DISTRIBUTED SYSTEMS

Assignment 2

Report

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1 Introduction

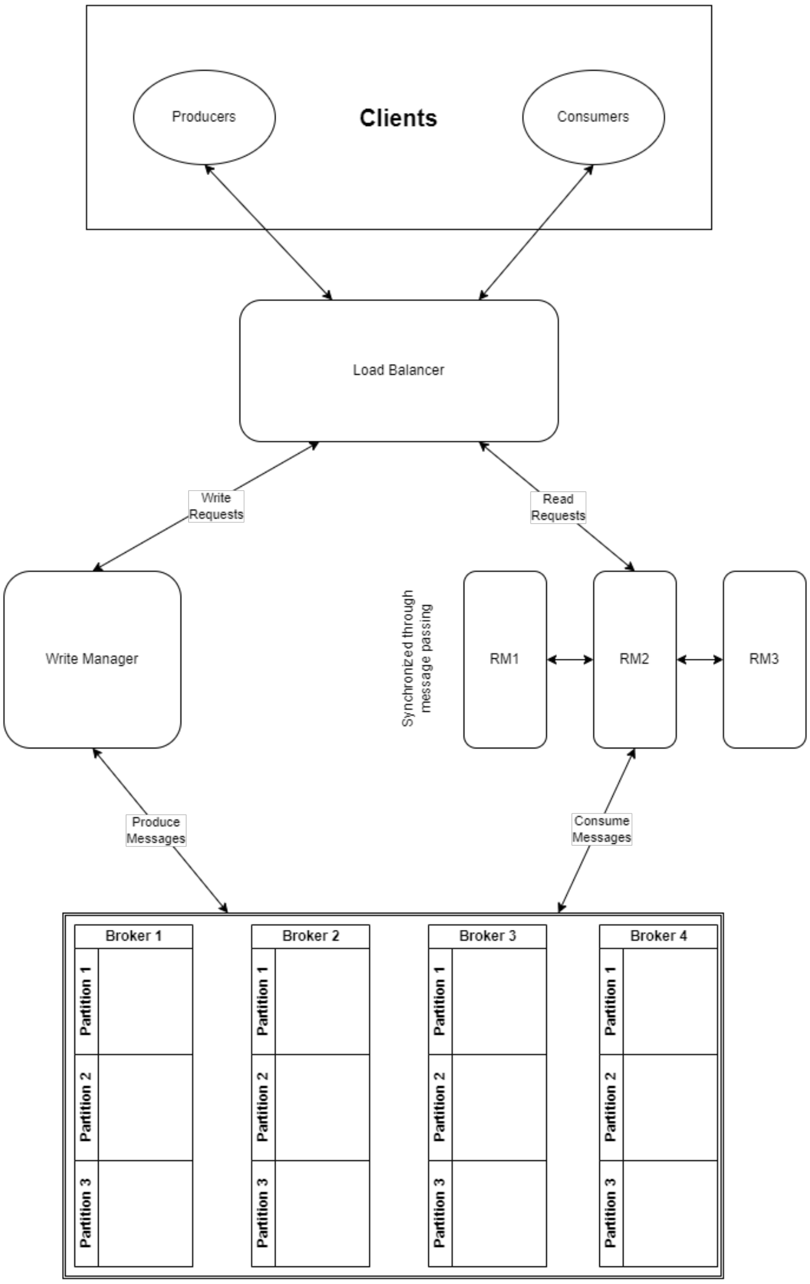
Distributed systems are an essential part of modern computing, and they play a vital role in ensuring scalability and fault tolerance. The basic broker implementation provided in Assignment 1 is not sufficient to meet the requirements of a large-scale system. As the number of topics and the volume of messages increases, a single broker can become a bottleneck and cannot handle the load, leading to performance issues and potential downtime.

To address this issue, in this assignment, a more sophisticated multi-broker distributed queue system is introduced, which partitions a topic queue into multiple partition queues. Partitioning is a common technique used in distributed queue systems to improve scalability and fault tolerance by allowing multiple brokers to handle different partitions of the same topic in parallel. This approach enables the system to handle a large number of topics and messages with better performance and fault tolerance.

