HELLENIC REPUBLIC
National and Kapodistrian
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PROJECT

NATIONAL AND KAPODISTRIAN UNIVERSITY OF ATHENS

FACULTY OF INFORMATICS AND TELECOMMUNICATIONS

M111: Big Data Management

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Part 1 Introduction

Task 1.1

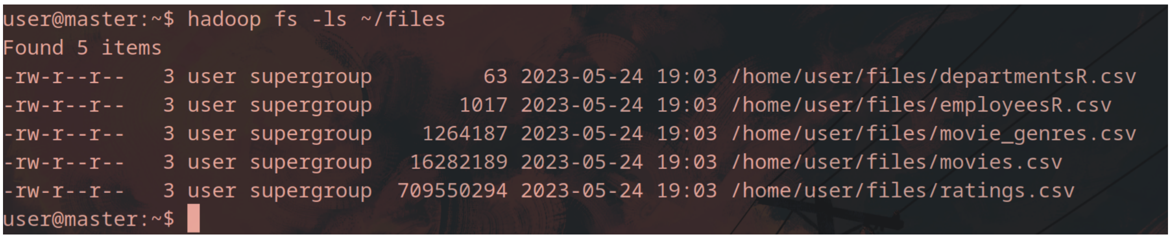
For creating a `files` directory in the HDFS, the following command was used

```
hadoop fs -mkdir -p ~/files
```

and to populate it with the project's `.csv` files

```
hadoop fs -put *.csv ~/files .
```

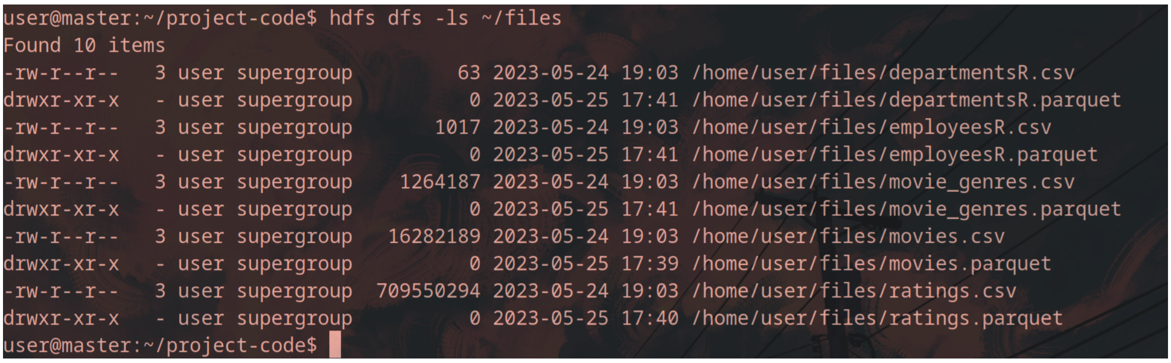
Since the only `.csv` files populating the working directory were the project's ones, it was fairly easy to fetch all of them using `*.csv`. Fig. 1 shows a print-screen of the `.csv` files lying within the created `files` directory.



```
user@master:~$ hadoop fs -ls ~/files
Found 5 items
-rw-r--r--   3 user supergroup         63 2023-05-24 19:03 /home/user/files/departmentsR.csv
-rw-r--r--   3 user supergroup       1017 2023-05-24 19:03 /home/user/files/employeesR.csv
-rw-r--r--   3 user supergroup    1264187 2023-05-24 19:03 /home/user/files/movie_genres.csv
-rw-r--r--   3 user supergroup   16282189 2023-05-24 19:03 /home/user/files/movies.csv
-rw-r--r--   3 user supergroup  709550294 2023-05-24 19:03 /home/user/files/ratings.csv
user@master:~$
```

Figure 1: HDFS directory containing the project's datasets in `.csv` format.

The same files were then saved in `.parquet` format, using Snip. 1, as can be seen in the print-screen of Fig 2.



```
user@master:~/project-code$ hdfs dfs -ls ~/files
Found 10 items
-rw-r--r--   3 user supergroup         63 2023-05-24 19:03 /home/user/files/departmentsR.csv
drwxr-xr-x   - user supergroup          0 2023-05-25 17:41 /home/user/files/departmentsR.parquet
-rw-r--r--   3 user supergroup       1017 2023-05-24 19:03 /home/user/files/employeesR.csv
drwxr-xr-x   - user supergroup          0 2023-05-25 17:41 /home/user/files/employeesR.parquet
-rw-r--r--   3 user supergroup    1264187 2023-05-24 19:03 /home/user/files/movie_genres.csv
drwxr-xr-x   - user supergroup          0 2023-05-25 17:41 /home/user/files/movie_genres.parquet
-rw-r--r--   3 user supergroup   16282189 2023-05-24 19:03 /home/user/files/movies.csv
drwxr-xr-x   - user supergroup          0 2023-05-25 17:39 /home/user/files/movies.parquet
-rw-r--r--   3 user supergroup  709550294 2023-05-24 19:03 /home/user/files/ratings.csv
drwxr-xr-x   - user supergroup          0 2023-05-25 17:40 /home/user/files/ratings.parquet
user@master:~/project-code$
```

Figure 2: HDFS directory containing the project's datasets in both `.csv` and `.parquet` formats.

