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PERFORMANCE OF GRAPH AND RELATIONAL DATABASES IN COMPLEX QUERIES

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**Featured Application: Authors are encouraged to provide a concise description of the specific application or a potential application of the work. This section is not mandatory.**

**Abstract:** In developing NoSQL databases, a main motivation has been to achieve more efficient query performance compared with relational databases. The graph database is a NoSQL paradigm where the navigation is based on links instead of joining tables. Link based navigation has been seen more efficient as query approach than join operations of tables. Existing studies strongly support this assumption. However, query complexity has received less attention. For example, in enterprise information systems queries are usually complex and data should be collected from several data records. In the present study, we compare the query performance of a graph-based database (Neo4j) and a relational database (MariaDB). The outcome is that although Neo4j is more efficient in simple queries, MariaDB is essentially more efficient when the complexity of queries increases.

**Keywords:** keyword 1; keyword 2; keyword 3 (List three to ten pertinent keywords specific to the article yet reasonably common within the subject discipline.)

1. Introduction

Performance has been one of the motivations to use NoSQL databases instead of traditional SQL databases. With data and queries suitable for the data model, NoSQL databases might offer significant performance benefits. In the present study, we compare traditional relational model and NoSQL graph model. The graph model, of the four major NoSQL types, consists of nodes and edges, and it has its own benefits when handling relationship rich data. While in SQL databases multiple tables may need to be joined for a relational query, in graph databases relational information can be queried by navigating through the graph.

There are already several studies where the performance of graph databases, especially Neo4j, have been compared with the traditional SQL databases, see e.g. [4,5,6,7,8]. Often the results show better performance of graph databases. However, those studies are mostly based on quite simple queries. In the present study, we investigate the performance of databases in the situation where query complexity grows. Complex queries are substantial for example in enterprise information systems where data are strongly structured, and queries collect data from various record (tables in SQL databases.) As an example of enterprise related data, we use a simulated structured database containing data needed to compose an invoice piece by piece. We also investigate what are the effects of query optimization and indexing in differed databases. Thus, we aim to find the most efficient setting in the query formulation of complex queries.

In enterprise use, performance is often crucial. Thus, it is very important to take into consideration when choosing the database model. Our main question is to find out how an SQL database and a graph database performance compare when query complexity grows. Recursive query performance and the effect of indexing on the performance are also studied. The databases compared in the present study are MySQL 5.1.41, MariaDB 10.5.6 and Neo4j 4.1.3. Instead of using existing benchmarks such as [1] or [2], a dedicated test bench was implemented for the present study. The test bench is called Invoicing Database Test Bench and its source code is available from GitHub [3]. The program generates a selected amount of data for the test invoicing database schema and performs various query tests.

Designing and Creating our own test dataset and a program for generating new dataset were necessary because the existing datasets do not support complex queries. Our dataset is public. The source code for generating the data is available in GitHub, and, thus, it is possible for anyone to repeat this test by installing the same test settings.

An old MySQL version is involved in the comparison to make our research compatible with earlier studies. From this perspective MariaDB is a natural choice for a modern database because Maria DB is a descendant of MySQL. There are also not yet many studies about MariaDB yet, especially comparing it to a graph database. When making the present study, DB-Engines site ranks MariaDB as 8th out of 138 of relational databases [14]. Neo4j ranks the first out of 32 databases on the same sites. As both of the databases are quite popular, they are often candidates to be used in many enterprises. One of the goals of this study is to find out differences in what use case the databases should be used.

The rest of the paper is organized as follows. Section 2 reviews previous work related to Neo4j and MariaDB performance analysis. Section 3 introduces the schema that is used for the test data. Section 4 presents the implemented benchmarking program. Section 5 presents the test queries. Section 6 presents the test results. Section 7 discusses the results and Section 8 has the conclusions.

2. Related work

SQL database and Neo4j have been compared in several studies including [4,5,6,7,8]. Khan et al. compared tuned Oracle 11g and Neo4j 3.03 Community Edition [4]. Healthcare data was used including data of patients, medicines and medical staff. Performance of the databases was evaluated with ten different count(\*) queries. Many of the queries also performed some table joins. Physical database tuning technique called tablespaces was used for Oracle. The same databases were compared without physical database tuning by Khan et al. [6]. The physical database tuning technique decreased the overall average query time of Oracle from 4.34 to 2.78 seconds. However, the overall average query time for Neo4j in query tests was only 0.67 seconds. Thus, Neo4j performed better compared to Oracle.

