
      'jar': 'jars/ngdbc-2.7.7.jar'
    }
  },
]
```

9.14 SingleStore

<https://www.singlestore.com/>

JDBC driver: <https://mariadb.com/kb/en/about-mariadb-connector-j/>

```
[
  {
    'name': 'SingleStore',
    'info': 'This is a demo of SingleStore',
    'active': True,
    'JDBC': {
      'driver': 'org.mariadb.jdbc.Driver',
      'url': 'jdbc:mariadb://localhost:3306/database',
      'auth': ['user', 'password'],
      'jar': 'mariadb-java-client-2.4.0.jar'
    }
  },
]
```

9.14.1 MemSQL

<https://www.singlestore.com/>

JDBC driver: <https://mariadb.com/kb/en/about-mariadb-connector-j/>

```
[
  {
    'name': 'MemSQL',
    'info': 'This is a demo of MemSQL',
    'active': True,
    'JDBC': {
      'driver': 'org.mariadb.jdbc.Driver',
      'url': 'jdbc:mariadb://localhost:3306/database',
      'auth': ['user', 'password'],
      'jar': 'mariadb-java-client-2.4.0.jar'
    }
  },
]
```

9.15 TimescaleDB

<https://www.timescale.com/>

JDBC driver: <https://jdbc.postgresql.org/>

```
[
  {
    'name': 'TimescaleDB',
    'info': 'This is a demo of TimescaleDB',
    'active': True,
    'JDBC': {
      'driver': 'org.postgresql.Driver',
      'url': 'jdbc:postgresql://localhost:5432/database',

```

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```
        'auth': ['user', 'password'],
        'jar': 'jars/postgresql-42.2.5.jar'
    },
]
```

9.16 Vertica

<https://www.vertica.com/>

JDBC driver: <https://www.vertica.com/download/vertica/client-drivers/>

```
[
  {
    'name': 'Vertica',
    'info': 'This is a demo of Vertica',
    'active': True,
    'JDBC': {
      'driver': "com.vertica.jdbc.Driver",
      'url': 'jdbc:vertica://localhost:5433/database',
      'auth': ["user", "password"],
      'jar': "jars/vertica-jdbc-11.1.0-0.jar"
    },
  },
]
```

EVALUATION

After an experiment has finished, the results can be evaluated. We show here some example evaluations to illustrate what is possible.

10.1 Example Evaluations

Some example evaluations

- *Global Metrics*
 - *average position*
 - *latency and throughput*
 - *ingestion*
 - *hardware metrics*
 - *host metrics*
- *Drill-Down Timers*
 - *relative position*
 - *average times*
- *Slices of Timers*
 - *heatmap of factors*
- *Drill-Down Queries*
 - *total times*
 - *normalized total times*
 - *latencies*
 - *throughputs*
 - *sizes of result sets*
 - *errors*
 - *warnings*
- *Slices of Queries*
 - *latency and throughput*
 - *hardware metrics*

- *timers*
- *Slices of Queries and Timers*
 - *statistics* - measures of tendency and dispersion, sensitive and insensitive to outliers
 - *plots* of times
 - *box plots* of times
- summarizing and exhaustive latex reports containing *further data* like
 - precision and identity checks of *result sets*
 - *error messages*
 - *warnings*
 - *benchmark times*
 - *experiment workflow*
 - *initialization scripts*
- an interactive *inspection tool*
- a Latex report containing most of these

10.1.1 Informations about DBMS

The user has to provide in a `config` file

- a unique name (**connectionname**)
- JDBC connection information

If a monitoring interface is provided, `hardware metrics` are collected and aggregated. We may further provide describing information for reporting.

10.1.2 Global Metrics

10.1.2.1 Latency and Throughput

For each query, latency and throughput is computed per DBMS. This chart shows the geometric mean over all queries and per DBMS. Only successful queries and DBMS not producing any error are considered there.

10.1.2.2 Average Ranking

We compute a ranking of DBMS for each query based on the sum of times, from fastest to slowest. Unsuccessful DBMS are considered last place. The chart shows the average ranking per DBMS.