The introduction of partitioning requires a new partitioning mechanism to allow the division of a topic's data into multiple partitions. Additionally, a new component, called the broker manager, is introduced to act as an intermediary between producers and consumers and brokers. The broker manager handles client and topic metadata, and mappings between consumers, topics, and partitions. It also handles broker cluster configuration management, such as adding and removing brokers. The broker manager also implements a health check mechanism, service discovery mechanism, and write-ahead logging (WAL) mechanism to persist the metadata it maintains, allowing it to restore the metadata in the event of a failure.

Furthermore, each broker is responsible for managing its assigned partitions of a topic and persisting the partition data, allowing it to restore the partition in the event of a failure. The brokers should also service requests from producers and consumers as directed by the manager.

2 System Architecture



3 System Components

Here is the description of the components of the system with details of their functionality, methods and attributes.

3.1 Load Balancer

This component redirects the write requests (from the producer) to the Write Manager and the read requests (from the consumers) to the multiple Read Managers in a round-robin fashion.

The following endpoints are handled:

1. **POST at /broker**: redirect the request to a Write Manager to add a broker
2. **POST, GET at /topics**: redirect the request to a Write Manager to add or list topics
3. **POST at /producer/register**: redirect the request to a Write Manager to register a producer to a topic
4. **POST at /producer/produce**: redirect the request to a Write Manager to produce a message at a topic
5. **POST at /consumer/register**: redirect the request to a Read Manager to register a consumer to a topic
6. **POST at /consumer/consume**: redirect the request to a Read Manager to consume a message of a topic

Appropriate Error Handling is done to report the type of error that has occurred (HTTP Error, HTTP Connection Error, NULL Response, etc) and which component is responsible for the error (Write Manager or Read Manager and which particular Read Manager).

3.2 Write Manager

This component is responsible for handling the write requests from the producer. This component has been implemented as a class (defined in models/write_manager.py) with all the functionalities and a Flask Server (defined in write_manager_app.py) that serves the endpoints that allow other components to access these functionalities.

3.2.1 Functions

1. **create_tables**: Function to create all the tables required in the component if they do not already exist.
2. **drop_tables()**: Function to delete the tables to reset the Write Manager data.
3. **add_broker(port: int)**: Function to register a broker at the Write Manager. Stores the port maintaining the ID associated with the broker. It also forwards this message to the RM to maintain data sync.
4. **add_topic(topic_name: str)**: Function to add a new topic at the WM (Write Manager). This adds a topic to the Topic Database and initialises it with one partition assigning a random broker to this partition. The WM forwards the request to the particular broker (to initialise a queue for the partition) and also synchronizes the information about creating a topic with other RMs (Read Managers). The health check mechanism notes that the particular broker has been requested at the current time.
5. **list_topics()**: Function to list all the topics added at the WM. Retrieves the list from the database.
6. **register_producer(topic_name: str)**: Function to register a producer to a given topic. If the topic does not exist, it is created using the add_topic function. This function adds the registration into the Metadata returning a producer id. The Health Check mechanism adds the current time as the first heartbeat of the producer.
7. **produce_message(producer_id: int, topic_name: str, message: str)**: Function to allow a producer to publish a message to a topic. First, it is ensured that the producer id is valid and the producer is registered to the topic. Then a partition of the topic is selected (in a round-robin fashion) and the request is forwarded to the particular broker to enqueue the message at the partition. The Health Check mechanism updates the last access time of the broker and the producer. If the number of messages of a particular topic exceeds a threshold, a new partition is created for the particular topic using the add_partition function.

3.2.2 Database Structures

These database structures maintain the persistence of the Write Manager. Locks have been used to ensure that concurrent requests can be handled without any errors. Appropriate Error Handling has been done to correctly catch, identify and report the type of error.

1. **BrokerDBMS** (database_structures/write_manager/broker_dbms.py): Handles the data of the brokers maintaining the broker port with an ID. Has functionalities

to add a new broker given a port, delete a broker given a port, get the current number of brokers and get a random broker port.