Part 2 Basics

Task 2.1 Repartition and Broadcast Joins

Task 2.2 Tweaking the Catalyst Optimiser

Without Optimization (Sort Merge Join):

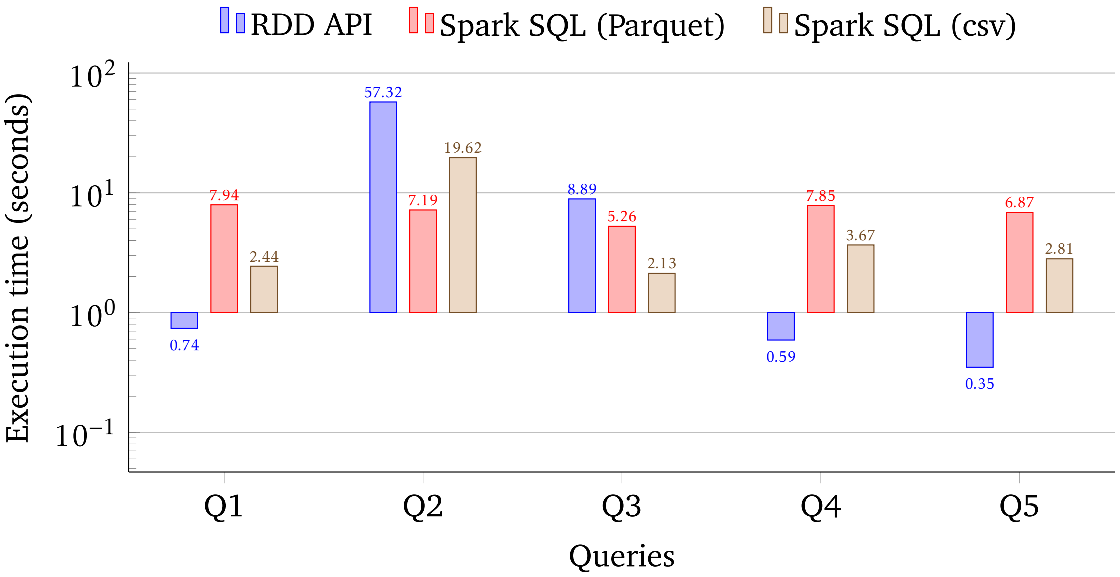


Figure 3: Caption

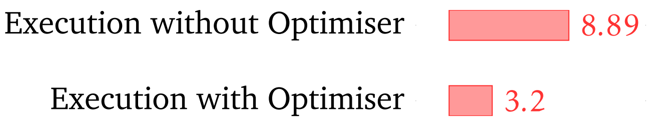


Figure 4: Execution time, for a particular query, with and without Spark's SQL Optimiser.

```
== Physical Plan ==
*(6) SortMergeJoin [mv_id#8], [mv_id#1], Inner
```

This is a Sort Merge Join, which is an operation where two dataframes are joined by sorting the data and then merging the sorted data. This type of join is used when the data is too large to fit into memory for a Broadcast Join.
The stages of this join operation involve filtering data where mv_id is not null, limiting the result set to 100, then sorting the data and performing the join operation. The SortMergeJoin operation requires that both sides of the join have been partitioned and sorted by the join key (mv_id in this case). Hence, there are additional Sort and Exchange operations before the join.

```
+- *(2) GlobalLimit 100
+- Exchange SinglePartition
+- *(1) LocalLimit 100
```

These operations represent the limit that is applied to the ”movie_genres” table (the query limits the result set to 100). The GlobalLimit means that the limit is applied across the entire dataset, not just per partition.
The time taken for the entire operation is 13.2132 seconds.
With Optimization (Broadcast Hash Join):

```
== Physical Plan ==
*(3) BroadcastHashJoin [mv_id#8], [mv_id#1], Inner, BuildLeft
```

This is a Broadcast Hash Join, which is a type of join operation where the smaller DataFrame is broadcast to all the nodes containing partitions of the larger DataFrame for comparison and join operations. This type of join can be significantly faster than a sort-merge join because it doesn't require the data to be sorted first, and it can be done entirely in memory if the smaller DataFrame is small enough.

```
:- BroadcastExchange HashedRelationBroadcastMode(List(cast(input[0,
 ↪  int, false] as bigint)
```