Holzschuher et al. tested Neo4j version 1.8 performance with different backend solutions [5]. Neo4j was benchmarked as embedded with native object access, as a dedicated server through RESTful Web Services, with embedded Cypher queries, with Cypher through REST optimized for remote execution and with Gremlin queries through REST. MySQL version 5.5.27 was also included with Java Persistence API based backend. Queries were done using Cypher, Gremlin and SQL query languages. The test data consisted of data of persons and their relationships. Relational test queries were executed such as friends of friends. As the database got larger, the advantages of Neo4j over MySQL become more prevalent. Neo4j performance stayed nearly constant when MySQL performance dropped by factors 5 and 7-9. Both Neo4j query languages Gremlin and Cypher had performance benefits over MySQL with JPA.

Vicknair et al. compared MySQL Community Server version 5.1.42 and Neo4j version 1.0-b11 in 2010 [7]. The graph database was stored into a relational database as nodes and edges. Three types of structural and three types of data queries were made. First structural query found all the orphan nodes and the two other ones traversed the graph in the depths of 4 and 128. The data queries were count(\*) queries counting nodes with certain payloads. Neo4j performed better in structural queries. However, with the integer-based queries MySQL was more efficient due to the fact that the tested Neo4j used Lucene indexing. As it treated the data as text by default, conversions had to be made and thus they impacted the performance. The work [7] by Vicknair et al. has been referenced in [4,5,6].

Batra et al. compared MySQL version 5.1.41 and Neo4j Community version 1.6 in 2012 [8]. They used a schema with tables user, friends, fav\_movies and actors for testing, and they tested the databases with three queries: “Find all friends of Esha”, “Find all favourite movies of Esha’s friends” and “Find the lead actors of Esha’s friends favourite movies”. Queries were executed on 100 and 500 objects. Neo4j had 2-5 times faster query times with 100 objects data set and 15-30 times faster in 500 objects data set. The work by Batra et al [8] has similarity to the present study as the data is stored into SQL database with a relational schema unlike in the work by Vicknair et al [7]. The work [8] by Batra et al is referenced in [5].

There also exist previous performance studies where MariaDB is involved. Tongkaw et al. compared the performance of MariaDB 10.0.21 and MySQL 5.6 [9]. They used Sysbench and OLTP [2] software. OLTP-Simple and OLTP-Seats workloads were used. Both databases consumed the same number of resources. However, when an increasing the number of threads in OLTP-Simple and the number of workers in OLTP-Seats was used, MySQL became clearly more effective outperforming MariaDB. Shalygina et al. studied the Common Table Expression capabilities of MariaDB along with Postgres [10]. The study showed that Postgres had better results, when only a few steps of recursion was needed. However, MariaDB was a better choice for a long recursive process on a huge amount of data.

3. Invoicing database

The test database is a general example of an invoicing database. As it is an invoicing database, one of the most important use cases is the calculation of the price for a customer invoice. This is done by calculating the used time for work of different work types and the price of the items used when working. Invoices might also have relations to other invoices if several invoices are sent to the customer.

The database has 10 tables. The basic tables are customer, invoice, target, work, worktype and item. These tables contain the customer information, customer’s invoices, the target where the work is done, a listing of each work, a listing of different worktypes with different prices and information about the items used for each work. Relational data between the tables is stored into M:N tables worktarget, workinvoice, useditem and workhours. Figure 1 shows database in relational format.

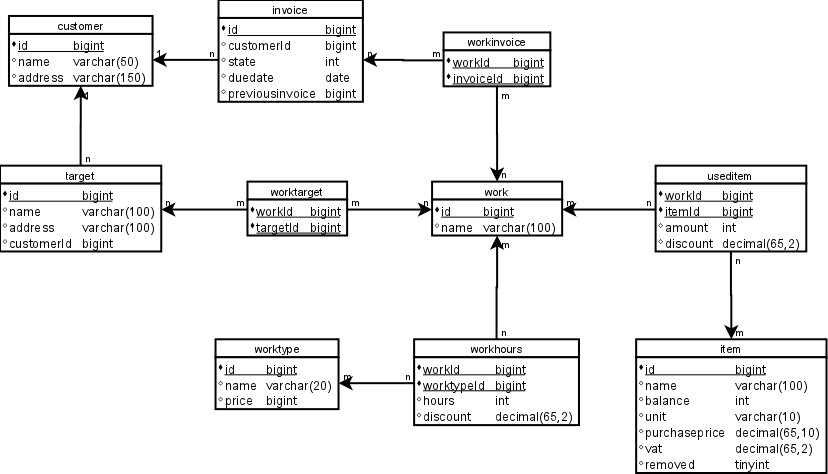


Figure 1: Invoicing database in relational format.