2. **PartitionDBMS** (database_structures/write_manager/partition_dbms.py): Handles the data of the partitions matching the broker id to the partition. Allows adding a partition given a partition name and broker id, getting the broker port from the partition by using an inner join with the Broker DBMS.
3. **TopicDBMS_WM** (database_structures/write_manager/topic_dbms.py): Handles the data of the topics noting the topic name, number of messages, number of partitions, the current partition offset used during the round robin and a list of partition ids. Allows adding a topic, adding a partition to a topic, listing topics, getting the current partition based on round-robin logic and getting the number of partitions assigned to a topic.
4. **ProducerDBMS** (database_structures/producer_dbms.py): Handles the data of the producers noting the topic name and associating it with an id. Allows adding producers given a topic, getting the number of producers, and checking if a producer id is valid and whether it is linked to the topic.

3.3 Read Manager

This component is responsible for handling the read requests from the consumers. This component has been implemented as a class (defined in models/read_manager.py) with all the functionalities and a Flask Server (defined in read_manager_app.py) that serves the endpoints that allow other components to access these functionalities.

3.3.1 Functions

1. **create_tables**: Function to create all the tables required in the component if they do not already exist.
2. **drop_tables()**: Function to delete the tables to reset the Read Manager data.
3. **add_broker(port: int)**: Function to register a broker at the Read Manager. Stores the port maintaining the ID associated with the broker. This function is created to maintain data synchronisation between WM and RMs.
4. **add_topic(topic_name: str)**: Function to add a new topic at the RM. This adds a topic to the Topic Database. This function is created to maintain data synchronisation between WM and RMs.
5. **list_topics()**: Function to list all the topics added at the RM. Retrieves the list from the database.
6. **register_consumer(topic_name: str, sync: int)**: Function to register a consumer to a given topic. If the topic does not exist, an exception is thrown. This

function adds the registration into the Metadata returning a consumer id. The Health Check mechanism adds the current time as the first heartbeat of the consumer. This information is also synced with the various other RMs. A sync variable is sent so that the RM can know whether the call is from synchronisation or a direct call. If it is a synchronisation call, then the message is not forwarded to other RMs.

7. **consume_message(consumer_id: int, topic_name: str, sync: int)**: Function to allow a producer to consume a message of a topic. First, it is ensured that the consumer id is valid and the consumer is registered to the topic. Then a partition of the topic is selected (in a round-robin fashion), the offset at the partition is retrieved and the request is forwarded to the particular broker to dequeue the message at the partition. The Health Check mechanism updates the last access time of the broker and the consumer. A sync variable is sent so that the RM can know whether the call is from synchronisation or a direct call. If it is a synchronisation call, then the message is not forwarded to other RMs.

3.3.2 Database Structures

These database structures maintain the persistence of the Read Manager. Locks have been used to ensure that concurrent requests can be handled without any errors. Appropriate Error Handling has been done to correctly catch, identify and report the type of error.

1. **BrokerDBMS**: Same as the WM BrokerDBMS.
2. **PartitionDBMS**: Same as the WM PartitionDBMS.
3. **TopicDBMS_WM**: Same as the WM TopicDBMS.
4. **ConsumerDBMS**: (database_structures/consumer_dbms.py): Handles the data of the consumers noting the topic name, and the offset as a dictionary linking the partition name with the offset and associating the consumer with an id. Allows adding consumers given a topic, adding a partition to a topic so that all consumer offsets to the partition get initialised to 0, getting the number of consumers, checking if a consumer id is valid and whether it is linked to the topic, getting the offset given a consumer id and a partition name

3.4 Broker

This component is responsible for handling the queues of all the partitions. This component has been implemented as a class Broker (defined in models/broker.py) with all the functionalities, a Flask Server (defined in broker_app.py) that serves the endpoints that allow other components to access these functionalities, and another class MyBroker (defined in myqueue/broker.py) with the functionality to send requests to this Flask server. Appropriate Error Handling is done to catch, identify and report the correct errors.