10.1.2.3 Time of Ingest per DBMS

This is part of the informations provided by the user. The tool does not measure time of ingest explicitly.

10.1.2.4 Hardware Metrics

The chart shows the metrics obtained from monitoring. Values are computed as arithmetic mean across benchmarking time. Only successful queries and DBMS not producing any error are considered.

10.1.2.5 Host Metrics

The host information is provided in the config file. Here, cost is based on the total time.

10.1.3 Drill-Down Timers

10.1.3.1 Relative Ranking based on Times

For each query and timer, the best DBMS is considered as gold standard = 100%. Based on their times, the other DBMS obtain a relative ranking factor. Only successful queries and DBMS not producing any error are considered. The chart shows the geometric mean of factors per DBMS.

10.1.3.2 Average Times

This is based on the mean times of all benchmark test runs. Measurements start before each benchmark run and stop after the same benchmark run has been finished. The average value is computed per query. Parallel benchmark runs should not slow down in an ideal situation. Only successful queries and DBMS not producing any error are considered. The chart shows the average of query times based on mean values per DBMS and per timer.

Note that the mean of mean values (here) is in general not the same as mean of all runs (different queries may have different number of runs).

10.1.4 Slice Timers

10.1.4.1 Heatmap of Factors

The relative ranking can be refined to see the contribution of each query. The chart shows the factor of the corresponding timer per query and DBMS. All active queries and DBMS are considered.

10.1.5 Drill-Down Queries

10.1.5.1 Total Times

This is based on the times each DBMS is queried in total. Measurement starts before first benchmark run and stops after the last benchmark run has been finished. Parallel benchmarks should speed up the total time in an ideal situation. Only successful queries and DBMS not producing any error are considered. Note this also includes the time needed for sorting and storing result sets etc. The chart shows the total query time per DBMS and query.

10.1.5.2 Normalized Total Times

The chart shows total times per query, normalized to the average total time of that query. Only successful queries and DBMS not producing any error are considered. This is also available as a heatmap.

10.1.5.3 Throughputs

For each query, latency and throughput is computed per DBMS. Only successful queries and DBMS not producing any error are considered there.

10.1.5.4 Latencies

For each query, latency and throughput is computed per DBMS. Only successful queries and DBMS not producing any error are considered there.

10.1.5.5 Sizes of Result Sets

For each query, the size of received data per DBMS is stored. The chart shows the size of result sets per DBMS and per timer. Sizes are normalized to minimum per query. All active queries and DBMS are considered.

10.1.5.6 Errors

The chart shows per DBMS and per timer, if an error has occurred. All active queries and DBMS are considered.

10.1.5.7 Warnings

The chart shows per DBMS and per timer, if a warning has occurred. All active queries and DBMS are considered.

10.1.6 Slice Queries

10.1.6.1 Latency and Throughput per Query

For each query, latency and throughput is computed per DBMS. This is available as dataframes, in the evaluation dict and as png files per query. Only successful queries and DBMS not producing any error are considered there.

10.1.6.2 Hardware Metrics per Query

These metrics are collected from a Prometheus / Grafana stack. This expects time-synchronized servers.

10.1.6.3 Timers Per Query

This is based on the sum of times of all single benchmark test runs. These charts show the average of times per DBMS based on mean value. Warmup and cooldown are not included. If data transfer or connection time is also benchmarked, the chart is stacked. The bars are ordered ascending.

10.1.7 Slice Queries and Timers

10.1.7.1 Statistics Table

These tables show *statistics* about benchmarking time during the various runs per DBMS as a table. Warmup and cooldown are not included. This is for inspection of stability. A factor column is included. This is computed as the multiple of the minimum of the mean of benchmark times per DBMS. The DBMS are ordered ascending by factor.

10.1.7.2 Plot of Values

These plots show the variation of benchmarking time during the various runs per DBMS as a plot. Warmup and cooldown are included and marked as such. This is for inspection of time dependence.