In graph format, edges are used to represent the relationships. For N:M relationships, bidirectional edges are used. The tables customer, invoice, target, work, and worktype are represented as nodes. The edges between the nodes are PAYS between the customer and invoice, CUSTOMER\_TARGET between the customer and target, WORK\_TARGET between work and target, WORK\_INVOICE between work and invoice, WORKHOURS between the work and worktype and USED\_ITEM between work and item. Figure 2 shows database in graph format.



Figure 2: Invoicing database in graph format.

4. Test program

The test data are generated using a Java program. The customer and target generation uses sample data that are based on openly available name and address data sets [13], [12]. The generation process is divided into three parts. Items and work types need to be generated first, then work and customer data. The Java program has threaded classes for each part. Multiple threads can be used to insert the generated data. For random data generation, controlled random seeds are used, making the generation repeatable.

The generation is controlled with parameters for: numbers of work types; numbers of items; numbers of related invoices, targets and work for a customer; number of works; number of customers; numbers of relations between worktypes and works; numbers of invoices and targers for each customer; and numbers of workinvoice and worktarget relationships.

The program has a class called QueryTester that is used to perform the query tests. Query tests are repeated the selected number of times. The test program collects the performance figures from the executions into a list structure. The program removes the biggest and the smallest number from the list and calculates an average and a standard deviation from the rest of the results.

5. Test queries

The query tests contain different relational queries for calculating the price of work and invoice and a recursive query. These queries test different capabilities of the databases. As both relational and graph databases are tested, the queries are in SQL and Cypher form. The query tests are ordered from simple to complex starting from the work price and the work price with items ending in the work prices and work prices for a given customer. There is also a recursive query test.

The 5 queries were chosen as they represent typical queries that would be executed in the chosen test database. Finding and calculating invoice related information is what the database would be most used for, and this is what all the test queries do. As querying all the information required for invoice ends up in complex query, simpler queries were included in order to see how databases perform with different complexity of queries.

Calculating the invoice prices is one of the most important queries. The schema does not store invoice prices explicitly. The price has to be calculated based on the amount of the workhours and the items used. The “price of work” and the “price of work with items” are the subqueries for calculating this price. The query calculating invoice prices for a given customer add customer information into this query. The recursive query queries all the interrelated invoices. One practical example is that customer has not paid the invoice and there will be additional invoices based on the same invoice.

5.1. Query optimization

In addition to just testing databases with the queries, we looked into improving the query performance, and in particular indexing. Both MySQL and MariaDB index primary key and foreign key by default while Neo4j does not create indexes for properties by default. The effect of indexing is also different when comparing an SQL database with a graph database. When querying relations, in SQL databases the relations are formed by joining the tables based on primary key and foreign key information. Thus, SQL databases usually benefit from the indexing of primary keys and foreign keys. In a graph database, we are traversing the graph when querying data. As such, it does not benefit from indexing the properties the way SQL databases do.

In order to study the effects of indexing, certain columns and properties that were used in queries were indexed in all the databases. Table 1 shows the extra indexes created. As ids in customer and invoice tables are indexed by default in MySQL and MariaDB, an extra index was not needed.

|  |  |  |
| --- | --- | --- |
| Table/Node | SQL | Neo4j |
| Customer | - | customerId |
| Invoice | previousinvoice | invoiceId, previousinvoice |
| Item | purchaseprice | purchaseprice |
| Workhours | hours, discount | hours, discount |
| Worktype | price | price |
| Useditem | amount, discount | amount, discount |

Table 1: Indexed columns/properties in SQL and Neo4j.

Besides indexing, in Neo4j 4.1.3 the queries can be optimized using CALL subqueries [13]. The CALL clause makes it possible to execute subqueries in other queries. It is like a function that gets input parameters from the main query and returns some values. The subquery is executed for each incoming input row from calling the query from the main query. CALL has been supported from Neo4j 4.1 onwards. In the present study, Cypher queries with and without CALL are used in order for backward compatibility. This way it is also possible to see how much CALL subquery improves the query performance.