The BroadcastExchange operation represents broadcasting the smaller DataFrame to the worker nodes. The broadcasting operation will transform the DataFrame into a more efficient data structure (a hash table) to speed up the subsequent join operation.
The time taken for the entire operation is 3.7529 seconds, which is significantly faster than the time taken when the optimization is not enabled. The optimizer has chosen a more efficient join strategy (broadcast hash join instead of sort merge join) based on the size of the data and the nature of the operation, which leads to a faster execution time.
Overall, the difference between these two execution plans demonstrates the power and importance of the Spark Catalyst optimizer in efficiently executing Spark jobs. It can make smart decisions, such as using a BroadcastHashJoin instead of a SortMergeJoin, which significantly improves performance.

Part 3 Code Snippets

Snippet 1: csv_to_parquet.py

```python
from pyspark.sql import SparkSession
from pyspark.sql.types import StructField, StructType, IntegerType,
 ↪  FloatType, StringType


def convert_csv_to_parquet():
    # Create spark instance
    spark = SparkSession \
            .builder \
            .appName("Add schemas to CSVs and make Parquet files") \
            .getOrCreate()


    # Set schemas of csv files needed in Part 1 of the project
    movies_schema = StructType([
        StructField("mv_id", IntegerType()),
        StructField("name", StringType()),
        StructField("description", StringType()),
        StructField("year", IntegerType()),
        StructField("duration", IntegerType()),
        StructField("prod_cost", IntegerType()),
        StructField("revenue", IntegerType()),
        StructField("popularity", FloatType())
        ])

    ratings_schema = StructType([
        StructField("usr_id", IntegerType()),
        StructField("mv_id", IntegerType()),
        StructField("rating", FloatType()),
        StructField("time_stamp", IntegerType())
        ])

    movie_genres_schema = StructType([
        StructField("mv_id", IntegerType()),
        StructField("genre", StringType())
        ])

    # Set schemas of csv files need in Part 2 of the project
    employeesR_schema = StructType([
        StructField("id", IntegerType()),
        StructField("name", StringType()),
        StructField("dep_id", IntegerType())
        ])

    departmentsR_schema = StructType([
        StructField("dep_id", IntegerType()),
        StructField("dep_name", StringType())
        ])


    # Load the aforementioned csv files into dataframes
    movies_df = spark.read.format('csv') \
            .options(header='false') \
            .schema(movies_schema) \
            .load("hdfs://master:9000/home/user/files/movies.csv")

    ratings_df = spark.read.format('csv') \
            .options(header='false') \
            .schema(ratings_schema) \
            .load("hdfs://master:9000/home/user/files/ratings.csv")

    movie_genres_df = spark.read.format('csv') \
            .options(header='false') \
            .schema(movie_genres_schema) \
            .load("hdfs://master:9000/home/user/files/movie_genres.csv")

    employeesR_df = spark.read.format('csv') \
            .options(header='false') \
            .schema(employeesR_schema) \
            .load("hdfs://master:9000/home/user/files/employeesR.csv")

    departmentsR_df = spark.read.format('csv') \
            .options(header='false') \
            .schema(departmentsR_schema) \
            .load("hdfs://master:9000/home/user/files/departmentsR.csv")


    # Save the dataframes as Parquet
    movies_df.write.parquet("hdfs://master:9000/home/user/files/movies.parquet")
    ratings_df.write.parquet("hdfs://master:9000/home/user/files/ratings.parquet")
    movie_genres_df.write.parquet("hdfs://master:9000/home/user/files/movie_genres.parquet")
    employeesR_df.write.parquet("hdfs://master:9000/home/user/files/employeesR.parquet")
    departmentsR_df.write.parquet("hdfs://master:9000/home/user/files/departmentsR.parquet")
```