Note this is only reliable for non-parallel runs.

10.1.7.3 Boxplot of Values

These plots show the variation of benchmarking time during the various runs per DBMS as a boxplot. Warmup, cooldown and zero (missing) values are not included. This is for inspection of variation and outliers.

10.1.7.4 Histogram of Values

These plots show the variation of benchmarking time during the various runs per DBMS as a histogram. The number of bins equals the minimum number of result times. Warmup, cooldown and zero (missing) values are not included. This is for inspection of the distribution of times.

10.1.8 Further Data

10.1.8.1 Result Sets per Query

The result set (sorted values, hashed or pure size) of the first run of each DBMS can be saved per query. This is for comparison and inspection.

10.1.8.2 All Benchmark Times

The benchmark times of all runs of each DBMS can be saved per query. This is for comparison and inspection.

10.1.8.3 All Errors

The errors that may have occurred are saved for each DBMS and per query. The error messages are fetched from Python exceptions thrown during a benchmark run. This is for inspection of problems.

10.1.8.4 All Warnings

The warnings that may have occurred are saved for each DBMS and per query. The warning messages are generated if comparison of result sets detects any difference. This is for inspection of problems.

10.1.8.5 Initialization Scripts

If the result folder contains init scripts, they will be included in the dashboard.

10.1.8.6 Bexhoma Workflow

If the result folder contains the configuration of a `bexhoma` workflow, it will be included in the dashboard.

DASHBOARD

The dashboard helps in interactive evaluation of experiment results.

11.1 Start

The dashboard is started using a Python script:

```
python dashboard.py -h
```

```
usage: dashboard.py [-h] [-r RESULT_FOLDER] [-a] [-u USER] [-p PASSWORD] [-d]
```

```
Dashboard for interactive inspection of dbmsbenchmarker results.
```

```
optional arguments:
```

```
-h, --help                show this help message and exit  
-r RESULT_FOLDER, --result-folder RESULT_FOLDER  
                        Folder storing benchmark result files.  
-a, --anonymize          Anonymize all dbms.  
-u USER, --user USER    User name for auth protected access.  
-p PASSWORD, --password PASSWORD  
                        Password for auth protected access.  
-d, --debug              Show debug information.
```

It has two options:

- `--result-folder`: Path of a local folder containing result folders. This parameter is the same as for `benchmark.py`
- `--anonymize`: If this flag is set, all DBMS are anonymized following the parameters in their `configuration`.

When you start the dashboard it is available at `localhost:8050`.

11.1.1 Select Experiment

You will be shown a list of experiments available at the path you have provided. Select one experiment. Optionally you can activate to have some default panels that will be included at start.

11.2 Concept

The dashboard analyzes the data in [three dimensions](#) using various [aggregation functions](#):

11.2.1 Data

The cells of the runtime cube contain timer (connection, execution, data transfer, run and session) and derived metrics (latencies, throughput). The cells of the monitoring cube contain hardware metrics.

11.2.2 Graph Panels

The dashboard is organized into 12 columns and several rows depending on the screen size. For a single graph panel you can

- change width (number of columns)
- change height (number of rows)
- change ordering on the dashboard
- activate settings
- download underlying data as csv.

11.2.2.1 Graph Types

Available types of display are

- Line Plot
- Boxplot
- Histogramm
- Bar Chart
- Heatmap
- Table of Measures
- Table of Statistics

These can be applied to sliced / diced / aggregated data of the cubes.