5.2. Short query, price of work

The first test query calculates the price of works. One work can have different work types with different prices. The price of one work is defined by the number of hours done of the work type. There can also be a discount on the prices and the discount is included in calculation. This query shows how databases perform with a fairly simple query. Table 2 shows the queries to query the price of work in SQL and Cypher.

|  |
| --- |
| SQL |
| SELECT work.id AS workId, SUM((worktype.price \* workhours.hours \*  workhours.discount))  AS price  FROM work  INNER JOIN workhours  ON work.id = workhours.workId  INNER JOIN worktype  ON worktype.id = workhours.worktypeId  GROUP BY work.id |
| Cypher |
| MATCH (wt:worktype)-[h:WORKHOURS]->(w:work)  WITH SUM(h.hours\*h.discount\*wt.price)  as price, w  RETURN w.workId as workId, price |
| Cypher with CALL |
| MATCH (w:work) CALL {  WITH w  MATCH (wt:worktype)-[h:WORKHOURS]->(w)  RETURN SUM((h.hours\*h.discount\*wt.price))  as price  } RETURN w.workId as workId, price |
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Table 2: Price of work query in SQL and Cypher

5.3. Long query, price of work with items

The query for the price of work with items is an extended version of the query for the price of work. This query adds item prices into work prices. As items are also included, a longer relational query is needed. With this query it is possible to see how databases perform when more relations and calculations are included in the query. Item purchase price is a floating-point number so this will add more challenges to the calculations. Table 3 shows the queries for the price of work with items in SQL and Cypher.

|  |
| --- |
| SQL |
| SELECT work.id AS workId,  SUM((worktype.price \* workhours.hours \*  workhours.discount) + (item.purchaseprice  \* useditem.amount \* useditem.discount))  AS price  FROM work  INNER JOIN workhours  ON work.id = workhours.workId  INNER JOIN worktype  ON worktype.id = workhours.worktypeId  INNER JOIN useditem  ON work.id = useditem.workId  INNER JOIN item  ON useditem.itemId = item.id  GROUP BY work.id |
| Cypher |
| MATCH (wt:worktype)-[h:WORKHOURS]->(w:work)  -[u:USED\_ITEM]->(i:item)  WITH SUM((h.hours\*h.discount\*wt.price)+  (u.amount\*u.discount\*i.purchaseprice))  as price, w  RETURN w.workId as workId, price |
| Cypher with CALL |
| MATCH (w:work)  CALL {  WITH w  MATCH (wt:worktype)-[h:WORKHOURS]->(w)-  [u:USED\_ITEM]->(i:item)  RETURN SUM((h.hours\*h.discount\*wt.price)+  (u.amount\*u.discount\*i.purchaseprice))  as price }  RETURN w.workId as workId, price |

Table 3: The price of work with items query in SQL and Cypher.

5.4. Complex query, invoice price

This query calculates the sum of a work price for each invoice. The query contains two subqueries. The first one finds the relation of the invoices and work. The second query is the previously presented “price of work with items”. The results of these queries are joined and the sums of prices are aggregated based on the id of the invoice. This is one of the heaviest queries and as such it is useful to see the performance differences when executing a complex query. Table 4 present the queries for calculating the invoice price in SQL and Cypher.

|  |
| --- |
| SQL |
| SELECT q1.invoiceId, SUM(q2.price) AS invoicePrice  FROM (   SELECT workinvoice.invoiceId, workinvoice.workId   FROM workinvoice  INNER JOIN invoice  ON workinvoice.invoiceId =  invoice.id)  AS q1 INNER JOIN (  SELECT workhours.workid AS workId,  SUM((worktype.price \* workhours.hours \*  workhours.discount) + (item.purchaseprice \*  useditem.amount \* useditem.discount))  AS price  FROM workhours  INNER JOIN worktype  ON workhours.worktypeid = worktype.id  INNER JOIN useditem  ON workhours.workid = useditem.workid  INNER JOIN item  ON useditem.itemid = item.id  GROUP BY workhours.workid)  AS q2 USING (workId)  GROUP BY q1.invoiceId |
| Cypher |
| MATCH (inv:invoice)-[:WORK\_INVOICE]->(w:work)  WITH inv, w  OPTIONAL MATCH (wt:worktype)-[h:WORKHOURS]  ->(w:work)-[u:USED\_ITEM]->(i:item)  WITH inv, w, SUM((h.hours\*h.discount\*wt.price) +  (u.amount\*u.discount\*i.purchaseprice))  as workPrice RETURN inv,  SUM(workPrice) as invoicePrice |
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|  |
| Cypher with CALL |  |
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|  |
|  |
| CALL {   WITH inv   MATCH (inv)-[:WORK\_INVOICE]->(w:work)   RETURN w }  CALL {   WITH w   MATCH (wt:worktype)-[h:WORKHOURS]->(w)-  [u:USED\_ITEM]->(i:item)  RETURN SUM((h.hours\*h.discount\*wt.price)+  (u.amount\*u.discount\*i.purchaseprice)) as workPrice  }  RETURN inv, SUM(workPrice)  as invoicePrice |  |
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Table 4: The query for invoice prices in SQL and Cypher.