Snippet 2: rdd.py

```
from utils import timeit


def create_rdd(spark):
    movies_rdd   = spark.textFile("hdfs://master:9000/home/user/files/movies.csv")
    ratings_rdd  = spark.textFile("hdfs://master:9000/home/user/files/ratings.csv")
    genres_rdd   = spark.textFile("hdfs://master:9000/home/user/files/movie_genres.csv")

    return movies_rdd, ratings_rdd, genres_rdd
```

```python


def query1(spark):
    # Fetch initial RDD from a csv
    movies_rdd, _, _ = create_rdd(spark)

    # Get the difference betwen revenue and production cost (i.e. profits) of every
    # movie after 1995
    movies = movies_rdd.map(lambda line: line.split(',')) \
                       .filter(lambda field: len(field) > 7 and field[3].isdigit() and field[6].isdigit() and field[5].isdigit()) \
                       .map(lambda field: (int(field[3]), (int(field[6]), int(field[5])))) \
                       .filter(lambda field: field[0] > 1995 and field[1][0] > 0 and field[1][1] > 0) \
                       .map(lambda field: (field[0], str(field[1][0] - field[1][1]))) \
                       .reduceByKey(lambda v1, v2: v1 + ", " + v2) \
                       .sortBy(lambda pair: pair[0])

    execution_time, result = timeit(movies.collect)

    with open('../output/rdd_results/Q1RDD.txt', 'w') as f:
        for year, movie in result:
            f.write("year %s, profits [%s]\n" % (year, movie))

    return execution_time


def query2(spark):
    # Fetch initial RDDs from the csv files
    movies_rdd, ratings_rdd, _ = create_rdd(spark)

    # Get the movie id, the average rating and the total number of ratings for the
    # movie \Cesare deve morire"
    mapped_movies = movies_rdd.map(lambda line: line.split(',')) \
                              .filter(lambda fields: len(fields) == 8 and fields[3].isdigit() and fields[6].isdigit()) \
                              .filter(lambda fields: fields[1] == "Cesare deve morire") \
                              .map(lambda fields: (int(fields[0]), ('movies', fields[1])))

    mapped_ratings = ratings_rdd.map(lambda line: line.split(',')) \
                                .filter(lambda fields: len(fields) == 4) \
                                .map(lambda fields: (int(fields[1]), (float(fields[2]), 1))) \
                                .reduceByKey(lambda x, y: (x[0] + y[0], x[1] + y[1])) \
                                .map(lambda pair: (pair[0], ('ratings', pair[1][0] / pair[1][1], pair[1][1])))

    union = mapped_movies.union(mapped_ratings)

    movie_stats = union.groupByKey() \
                       .flatMap(lambda kv: [(kv[0], m[1], m[2]) for m in kv[1] if m[0] == 'ratings' for g in kv[1] if g[0] == 'movies'])

    execution_time, stats = timeit(movie_stats.collect)


    with open('../output/rdd_results/Q2RDD.txt', 'w') as f:
        f.write("Movie ID: %i, Number of ratings: %i, Average rating: %.2f" % (stats[0][0], stats[0][2], stats[0][1]))

    return execution_time


def query3(spark):
    # Fetch initial RDDs from the csv files
    movies_rdd, _, genres_rdd = create_rdd(spark)

    # Get the best Animation movie in terms of revenue for 1995
    mapped_movies = movies_rdd.map(lambda line: line.split(',')) \
                              .filter(lambda fields: len(fields) == 8 and fields[3].isdigit() and fields[6].isdigit()) \
                              .filter(lambda fields: int(fields[3]) == 1995 and int(fields[5]) > 0 and int(fields[6]) > 0) \
                              .map(lambda fields: (int(fields[0]), ('movies', fields[1], int(fields[6]))))

    mapped_genres = genres_rdd.map(lambda line: line.split(',')) \
                              .filter(lambda fields: len(fields) == 2
                               ↪  and fields[0].isdigit() and
                               ↪  fields[1] == 'Animation') \
                              .map(lambda fields: (int(fields[0]),
                               ↪  ('genres', fields[1])))

    # Union of the two RDDs
    union = mapped_movies.union(mapped_genres)

    # Group by key and transform the result
    joined = union.groupByKey() \
                  .flatMap(lambda kv: [(m[1], m[2]) for m in kv[1] if
                   ↪  m[0] == 'movies' for g in kv[1] if g[0] ==
                   ↪  'genres'])

    # Action takes place through the joined(), so the timeit()
     ↪  function is placed accordingly
    execution_time, best_animation_movie = timeit(joined.reduce,
     ↪  lambda movie, next_movie: movie if movie[1] > next_movie[1]
     ↪  else next_movie)

    with open('../output/rdd_results/Q3RDD.txt', 'w') as f:
        f.write("Best Animation Movie of 1995: {}, Revenue:
         ↪  {}".format(best_animation_movie[0],
         ↪  best_animation_movie[1]))

    return execution_time


def query4(spark):
    # Fetch initial RDDs from the csv files
    movies_rdd, _, genres_rdd = create_rdd(spark)

    # Get the most popular Comedy movie for each year after 1995
    mapped_movies = movies_rdd.map(lambda line: line.split(',')) \
                              .filter(lambda field: len(field) == 8
                               ↪  and field[3].isdigit() and
                               ↪  field[6].isdigit()) \
                              .filter(lambda field: int(field[3]) >
                               ↪  1995 and float(field[7]) > 0) \
                              .map(lambda field: (int(field[0]),
                               ↪  ('movies', int(field[3]), field[1],
                               ↪  float(field[7]))))

    mapped_genres = genres_rdd.map(lambda line: line.split(',')) \
                              .filter(lambda field: len(field) == 2 and field[0].isdigit()) \
                              .filter(lambda field: field[1] == 'Comedy') \
                              .map(lambda field: (int(field[0]), ('genres', field[1])))

    # Make union of movies and genres
    union = mapped_movies.union(mapped_genres)

    # Extract the best comedy per year
    best_comedy = union.groupByKey() \
                       .flatMap(lambda kv: [(m[1], (m[2], m[3])) for m in kv[1] if m[0] == 'movies' for g in kv[1] if g[0] == 'genres']) \
                       .reduceByKey(lambda x, y: x if x[1] > y[1] else y) \
                       .sortBy(lambda pair: pair[0])

    execution_time, best_comedy = timeit(best_comedy.collect)

    with open('../output/rdd_results/Q4RDD.txt', 'w') as f:
        for movie in best_comedy:
            f.write("The most popular Comedy of %i was %s, with a popularity score of %.2f\n" % (movie[0], movie[1][0], movie[1][1]))

    return execution_time


def query5(spark):
    # Fetch initial RDD from a csv
    movies_rdd, _, _ = create_rdd(spark)

    # Get the average revenue for each year
    mapped_movies = movies_rdd.map(lambda line: line.split(',')) \
                              .filter(lambda fields: len(fields) == 8 and fields[3].isdigit() and fields[6].isdigit()) \
                              .filter(lambda fields: int(fields[3]) > 0 and int(fields[6]) > 0) \
                              .map(lambda fields: (int(fields[3]), (int(fields[6]), 1))) \
                              .reduceByKey(lambda revenue,
                               ↪  next_revenue: (revenue[0] +
                               ↪  next_revenue[0], revenue[1] +
                               ↪  next_revenue[1])) \
                              .map(lambda fields: (fields[0],
                               ↪  fields[1][0] / fields[1][1])) \
                              .sortBy(lambda pair: pair[0])

    execution_time, results = timeit(mapped_movies.collect)

    with open('../output/rdd_results/Q5RDD.txt', 'w') as f:
        for result in results:
            f.write("Year %i had an average movie revenue of %.2f\n"
             ↪  % (result[0], result[1]))

    return execution_time
```