3.4.1 Functions

1. **reset_dbms**: Function to reset all the tables in the component.
2. **create_topic(topic_name: str)**: Function to add a new topic at the broker. It checks if the topic already exists and returns an error if it does.
3. **list_topics()**: Function to list all the topics added at the broker. Retrieves the list from the database.
4. **enqueue(topic_name: str, message: str)**: Function to add a message to the topic queue. It checks if the topic exists and then gets the topic queue and appends the message to the end of the queue.
5. **dequeue(topic_name: str, offset: int)**: Function to dequeue a message from a topic queue at the given offset. It checks if the topic exists and if any message is left to be retrieved and then retrieves the message from the topic queue at the offset.

3.4.2 Database Structures

1. **Topic DBMS** (database_structures/topic_dbms.py): Handles the topic/ partition and the message queue for the topic/partition. Allows adding a topic, getting the topic list, and getting the topic queue, A TopicQueueDBMS class is also defined here that works on the same table but handles the topic queue enqueuing, retrieving at an offset and checking the remaining size of the queue.
2. **Message DBMS** (database_structures/message_dbms.py): Handles the message data at the broker level. The topic queues just store the ids of the messages. The message corresponding to the id is maintained here. It allows functionality to add a message and retrieve a message given an id.

4 Features and Design Choices

4.1 Handling Concurrent Requests

When a Flask Server receives a request from a client, it must be able to handle it effectively. To handle multiple requests simultaneously, the Flask Server can use a multi-threaded approach. The threaded=True parameter in the app.run() function call enables Flask to handle multiple requests concurrently by creating multiple threads within the server. Each thread can handle a separate request, and Flask can manage them all in parallel.

A Write Manager and Load Balancer are components that are often used in our distributed system and these will handle large amounts of traffic. By enabling the threaded=True parameter in these components, Flask can handle concurrent requests in parallel. This means that multiple clients can send requests to the Flask Server at the same time, and the server can respond to each request without having to wait for the previous request to complete.

To verify that the Flask Server can handle concurrent requests with the threaded=True parameter, a dummy application was created. This application had an endpoint that would sleep for a certain duration before returning a successful response. By testing this endpoint with the threaded=True parameter set, the server was able to handle multiple concurrent requests via Postman but with the threaded=False parameter set the server could not handle concurrent requests and waited until the previous request was completed.

4.2 Partitioning

In a distributed messaging system, messages are published to a topic, which acts as a logical grouping of messages. When a topic receives a large volume of messages, it can become difficult to handle them efficiently. To address this, the topic is divided into multiple partitions, which are essentially smaller subsets of the topic.

Each partition is assigned to a specific broker randomly, which is responsible for storing and managing the messages in that partition. By dividing the topic into partitions, the system can scale horizontally, as each broker can handle a smaller subset of the messages.

Initially, a topic has only one partition, which is sufficient for handling a small volume of messages. However, as the number of messages increases, the system automatically increases the number of partitions for that topic. This allows the system to handle larger volumes of messages without becoming overwhelmed.

By dynamically adjusting the number of partitions, the system can allocate resources more efficiently. For example, if a topic receives only a small volume of messages, it can have a small number of partitions, which means that fewer brokers are needed to handle the messages. This helps to prevent the wastage of resources, as brokers are only allocated to topics that require them.

In summary, partitioning a topic allows a distributed messaging system to handle large volumes of messages efficiently by dividing the workload among multiple brokers. By dynamically adjusting the number of partitions based on the volume of messages, the system can scale up or down as needed, while avoiding unnecessary resource usage.

4.3 Round Robin

When using a distributed messaging system, it's common to have multiple partitions in a topic to handle a large volume of messages efficiently. Each partition acts as an independent unit of the topic, and it's responsible for storing a subset of messages in the order they were received.

In such a scenario, the producer, who sends the message to the messaging system, doesn't need to specify the partition id to which the message needs to be published. The messaging system takes care of distributing the message to one of the available partitions based on a partitioning scheme defined by the system.

This approach is logical because it simplifies the job of the producer, who doesn't need to know anything about the internal details of the messaging system. The producer only needs to publish the message on the topic, and the messaging system takes care of distributing the message to the appropriate partition.