There are also some preset graphs

- Heatmap of Errors
- Heatmap of Warnings
- Heatmap Result Set Size
- Heatmap Total Time
- Heatmap Latency Run
- Heatmap Throughput Run
- Heatmap Timer Run Factor
- Bar Chart Run drill-down

- Bar Chart Ingestion Time

11.3 Menu

The menu allows you to

- open the *filtering* panel
- open the *favorites* panel
- *select* (change to) an experiment
- see details about the current experiment
- activate all panels on the current dashboard
- close all active panels on the current dashboard
- add a *graph* (panel)
- open the *settings* panel

11.4 Favorites

The favorites menu allows you to

- load a dashboard
- append a list of panels to the current dashboard
- save the current list of panels as a favorite
- download a favorite
- upload a favorite

11.5 Settings

In the settings panel you can select the

- *Kind of measure* you want to inspect (kind, name)
- *Type* of plot (graph type, x-axis, annotate)
- *Aggregation functions*. The order of aggregation is
 1. Query (run dimension)
 2. Total (query dimension)
 3. Connection (configuration dimension) Aggregation in the connection dimension can be drilled-down (color by)
- a **number of warmup runs** and a **number of cooldown runs** This means the first n runs resp. the last n runs are ignored in evaluation. **Note** this is only reliable for non-parallel connections.

11.6 Filter

In the filter panel you can

- filter
 - one or more connections (configurations) using
 - * a checkbox list of single connections
 - * property filters
 - DBMS
 - Cluster node
 - Number of clients
 - CPU
 - GPU
 - single queries
- receive details about
 - the connections (configurations)
 - * Configuration
 - * DBMS
 - * Resources
 - and the queries like
 - * Configuration
 - * Number of runs
 - * Result sets

INSPECTOR

See the [rendered example](#) for more details.

DEBUG TOOL

There is a debug tool, that helps to analyze result folders: `python evaluate.py -h`

```
usage: evaluate.py [-h] [-r RESULT_FOLDER] [-e EXPERIMENT] [-q QUERY] [-c CONNECTION]
↳ [-n NUM_RUN] [-d] [-rt] {resultsets,errors,warnings,query}

A debug tool for DBMSBenchmark. It helps to analyze a result folder. It depends on
↳ the evaluation cube, so that cube must have been created before.

positional arguments:
  {resultsets,errors,warnings,query}
                                show debug infos about which part of the outcome

optional arguments:
  -h, --help                    show this help message and exit
  -r RESULT_FOLDER, --result-folder RESULT_FOLDER
                                folder for storing benchmark result files, default is given
↳ by timestamp
  -e EXPERIMENT, --experiment EXPERIMENT
                                code of experiment
  -q QUERY, --query QUERY
                                number of query to inspect
  -c CONNECTION, --connection CONNECTION
                                name of DBMS to inspect
  -n NUM_RUN, --num-run NUM_RUN
                                number of run to inspect
  -d, --diff                    show differences in result sets
  -rt, --remove-titles         remove titles when comparing result sets
```

It depends on the evaluation cube. In case, it can be generated by `dbmsbenchmark -e yes -r 1647993954` read for example for experiment 1647993954.

13.1 Show Queries

We can take a look at the actual queries that have been sent: `python evaluate.py -e 1647993954 -q 1 -n 0 query`

This shows the query string for query number 2, first run.

13.2 Show Result Sets

We can take a look at the actual queries that have been sent: `python evaluate.py -e 1647993954 -q 2 resultsets`

This shows the query string for query number 2.

13.3 Show Errors

We can take a look at the actual queries that have been sent: `python evaluate.py -e 1647993954 errors`

13.4 Show Warnings

We can take a look at the actual queries that have been sent: `python evaluate.py -e 1647993954 warnings`

CONTRIBUTING TO DBMSBENCHMARKER

You would like to contribute? Great!

Some things that you can help on include:

- **New Workloads:** The `example/` folder includes the TPC-H and TPC-DS (reading) queries in various dialects. We are interested in adding other relevant workloads.
- **Evaluation Tools:** The dashboard contains some important prepared charts. However, adding functionality and keeping up to date with Dash could use some help.
- **Documentation:** If a point in the documentation is unclear, we look forward to receiving tips and suggestions for improvement.
- **Testing:** If the behavior is not as expected and you suspect a bug, please report it to our [issue tracker](#).
- **Use Cases:** If you have had any experiences with peculiarities, mistakes, ambiguities or oddities or particularly beautiful cases etc., we are interested in hearing about them and passing them on to others.