Snippet 3: sql_csv.py

```
from pyspark.sql.functions import collect_list
from pyspark.sql.types import StructField, StructType, IntegerType,
 ↪  FloatType, StringType
from utils import timeit, save_dataframe_output


# Set schemas of csv files
movies_schema = StructType([
    StructField("mv_id", IntegerType()),
    StructField("name", StringType()),
    StructField("description", StringType()),
    StructField("year", IntegerType()),
    StructField("duration", IntegerType()),
    StructField("prod_cost", IntegerType()),
    StructField("revenue", IntegerType()),
    StructField("popularity", FloatType())
])

ratings_schema = StructType([
    StructField("usr_id", IntegerType()),
    StructField("mv_id", IntegerType()),
    StructField("rating", FloatType()),
    StructField("time_stamp", IntegerType())
])

movie_genres_schema = StructType([
    StructField("mv_id", IntegerType()),
    StructField("genre", StringType())
])


def create_temp_tables(spark):
    # Load the aforementioned csv files into dataframes
    movies_df = spark.read.format('csv') \
            .options(header='false') \
            .schema(movies_schema) \
            .load("hdfs://master:9000/home/user/files/movies.csv")

    ratings_df = spark.read.format('csv') \
            .options(header='false') \
            .schema(ratings_schema) \
            .load("hdfs://master:9000/home/user/files/ratings.csv")

    movie_genres_df = spark.read.format('csv') \
            .options(header='false') \
            .schema(movie_genres_schema) \
            .load("hdfs://master:9000/home/user/files/movie_genres.csv")

    # Create temporary tables
    movies_df.createOrReplaceTempView("movies")
    ratings_df.createOrReplaceTempView("ratings")
    movie_genres_df.createOrReplaceTempView("genres")


def query1(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the difference betwen revenue and production cost (i.e. profits) of every movie after 1995
    query = """
        SELECT year, concat_ws(',', collect_list(cast((revenue - prod_cost) AS string))) AS profit
        FROM movies
        WHERE prod_cost > 0 AND revenue > 0 AND year > 1995
        GROUP BY year
        ORDER BY year
   """

    execution_time, _ = timeit(spark.sql(query).show)
    query_output = save_dataframe_output(spark.sql(query))

    return execution_time, query_output


def query2(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the movie id, the average rating and the total number of ratings for the movie \Cesare deve morire"
    query = """
        SELECT m.mv_id, COUNT(r.usr_id) AS user_count, AVG(r.rating) AS average_rating
        FROM movies AS m
        JOIN ratings AS r ON m.mv_id = r.mv_id
        WHERE m.name = 'Cesare deve morire'
        GROUP BY m.mv_id
    """

    execution_time, _ = timeit(spark.sql(query).show)
    query_output = save_dataframe_output(spark.sql(query))

    return execution_time, query_output


def query3(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the best Animation movie in terms of revenue for 1995
    query = """
        SELECT m.name AS movie_name, m.revenue AS revenue
        FROM movies AS m
        JOIN genres AS mg ON m.mv_id = mg.mv_id
        WHERE mg.genre = 'Animation' AND m.year = 1995 AND m.revenue > 0
        ORDER BY m.revenue DESC
        LIMIT 1
    """
    execution_time, _ = timeit(spark.sql(query).show)
    query_output = save_dataframe_output(spark.sql(query))

    return execution_time, query_output