When a consumer subscribes to a topic, it receives messages from all partitions of that topic in a round-robin fashion. This means that the messaging system will send messages from one partition to a consumer, then switch to another partition, and so on until all partitions have been covered. This approach ensures that the load is distributed evenly among all partitions and consumers.

In summary, when using a distributed messaging system with multiple partitions, the producer doesn't need to specify the partition id while publishing the message, and the messages are consumed in a round-robin fashion from all partitions, ensuring that the load is distributed evenly among all partitions and consumers.

4.4 Persistence

Making a system robust to failures is essential to ensure that it remains functional even during unexpected events such as server crashes. In order to achieve resilience against unexpected system failures, it is essential to ensure that all data is persistently stored, i.e., the data should be stored in a way that it can survive a system crash or other unexpected events. In the given scenario, the data about messages, producers, and consumers are persisted using a PostgreSQL database.

PostgreSQL is a popular and open-source relational database management system (RDBMS) that allows for reliable storage and retrieval of data. By using a PostgreSQL database, the system is ensuring that all the data related to messages, producers, and consumers are stored securely and persistently.

Therefore, if the flask server crashes, the data will remain safe and accessible in the database. This means that even if the system experiences a failure, the data can be retrieved and used when the flask server is restarted. This approach ensures that the system can recover from a failure and continue to function seamlessly without any loss of data or functionality.

In conclusion, using a PostgreSQL database to store all data related to messages, producers, and consumers is an effective way to ensure the robustness and resilience of the system. By using this approach, the system can recover from unexpected events and continue to function without any loss of data or functionality.

4.5 Maintaining Data Synchronisation

There are two types of managers: a write manager and multiple read managers. The write manager is responsible for updating the data, while the read managers access the data.

To ensure that the read managers always have access to the latest version of the data, synchronization between the write manager and read managers, as well as among read managers, is done via message passing. This means that when the write manager updates the data, it sends a message to each read manager notifying them of the change.

Furthermore, any metadata update that affects the read managers, such as changes in the topics, or the addition of brokers, is also sent to each read manager individually by the write manager. This ensures that all read managers are aware of any changes that may affect their functionality.

4.6 Broker Cluster Management

Broker Cluster Management involves managing the brokers, that is checking their status, and adding and removing brokers whenever necessary. We have handled the status management of the brokers in the Health Check Mechanism. The addition and removal of the brokers are handled by the Write and Read Managers.

Whenever a new broker is added, a request is sent to the Write Manager and the Read Managers. Also, whenever a broker has crashed, which can be realised by the health check mechanism, we have sent a request to the Write Manager and the Read Managers to remove the broker from their list so that future requests are not forwarded to that broker.

4.7 Health Check

We have implemented a health check mechanism for producers, consumers and brokers. The algorithm for the above three is as follows

- Create a table in the database to log the last updated time for each of the three above.
- The table has the following columns: Type (Producer, Consumer, Broker), ActorID, and LastUpdatedTime
- We update the last updated time when any of the functionalities are performed for the respective actors.
- We run the health checkup mechanism periodically and check whether any of the actors are inactive for an interval of more than the threshold difference.
- If so, we display the respective actor ids on the console.

4.8 Write Ahead Logging

Write Ahead Logging technique is used by various database management systems to ensure the durability and recoverability of data. The principle of WAL is that data should be first added to a journal or WAL file, that is the logs should be maintained before actually committing the changes to the database. This WAL file is strictly sequential. This makes our database system robust as now before rolling the changes into the main database, the log files are written so in case of crash or system failure the database could be easily recovered by either replaying the logs or rolling back towards the changes so as to reach a consistent state.

Since we used *PostgreSQL* as our database management system. The Write Ahead logging is already implemented in *PostgreSQL*.

By default, these WAL files are located in the PostgreSQL data directory for UNIX based system it is in */usr/local/pgsql/data/pg_wal/*, whereas for Windows it is stored inside *C:/Program Files/PostgreSQL/version/data*.

These log files can then be viewed in the human-readable form with the help of *pg_waldump* command.