14.1 Non-code contributions

Even if you don't feel ready or able to contribute code, you can still help out. There always things that can be improved on the documentation (even just proof reading, or telling us if a section isn't clear enough).

14.2 Code contributions

We welcome pull requests to fix bugs or add new features.

14.2.1 Licensing

In your git commit and/or pull request, please explicitly state that you agree to your contributions being licensed under "GNU Affero General Public License v3".

14.2.2 Git Usage

If you are planning to make a pull request, start by creating a new branch with a short but descriptive name (rather than using your master branch).

14.2.3 Coding Conventions

DBMSBenchmark tries to follow the coding conventions laid out in PEP8 and PEP257

- <http://www.python.org/dev/peps/pep-0008/>
- <http://www.python.org/dev/peps/pep-0257/>

14.2.4 Testing

Any new feature or functionality will not be accepted without tests. Likewise for any bug fix, we encourage including an additional test.

DBMS-BENCHMARKER

DBMS-Benchmarker is a Python-based application-level blackbox benchmark tool for Database Management Systems (DBMS). It aims at reproducible measuring and easy evaluation of the performance the user receives even in complex benchmark situations. It connects to a given list of DBMS (via JDBC) and runs a given list of (SQL) benchmark queries. Queries can be parametrized and randomized. Results and evaluations are available via a Python interface and can be inspected with standard Python tools like pandas DataFrames. An interactive visual dashboard assists in multi-dimensional analysis of the results.

See the [homepage](#) and the [documentation](#).

If you encounter any issues, please report them to our [Github issue tracker](#).

15.1 Key Features

DBMS-Benchmarker

- is Python3-based
- helps to **benchmark DBMS**
 - connects to all DBMS having a JDBC interface - including GPU-enhanced DBMS
 - requires *only* JDBC - no vendor specific supplements are used
 - benchmarks arbitrary SQL queries - in all dialects
 - allows planning of complex test scenarios - to simulate realistic or revealing use cases
 - allows easy repetition of benchmarks in varying settings - different hardware, DBMS, DBMS configurations, DB settings etc
 - investigates a number of timing aspects - connection, execution, data transfer, in total, per session etc
 - investigates a number of other aspects - received result sets, precision, number of clients
 - collects hardware metrics from a Prometheus server - hardware utilization, energy consumption etc
- helps to **evaluate results** - by providing
 - metrics that can be analyzed by aggregation in multi-dimensions, like maximum throughput per DBMS, average CPU utilization per query or geometric mean of run latency per workload
 - predefined evaluations like statistics
 - in standard Python data structures
 - in [Jupyter notebooks](#) see [rendered example](#)
 - in an interactive dashboard

For more informations, see a [basic example](#) or take a look in the [documentation](#) for a full list of options.

The code uses several Python modules, in particular for handling DBMS. This module has been tested with Clickhouse, DB2, Exasol, Hyperscale (Citus), Kinetica, MariaDB, MariaDB Columnstore, MemSQL, Mariadb, MonetDB, MySQL, OmniSci, Oracle DB, PostgreSQL, SingleStore, SQL Server, SAP HANA, TimescaleDB and Vertica.

15.2 Installation

Run `pip install dbmsbenchmarker` to install the package.

You will also need to have

- Java installed (we tested with Java 8)
- JAVA_HOME set correctly
- a JDBC driver suitable for the DBMS you want to connect to (optionally located in your CLASSPATH)

15.3 Basic Usage

The following very simple use case runs the query `SELECT COUNT(*) FROM test` 10 times against one local MySQL installation. As a result we obtain an interactive dashboard to inspect timing aspects.