```

```

def query4(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the most popular Comedy movie for each year after 1995
    query = """
        WITH ranked_movies AS (
            SELECT m.year, m.name, m.popularity,
            ROW_NUMBER() OVER(PARTITION BY m.year ORDER BY
 ↪  m.popularity DESC) AS rank
            FROM movies AS m
            JOIN genres AS mg ON m.mv_id = mg.mv_id
            WHERE mg.genre = 'Comedy' AND m.year > 1995 AND
 ↪  m.popularity > 0 AND m.revenue > 0
            )
        SELECT year, name, popularity
        FROM ranked_movies
        WHERE rank = 1
        ORDER BY year
    """

    execution_time, _ = timeit(spark.sql(query).show)
    query_output = save_dataframe_output(spark.sql(query))

    return execution_time, query_output


def query5(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the average revenue for each year
    query = """
        SELECT year, AVG(revenue) AS avg_revenue
        FROM movies
        WHERE year > 0 AND revenue > 0
        GROUP BY year
        ORDER BY year DESC
    """

    execution_time, _ = timeit(spark.sql(query).show)
    query_output = save_dataframe_output(spark.sql(query))

    return execution_time, query_output
```

Snippet 4: `sql_parquet.py`

```python
from pyspark.sql.functions import collect_list
from utils import timeit


def create_temp_tables(spark):
    # Fetch data
    movies_df = spark.read.parquet("hdfs://master:9000/home/user/files/movies.parquet")
    ratings_df = spark.read.parquet("hdfs://master:9000/home/user/files/ratings.parquet")
    genres_df = spark.read.parquet("hdfs://master:9000/home/user/files/movie_genres.parquet")

    # Create temporary relations
    movies_df.createOrReplaceTempView("movies")
    ratings_df.createOrReplaceTempView("ratings")
    genres_df.createOrReplaceTempView("genres")


def query1(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the difference betwen revenue and production cost (i.e. profits) of every movie after 1995
    query = """
        SELECT year, concat_ws(',', collect_list(cast((revenue - prod_cost) AS string))) AS profit
        FROM movies
        WHERE prod_cost > 0 AND revenue > 0 AND year > 1995
        GROUP BY year
        ORDER BY year
    """

    return timeit(spark.sql(query).show)


def query2(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the movie id, the average rating and the total number of ratings for the movie \Cesare deve morire"
    query = """
```

```python
        SELECT m.mv_id, COUNT(r.usr_id) AS user_count, AVG(r.rating) AS average_rating
        FROM movies AS m
        JOIN ratings AS r ON m.mv_id = r.mv_id
        WHERE m.name = 'Cesare deve morire'
        GROUP BY m.mv_id
    """

    return timeit(spark.sql(query).show)


def query3(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the best Animation movie in terms of revenue for 1995
    query = """
        SELECT m.name AS movie_name, m.revenue AS revenue
        FROM movies AS m
        JOIN genres AS mg ON m.mv_id = mg.mv_id
        WHERE mg.genre = 'Animation' AND m.year = 1995 AND m.revenue > 0
        ORDER BY m.revenue DESC
        LIMIT 1
    """

    return timeit(spark.sql(query).show)


def query4(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the most popular Comedy movie for each year after 1995
    query = """
        WITH ranked_movies AS (
            SELECT m.year, m.name, m.popularity,
            ROW_NUMBER() OVER(PARTITION BY m.year ORDER BY m.popularity DESC) AS rank
            FROM movies AS m
            JOIN genres AS mg ON m.mv_id = mg.mv_id
            WHERE mg.genre = 'Comedy' AND m.year > 1995 AND m.popularity > 0 AND m.revenue > 0
            )
        SELECT year, name, popularity
        FROM ranked_movies
        WHERE rank = 1
        ORDER BY year
    """

    return timeit(spark.sql(query).show)


def query5(spark):
    # Fetch relations
    create_temp_tables(spark)

    # Get the average revenue for each year
    query = """
        SELECT year, AVG(revenue) AS avg_revenue
        FROM movies
        WHERE year > 0 AND revenue > 0
        GROUP BY year
        ORDER BY year DESC
    """

    return timeit(spark.sql(query).show)
```