5.4. Complex query, invoice price

This recursive query finds all the sequential invoices related to given invoice id. The query is useful to test the recursive query capabilities of the databases. In SQL, Common Table Expressions are used to make the query. In Cypher there is a way to optimize a recursive query by negating irrelevant relationships. The optimized query does not return exactly the same result as the basic query. While the basic query returns a set of individual nodes, the optimized query returns a list structure containing nodes. However, it still returns similar results and as such it is a relevant query. Table 6 presents the queries for finding sequential invoices for a given invoice.

|  |
| --- |
| SQL |
| WITH RECURSIVE sequential\_invoices  AS (  SELECT id, customerId, state, duedate,  previousinvoice  FROM invoice  WHERE id=10000  UNION ALL  SELECT i.id, i.customerId, i.state, i.duedate,  i.previousinvoice  FROM invoice AS i  INNER JOIN sequential\_invoices AS j ON  i.previousinvoice = j.id  WHERE i.previousinvoice <> i.id)  SELECT \* FROM sequential\_invoices |
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|  |
|  |
| Cypher |  |
| MATCH (i:invoice { invoiceId:10000 })-  [p:PREVIOUS\_INVOICE \*0..]->(j:invoice) RETURN \* |  |
| Cypher optimized |  |
| MATCH inv=(i:invoice { invoiceId:10000})-  [p:PREVIOUS\_INVOICE \*0..]->(j:invoice)  WHERE NOT (j)-[:PREVIOUS\_INVOICE]->()  RETURN nodes(inv) |  |

Table 6: The Recursive query to get the sequential invoices related to defined invoice in SQL and Cypher

6. TEST EXECUTIONS

6.1. Test settings

The tests were performed with MacBook Pro Laptop with following specifications:

• macOS Catalina version 10.15.5

• 1,4 GHz quad core Intel Core i5

• 8 GB 2133 MHz LPDDR3

• Intel Iris Plus Graphics 645, 1536 MB

MySQL version 5.1.41, MariaDB version 10.5.6 and Neo4j community edition version 4.1.3 were installed on this computer. MariaDB and Neo4j were the latest when making the present study. MySQL version 5.1.41 is already considered as "end-of-life" when making the present study. However, it was used in a previous study [8] and version 5.1.42 in [7] as shown in related studies. MariaDB driver version 2.7 and Neo4j driver version 4.1.1 were used.

A dataset was generated using the test program. Table 7 presents the number of rows/objects generated for the dataset. For each row in the relationship tables useditem, workhours, workinvoice and worktarget, two respective edges were generated for the Neo4j graph database, as a many-to-many relationship is expressed as a bidirectional relationship.



Table 7: The numbers of the generated rows/objects in SQL and Neo4j.

6.2. Test results

Each query test was executed with 12 iterations. Each query result contains an average time for the query in milliseconds and coefficient of variation (CV) of the result list. As Neo4j has outperformed SQL databases in many previous studies, Neo4j was chosen as a reference database where others are compared with. Overall, the inclusion of CALL into a Cypher query made queries faster so Cypher queries with CALL were chosen as the reference queries. If Neo4j version above 4.1 would be used, CALL would be preferred for more performance. Non-indexed tests show percentages slower related to non-indexed Neo4j and indexed tests show percentages slower related to indexed Neo4j. The column “Slower than Neo4j 4.1.3 CALL” has the percentage how much slower the query is compared to Neo4J 4.1.3 Cypher reference query with call included. The column “Slower than Neo4j 4.1.3 CALL indexed” is the same reference query for indexed database. In recursive queries “Slower than Neo4j 4.1.3 Optimized” means how many percent the query is slower compared to recursively optimized Cypher query which is considered as reference. Indexed is the same query for indexed database.