15.3.1 Configuration

We need to provide

- a DBMS configuration file, e.g. in `./config/connections.config`

```
[
{
  'name': "MySQL",
  'active': True,
  'JDBC': {
    'driver': "com.mysql.cj.jdbc.Driver",
    'url': "jdbc:mysql://localhost:3306/database",
    'auth': ["username", "password"],
    'jar': "mysql-connector-java-8.0.13.jar"
  }
}
]
```

- the required JDBC driver, e.g. `mysql-connector-java-8.0.13.jar`
- a Queries configuration file, e.g. in `./config/queries.config`

```
{
  'name': 'Some simple queries',
  'connectionmanagement': {
    'timeout': 5 # in seconds
  },
  'queries':
  [
    {
      'title': "Count all rows in test",
```

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```
'query': "SELECT COUNT(*) FROM test",
'numRun': 10
}
]
}
```

15.3.2 Perform Benchmark

Run the CLI command: `dbmsbenchmarker run -e yes -b -f ./config`

- `-e yes`: This will precompile some evaluations and generate the timer cube.
- `-b`: This will suppress some output
- `-f`: This points to a folder having the configuration files.

This is equivalent to `python benchmark.py run -e yes -b -f ./config`

After benchmarking has been finished we will see a message like

```
Experiment <code> has been finished
```

The script has created a result folder in the current directory containing the results. `<code>` is the name of the folder.

15.3.3 Evaluate Results in Dashboard

Run the command: `dbmsdashboard`

This will start the evaluation dashboard at `localhost:8050`. Visit the address in a browser and select the experiment `<code>`.

Alternatively you may use a [Jupyter notebook](#), see a [rendered example](#).

15.4 Limitations

Limitations are:

- strict black box perspective - may not use all tricks available for a DBMS
- strict JDBC perspective - depends on a JVM and provided drivers
- strict user perspective - client system, network connection and other host workloads may affect performance
- not officially applicable for well known benchmark standards - partially, but not fully complying with TPC-H and TPC-DS
- hardware metrics are collected from a monitoring system - not as precise as profiling
- no GUI for configuration
- strictly Python - a very good and widely used language, but maybe not your choice

Other comparable products you might like

- [Apache JMeter](#) - Java-based performance measure tool, including a configuration GUI and reporting to HTML
- [HammerDB](#) - industry accepted benchmark tool based on Tcl, but limited to some DBMS

- [Sysbench](#) - a scriptable multi-threaded benchmark tool based on LuaJIT
- [OLTPBench](#) - Java-based performance measure tool, using JDBC and including a lot of predefined benchmarks
- [BenchBase](#) - successor of OLTPBench

15.5 Contributing, Bug Reports

If you have any question or found a bug, please report them to our [Github issue tracker](#). In any bug report, please let us know:

- Which operating system and hardware (32 bit or 64 bit) you are using
- Python version
- DBMSBenchmarker version (or git commit/date)
- DBMS you are connecting to
- Traceback that occurs (the full error message)

We are always looking for people interested in helping with code development, documentation writing, technical administration, and whatever else comes up. If you wish to contribute, please first read the [contribution section in the documentation](#).

15.6 Benchmarking in a Kubernetes Cloud

This module can serve as the **query executor** [2] and **evaluator** [1] for distributed parallel benchmarking experiments in a Kubernetes Cloud, see the [orchestrator](#) for more details.

15.7 References

If you use DBMSBenchmarker in work contributing to a scientific publication, we ask that you cite our application note [1]:

[1] [A Framework for Supporting Repetition and Evaluation in the Process of Cloud-Based DBMS Performance Benchmarking](#)

Erdelt P.K. (2021) A Framework for Supporting Repetition and Evaluation in the Process of Cloud-Based DBMS Performance Benchmarking. In: Nambiar R., Poess M. (eds) Performance Evaluation and Benchmarking. TPCTC 2020. Lecture Notes in Computer Science, vol 12752. Springer, Cham. https://doi.org/10.1007/978-3-030-84924-5_6

[2] [Orchestrating DBMS Benchmarking in the Cloud with Kubernetes](#)

Erdelt P.K. (2022) Orchestrating DBMS Benchmarking in the Cloud with Kubernetes. In: Nambiar R., Poess M. (eds) Performance Evaluation and Benchmarking. TPCTC 2021. Lecture Notes in Computer Science, vol 13169. Springer, Cham. https://doi.org/10.1007/978-3-030-94437-7_6