Snippet 5: `joins.py`

```
from utils import timeit


def create_rdd(spark):
    employees   = spark.textFile("hdfs://master:9000/home/user/files/employeesR.csv")
    departments = spark.textFile("hdfs://master:9000/home/user/files/departmentsR.csv")

    return employees, departments


def repartition_join(spark):
    # Fetch RDDs from the csv files
    employees, departments = create_rdd(spark)

    # Tag RDDs
    employees_tagged = employees \
                          .map(lambda line: line.split(',')) \
                          .map(lambda field: (int(field[0]), field[1], int(field[2]))) \
                         .map(lambda field: (field[2], ('employees', field)))

    departments_tagged = departments \
                           .map(lambda line: line.split(',')) \
                           .map(lambda field: (int(field[0]), field[1])) \
                           .map(lambda field: (field[0], ('departments', field)))

    # Concatenate all RDDS
    union = employees_tagged.union(departments_tagged)

    # Perform the join for each key
    def join_records(records):
        employees_records   = [field[1] for field in records if field[0] == 'employees']
        departments_records = [field[1] for field in records if field[0] == 'departments']
        return [(e[1], e[0], d[1]) for e in employees_records for d in departments_records]

    # Extract union result
    joined_rdd = union.groupByKey() \
                   .flatMap(lambda pair: join_records(pair[1]))

    return timeit(joined_rdd.collect)


def broadcast_join(spark):
    # Fetch RDDs from the csv files
    employees, departments = create_rdd(spark)

    employees_rdd = employees \
                      .map(lambda line: line.split(',')) \
                      .map(lambda field: (int(field[0]), field[1], int(field[2])))

    departments_rdd = departments \
                        .map(lambda line: line.split(',')) \
                        .map(lambda field: (int(field[0]), field[1]))

    # Create a dictionary for department data
    dep_dict = {field[0]: field[1] for field in departments_rdd.collect()}
```

```python

    # Broadcast the department data
    dep_broadcast = spark.broadcast(dep_dict)

    def map_func(field):
        # Extract the join key (department ID) and the department name using
        # the broadcast variable
        dep_id = field[2]
        dep_name = dep_broadcast.value.get(dep_id)

        # Joined data
        return (field[1], field[0], dep_name)

    joined_rdd = employees_rdd.map(lambda field: map_func(field))

    return timeit(joined_rdd.collect)
```

Snippet 6: `optimiser.py`

```python
import io
import contextlib
from utils import timeit


def create_temp_tables(spark):
    dataframe = spark.read.format("parquet")

    ratings_dataframe = dataframe.load("hdfs://master:9000/home/user/files/ratings.parquet")
    genres_dataframe = dataframe.load("hdfs://master:9000/home/user/files/movie_genres.parquet")

    ratings_dataframe.registerTempTable("ratings")
    genres_dataframe.registerTempTable("genres")


def use_optimiser(spark, disabled = "N"):

   # Fetch relations
   create_temp_tables(spark)

   if disabled == "Y":
      spark.conf.set("spark.sql.cbo.enable", False)
      spark.conf.set("spark.sql.autoBroadcastJoinThreshold", -1)
   elif disabled == "N":
      pass
   else:
      raise Exception ("This setting is not available.")

   query = """
           SELECT *
           FROM (SELECT * FROM genres LIMIT 100) AS g, ratings AS r
           WHERE r.mv_id = g.mv_id
      """

   stdout = io.StringIO()
   with contextlib.redirect_stdout(stdout):
        spark.sql(query).explain()

   # Get the captured standard output
   query_plan = stdout.getvalue()

   return timeit(spark.sql(query).show), query_plan
```

Snippet 7: `utils.py`

```
import io
import time
import contextlib


def timeit(func, *args, **kwargs):
    """
    Measure execution time of a function for a single run.

    Args:
        func: Function to be executed.
        *args: Variable length argument list for the function.
        **kwargs: Arbitrary keyword arguments for the function.

    Returns:
        tuple: A tuple containing the execution time and the result of the function call.
    """
    start = time.time()
    result = func(*args, **kwargs)
    end = time.time()
    execution_time = end - start

    return execution_time, result


def save_dataframe_output(dataframe):
    """
    Function to capture and return the complete output of a PySpark DataFrame.

    Args:
        dataframe (pyspark.sql.DataFrame): The DataFrame whose output is to be captured.

    Returns:
        str: The entire output of the DataFrame as a string.
    """

    # Calculate the number of rows in the DataFrame
    row_count = dataframe.count()

    # Create a StringIO object
    stdout = io.StringIO()

    # Execute show() on DataFrame and capture the output
    with contextlib.redirect_stdout(stdout):
        dataframe.show(n=row_count, truncate=False)

    # Get the captured standard output
    return stdout.getvalue()
```