6.2.1. Short query, price of work

Results for the query that queries the price of work are given in Table 8. From the generated dataset, the query returned 10000 rows/objects. With this query, Neo4j outperforms SQL databases as in several previous studies. MySQL is the slowest and MariaDB the second. Inclusion of CALL does not seem to bring benefits to Neo4j with this query. Indexing does not seem to bring much benefits either. CV values do not have a remarkable difference in these results.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Database | Avg | CV | Slower than Neo4j 4.1.3 CALL | Avg indexed | CV indexed | Slower than Neo4j 4.1.3 CALL indexed |
| MySQL 5.1.41 | 405 | 2,56 % | 64 % | 413 | 0,71 % | 65 % |
|  |
| MariaDB 10.5.6 | 209 | 8,90 % | 31 % | 204 | 7,13 % | 28 % |  |
|  |
| Neo4j 4.1.3 | 144 | 1,15 % | -1 % | 148 | 4,97 % | 1 % |  |
|  |
| Neo4j 4.1.3 CALL | 145 | 1,07 % | - | 146 | 1,63 % | - |  |
|  |

Table 8: Results for the query for the price of work.

6.2.2. Long query, price of work with items

Results for the query that queries the price of work can be found in Table 9. From the generated dataset, the query returned 10000 rows/objects. With this query, Neo4j outperforms SQL databases as in several previous studies. MySQL is the slowest and MariaDB the second. Inclusion of CALL does not seem to bring benefits to Neo4j with this query. Indexing does not seem to bring benefits either. The CV values of MySQL and MariaDB results are very low, Neo4j CV values being significantly higher.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Database | Avg | CV | Slower than Neo4j 4.1.3 CALL | Avg indexed | CV indexed | Slower than Neo4j 4.1.3 CALL indexed |
| MySQL 5.1.41 | 4952 | 0,63 % | 62 % | 4901 | 0,34 % | 40 % |
|  |
| MariaDB 10.5.6 | 2197 | 0,43 % | 15 % | 2193 | 0,23 % | -34 % |  |
|  |
| Neo4j 4.1.3 | 6880 | 18,82 % | 73 % | 8250 | 21,79 % | 64 % |  |
|  |
| Neo4j 4.1.3 CALL | 1859 | 8,67 % | - | 2931 | 13,53 % | - |  |
|  |

Table 9: Results for price of work with items query.

6.2.3. Complex query, invoice price

Table 10 shows results for the query that calculates invoice prices. From the generated dataset, the query returns 100000 rows/objects. Without CALL included in query Neo4j performs even worse than old MySQL 5.1.41. Inclusion of CALL gives significant performance benefit. However, MariaDB is still radically faster. Indexing gives also some performance benefits in MariaDB. However, with other databases it does not seem to improve performance. The CV values of MariaDB and indexed Neo4j with CALL are significantly higher than others, which are quite low.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Database | Avg | CV | Slower than Neo4j 4.1.3 CALL | Avg indexed | CV indexed | Slower than Neo4j 4.1.3 CALL indexed |
| MySQL 5.1.41 | 235817 | 1,03 % | 3 % | 236875 | 0,76 % | -28 % |
|  |
| MariaDB 10.5.6 | 4282 | 24,45 % | -5254 % | 3840 | 23,06 % | -7800 % |  |
|  |
| Neo4j 4.1.3 | 753587 | 0,73 % | 70 % | 957325 | 1,35 % | 68 % |  |
|  |
| Neo4j 4.1.3 CALL | 229256 | 1,66 % | - | 303365 | 19,61 % | - |  |
|  |

Table 10: Results for the query for the invoice prices.

6.2.4 Query with a defined key, invoice prices for a given customer

Results for the query that gets invoice prices for a given customer are given in Table 11. From the generated dataset, the query returns 10 rows/objects. MySQL 5.1.41 was left out as the performance was too poor: the query took over one hour on average. In practice, it would be unusable. With Neo4j, the inclusion of CALL does not give performance benefits. However, indexing seems to bring improvements with basic Cypher query. With indexing Neo4j finds the customer 0 from the graph faster. Although Neo4j performs well, MariaDB outperforms it by a small margin. The CV values of these results are overall high compared to previous results ones non-indexed MariaDB and Neo4j being quite low.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Database | Avg | CV | Slower than Neo4j 4.1.3 CALL | Avg indexed | CV indexed | Slower than Neo4j 4.1.3 CALL indexed |
| MariaDB 10.5.6 | 42 | 1,17 % | -38 % | 30 | 18,02 % | -97 % |
|  |
| Neo4j 4.1.3 | 56 | 25,17 % | -4 % | 50 | 17,91 % | -18 % |  |
|  |
| Neo4j 4.1.3 CALL | 58 | 1,63 % | - | 59 | 12,09 % | - |  |
|  |

Table 11: Results for the query for the invoice prices for a defined customer.