Snippet 8: `main.py`

```
# Import SparkSession
from pyspark.sql import SparkSession

# Import RDD queries
from rdd import query1 as rdd_query1
from rdd import query2 as rdd_query2
from rdd import query3 as rdd_query3
from rdd import query4 as rdd_query4
from rdd import query5 as rdd_query5

# Import SQL-on-csv queries
from sql_csv import query1 as sql_csv_query1
from sql_csv import query2 as sql_csv_query2
from sql_csv import query3 as sql_csv_query3
from sql_csv import query4 as sql_csv_query4
from sql_csv import query5 as sql_csv_query5

# Import SQL-on-Parquet queries
from sql_parquet import query1 as sql_parquet_query1
from sql_parquet import query2 as sql_parquet_query2
from sql_parquet import query3 as sql_parquet_query3
from sql_parquet import query4 as sql_parquet_query4
from sql_parquet import query5 as sql_parquet_query5

# Import RDD joins
from joins import broadcast_join
from joins import repartition_join

# Import Optimiser script
from optimiser import use_optimiser

# Import csv-to-parquet converter
from csv_to_parquet import convert_csv_to_parquet


def part1():
    ###################### Task 1 ######################
    # Convert CSVs to Parquet; run only once. Should you
    # wish to repeat the process, comment it out.
    convert_csv_to_parquet()


    ################## Tasks 2, 3 & 4  ##################
    times = {}

    # Calculate execution times for each query (Tasks 2, 3 & 4)
    for i in range(1, 6):
        spark = SparkSession \
                .builder \
                .appName("All-use session") \
                .getOrCreate()
        sc = spark.sparkContext

        rdd_query_name     = 'rdd_query%s' % (i)
        parquet_query_name = 'sql_parquet_query%s' % (i)
        csv_query_name     = 'sql_csv_query%s' % (i)

        times[rdd_query_name]               =
         ↪  globals()[rdd_query_name](sc)
        times[parquet_query_name], _       = globals()[parquet_query_name](spark)
        times[csv_query_name], query_output = globals()[csv_query_name](spark)

        # Save the query-output, in dataframe format, on a text file
        with open('../output/df_results/Q%sDF.txt' % i, 'w') as f:
            f.write(query_output)

        # Consistency in execution times
        spark.stop()
        sc.stop()
        print(times)

    # Compute execution times and write to a text file
    with open('../output/part_1_times.txt', 'w') as f:
        for query, execution_time in times.items():
            f.write('%s: %.2f seconds\n' % (query, execution_time))


def part2():
    ###################### Task 1 ######################
    times = {}

    spark = SparkSession \
                .builder \
                .appName("All-use session") \
                .getOrCreate() \
                .sparkContext

    times['Broadcast Join'], broadcast_result = broadcast_join(spark)
    times['Repartition Join'], _               = repartition_join(spark)

    # Compute execution times and write to a text file
    with open('../output/join_type_times.txt', 'w') as f:
        for query, execution_time in times.items():
            f.write('%s: %.2f seconds\n' % (query, execution_time))

    # Save the result to text files
    with open('../output/join_outputs.txt', 'w') as f:
        for result in broadcast_result:
            f.write(str(result) + '\n')

    # Consistency in execution times
    spark.stop()


    ###################### Task 2 ######################
    times = {}

    # Two instances are created since Spark tends to keep
    # metadata from each run in order to optimise reading
    # and calculating future queries.
    spark = SparkSession \
            .builder \
            .appName('Using Catalyst') \
            .getOrCreate()
    sc = spark

    times["Using Catalyst"], with_catalyst             =
     ↪  use_optimiser(spark)
    times["Without using Catalyst"], without_catalyst =
     ↪  use_optimiser(sc, disabled="Y")

    spark.stop()
    sc.stop()

    # Compute execution times and write to a text file
    with open('../output/catalyst_times.txt', 'w') as f:
        for query, execution_time in times.items():
            f.write('%s: %.2f seconds\n' % (query,
             ↪  execution_time[0]))

    # Save the optimised query plan to text file
    with open('../output/optimised_plan.txt', 'w') as f:
        f.write(with_catalyst)

    # Save the non-optimised query plan to text file
    with open('../output/non_optimised_plan.txt', 'w') as f:
        f.write(without_catalyst)


if __name__ == "__main__":
    part1()
    part2()
```

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