6.2.5 Recursive query, invoices related to invoice id 100000

The recursive query lists all the sequential invoices related to the invoice with given id. The tests were performed with 100 and 1000 invoices. With 10000 invoices Neo4j performance without optimization was so poor that it would have taken too long to complete. Table 12 presents the results when querying 100 sequential invoices and Table 13 presents results when querying 1000 invoices. The CV value of MariaDB is significantly higher because of its radically different result. Average of 1 divided by 0.4 standard deviation yields this result. Without the index, MariaDB has quite low CV, others having a notably higher value.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Database | Avg | CV | Slower than Neo4j 4.1.3 Optimized | Avg indexed | CV indexed | Slower than Neo4j 4.1.3 Optimized indexed |
| MariaDB 10.5.6 | 4473 | 0,33 % | 81 % | 1 | 40,00 % | -86800 % |
|  |
| Neo4j 4.1.3 | 150 | 12,00 % | -468 % | 153 | 4,33 % | -468 % |  |
|  |
| Neo4j 4.1.3 Optimized | 852 | 9,63 % | - | 869 | 12,44 % | - |  |
|  |

Table 12: Results for the recursive query with 100 rows/objects.

With 100 invoices, Neo4j seems to have the best performance without query optimization. The optimized query does not seem to improve performance. However, when indexes are used MariaDB benefits dramatically from indexing. The query takes just 1ms average clearly making MariaDB the best performer. Indexing does not improve performance for Neo4j. There is a variation in CV values, non-indexed MariaDB having the lowest value. Most variation was in the results of optimized Neo4j query results.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Database | Avg | CV | Slower than Neo4j 4.1.3 Optimized | Avg indexed | CV indexed | Slower than Neo4j 4.1.3 Optimized indexed |
| MariaDB 10.5.6 | 45004 | 0,46 % | 92 % | 10 | 6,40 % | -51070 % |
|  |
| Neo4j 4.1.3 | 1239446 | 12,09 % | 100 % | 1637223 | 16,71 % | 100 % |  |
|  |
| Neo4j 4.1.3 Optimized | 3662 | 27,24 % | - | 5117 | 5,71 % | - |  |
|  |

Table 13: Results for the recursive query with 1000 rows/objects.

As the number of invoices is increased to 1000, Neo4j performance drops dramatically. With the optimized query, though, Neo4j becomes much faster outperforming MariaDB. However, as MariaDB benefits from indexing, with indexing the query takes only ten milliseconds on average making it yet again the best performer. The performance is radically faster in comparison with Neo4j. MariaDB is 51070 % faster. Indexing does not improve performance for Neo4j.

7. Discussion

With the query tests performed, Neo4j was often outperformed by MariaDB. In some tests, Neo4j performed even worse than old MySQL 5.1.41. When comparing Neo4j with MySQL and MariaDB we are comparing a Java program with a C/C++ program. Obviously, the latter can be optimized better. It has to be also taken into consideration that MariaDB indexes primary keys and foreign keys by default. This gives benefits in every query where the table joins are done. Neo4j does not seem to benefit from indexing in many cases. One such case where indexing had benefits was when Neo4j needed to find the starting point from the graph.

The benefit of indexing in MariaDB is a benefit of the traditional relational database model. As the relations with the tables are created when executing the SQL query, indexing the keys becomes beneficial. The graph model does not benefit from such indexing as there are no tables that are joined by keys. Querying a graph database is done by traversing the graph. One of the benefits of the graph model can be seen in recursive query tests. By optimizing the query, performance becomes clearly better and, in this case, even better than SQL database with CTE query. However, with recursive queries, indexing still brings dramatical benefits for SQL database.

With the invoicing database schema used in the present study, calculating the price is done with complex queries. If this database was used in some real case, the usage of table views would probably be preferred to simplify the queries. When it comes to using views, it is also a benefit of SQL databases over Neo4j as at the time of writing this article Neo4j does not have an exact equivalent of such feature as views in SQL databases.

8. CONCLUSIONS

The present study compared MySQL 5.1.41, MariaDB 10.5.6 and Neo4j 4.1.3 with various query tests related to an invoicing database. A simulated enterprise dataset was used as test data. The query tests were performed using a Java program developed for the present study. The query tests included relational queries with increasing complexity and recursive queries. With the simpler relational queries, Neo4j had the best performance which correlates with previous results shown in [7] and [10]. However, with more complex queries MariaDB outperformed Neo4j.

The fact that a SQL database outperformed a graph database is a new finding that has not been presented in previous studies. As presented in previous studies, Neo4j often outperformed SQL databases. In study [4] for example, Neo4j outperformed Oracle in various tests using count(\*) queries. In the present study aggregation queries were also used but the result was different. The present study also indicated the benefit of indexing in SQL database in many of the tests. SQL databases seemed to benefit from indexing and in some cases very dramatically. However, Neo4j did not seem to benefit from indexing, apart from when a starting point in the graph was indexed.

Overall, MariaDB is the clear winner in the present study when it comes to performance with more complex queries. Especially in the query test for querying the invoice prices, MariaDB shows its performance. Indexing also gives clear benefits in MariaDB. Especially with recursive queries the improvement was dramatical. The results in the present study show how a relational database is still a strong alternative when it comes to performance compared with a NoSQL graph database.

3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Subsection

3.1.1. Subsubsection

Bulleted lists look like this:

* First bullet;
* Second bullet;
* Third bullet.

Numbered lists can be added as follows:

1. First item;
2. Second item;
3. Third item.

The text continues here.

3.2. Figures, Tables and Schemes

All figures and tables should be cited in the main text as Figure 1, Table 1, etc.



**Figure 1.** This is a figure. Schemes follow the same formatting.

**Table 1.** This is a table. Tables should be placed in the main text near to the first time they are cited.

|  |  |  |
| --- | --- | --- |
| **Title 1** | **Title 2** | **Title 3** |
| entry 1 | data | data |
| entry 2 | data | data 1 |

1 Tables may have a footer.

The text continues here (Figure 2 and Table 2).

|  |  |
| --- | --- |
| C:\Users\martin\Downloads\testFigure.tif | C:\Users\martin\Downloads\testFigure.tif |
| (**a**) | (**b**) |

**Figure 2.** This is a figure. Schemes follow another format. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel; (**b**) Description of what is contained in the second panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.

**Table 2.** This is a table. Tables should be placed in the main text near to the first time they are cited.

|  |  |  |  |
| --- | --- | --- | --- |
| **Title 1** | **Title 2** | **Title 3** | **Title 4** |
| entry 1 | data | data | data |
| data | data | data |
| data | data | data |
| entry 2 | data | data | data |
| data | data | data |
| entry 3 | data | data | data |
| data | data | data |
| data | data | data |
| data | data | data |
| entry 4 | data | data | data |
| data | data | data |

3.3. Formatting of Mathematical Components

This is example 1 of an equation:

|  |  |
| --- | --- |
| a = 1, | (1) |

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

This is example 2 of an equation:

|  |  |
| --- | --- |
| a = b + c + d + e + f + g + h + i + j + k + l + m + n + o + p + q + r + s + t + u + v + w + x + y + z | (2) |

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

Theorem-type environments (including propositions, lemmas, corollaries etc.) can be formatted as follows:

**Theorem 1.** Example text of a theorem. Theorems, propositions, lemmas, etc. should be numbered sequentially (i.e., Proposition 2 follows Theorem 1). Examples or Remarks use the same formatting, but should be numbered separately, so a document may contain Theorem 1, Remark 1 and Example 1.

The text continues here. Proofs must be formatted as follows:

**Proof of Theorem 1.** Text of the proof. Note that the phrase “of Theorem 1” is optional if it is clear which theorem is being referred to. Always finish a proof with the following symbol. □

The text continues here.

4. Discussion

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

5. Conclusions

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

6. Patents

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

**Supplementary Materials:** The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

**Author Contributions:** For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.” Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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**Appendix A**

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

**Appendix B**

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled starting with “A”—e.g., Figure A1, Figure A2, etc.

References

References must be numbered in order of appearance in the text (including citations in tables and legends) and listed individually at the end of the manuscript. We recommend preparing the references with a bibliography software package, such as EndNote, ReferenceManager or Zotero to avoid typing mistakes and duplicated references. Include the digital object identifier (DOI) for all references where available.

Citations and references in the Supplementary Materials are permitted provided that they also appear in the reference list here.

In the text, reference numbers should be placed in square brackets [ ] and placed before the punctuation; for example [1], [1–3] or [1,3]. For embedded citations in the text with pagination, use both parentheses and brackets to indicate the reference number and page numbers; for example [5] (p. 10), or [6] (pp. 101–105).

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