A Distributed Computation for Multi-Tenant Query Processing on large scale distributed data with Shared Resources

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Abstract—The growing reliance on large-scale datasets has created a need for efficient, scalable, and cost-effective systems for data management and querying. This project introduces a **Distributed Computing System with Shared Resources** to address the challenges of handling vast datasets for multiple companies in a secure and optimized manner. The system leverages a tree-based hierarchical architecture where data is partitioned and isolated into shards based on company identifiers, ensuring logical and physical separation of datasets.

Authorized users, such as product managers, can submit queries through an API, which authenticates the request and routes it intelligently to the corresponding data containers at the leaf nodes. This distributed model enables parallel processing, faster query execution, and result aggregation while maintaining data isolation and security. By sharing computational resources across multiple companies, the system reduces infrastructure costs, maximizes resource utilization, and eliminates redundancy.

Key features include **data sharding**, **query optimization**, and **result aggregation** using MapReduce-like techniques. The design supports scalability by adding nodes as needed, making it suitable for multi-tenant environments like SaaS platforms and big data analytics. This system provides a robust, efficient, and secure framework for querying and analyzing large datasets, empowering companies to make data-driven decisions without investing in standalone infrastructure.

Introduction

In today's data-driven world, companies increasingly rely on large-scale datasets to gain insights and make informed decisions. Managing and querying these datasets efficiently is a critical challenge, especially for organizations that deal with massive volumes of data. Building and maintaining individual infrastructure for each company to handle such workloads is not only costly but also resource-intensive. To address these challenges, this project introduces a **Distributed Computing System with Shared Resources**, designed to store and query large-scale data for multiple companies in an efficient, secure, and cost-effective manner.

The system leverages the principles of **distributed computing**, **data sharding**, and **tree-based hierarchical architecture** to distribute query computing by routing to multiple nodes. Each company's data is partitioned into isolated shards, stored securely in data containers at the **leaf nodes** of the system. When an authorized user, such as a product manager or analyst, submits a query through the system's API, it is routed intelligently through the architecture. The query is processed and executed only on the specific dataset associated with the user's company, ensuring both data isolation and fast response times.

What makes this system particularly powerful is its ability to share computational resources across multiple companies without compromising data security. For example, a product manager from Company A can use the system to query large datasets for sales analysis, while the same computational infrastructure is being used by Company B for inventory forecasting. The system ensures that both companies can operate independently, reducing the burden of maintaining separate infrastructure for each organization.

This shared resource model significantly lowers operational costs and improves efficiency. Instead of dedicating servers and computational resources to each company, the system allows for dynamic resource allocation. During low activity periods, unused resources can be redirected to other companies or queries, maximizing utilization and reducing waste. This approach is especially beneficial for scenarios involving multi-tenant platforms, where numerous organizations rely on a single service provider for data storage and analytics.

The system is designed to cater to real-world needs where companies require fast, reliable, and secure access to their data. It incorporates features like **authentication**, **query optimization**, and **result aggregation**, ensuring that users can retrieve insights efficiently. By utilizing a tree-based structure, the system enables scalability, allowing it to handle growing datasets and user demands with ease.

In summary, this project provides a scalable, secure, and cost-effective solution for querying large datasets in a multi-tenant environment. It empowers organizations to leverage shared computational resources for big data analytics, eliminating the need for dedicated infrastructure while maintaining high performance and data security.

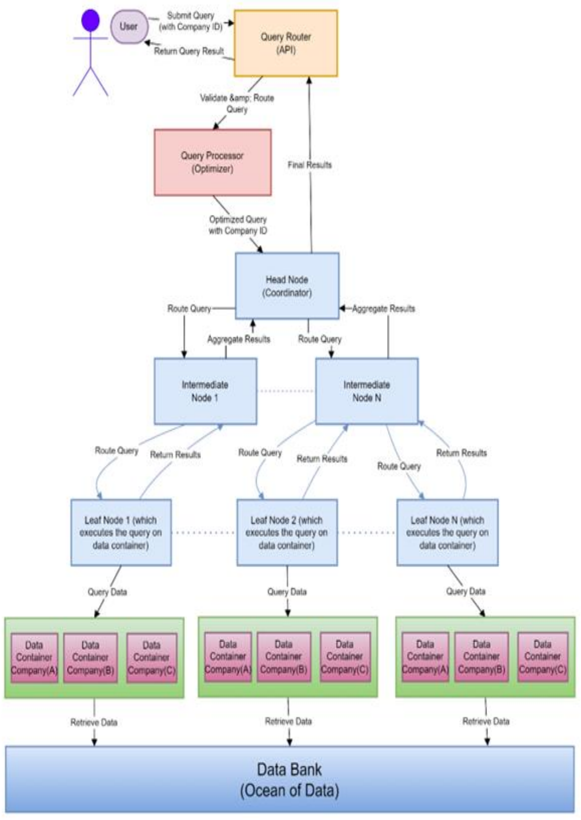
Literature Survey:

S.No	Title	Methodology	Advantages	Limitations
1	The Next Decade of Distributed Databases	Review of distributed database architectures and future challenges	Comprehensive architectural insights, identifies future trends in scalability and performance.	Lacks practical, system-level evaluation. which project bridges this with practical implementation.
2	Efficient Query Processing in Distributed Databases with Data Sharding	Reviews query optimization and sharding techniques in distributed systems.	Provides practical insights on partitioning and query optimization.	May not be efficient in complex systems. this project optimizes sharding dynamically.
3	FaSST: Fast and Scalable Sharding for Distributed Databases	Proposes dynamic sharding for query execution optimization in distributed DBs.	Scalable, reduces latency and data migration costs.	Requires complex monitoring. this project automates query routing and partition adjustments.
4	Spanner: Google's Globally-Distributed Database	Describes Google's globally distributed database with strong consistency.	Strong consistency, global distribution, high reliability.	Complexity due to synchronized clocks. this project explores alternative consistency models.
5	DynamoDB: A Key-Value Store for Highly Available and Scalable Databases	Describes DynamoDB's architecture for high availability and scalability.	High availability, fault tolerance, seamless horizontal scaling.	Eventual consistency model may not be suitable. this project uses hybrid consistency models.
6	Data Partitioning and Indexing for Big Data Analytics	Focus on partitioning and indexing strategies for query optimization.	Focuses on optimizing queries for big data analytics, discusses real-world use cases.	Indexing techniques may not work for all queries. this project uses advanced dynamic indexing.
7	A Survey of Modern Distributed Data Management	Survey of modern distributed data management techniques.	Broad coverage of distributed data management, identifies future challenges.	Lacks detailed benchmarks. this project provides detailed benchmarks and real-world performance data.
8	Distributed Query Processing on Big Data with Fault Tolerance	Explores fault-tolerant query processing in distributed systems.	Focus on minimizing latency, ensures fault-tolerant processing in big data systems.	High overhead for fault tolerance. this project uses optimized query routing to reduce overhead.
9	Efficient Query Routing and Execution in Distributed Systems	Proposes algorithms for efficient query routing in distributed systems.	Optimizes routing, reduces response times, scales with data growth.	High complexity, requires significant resources. this project simplifies and scales query routing.
10	Distributed Data Stores for Large Scale Applications	Reviews design of distributed data stores with focus on sharding and replication.	Covers large-scale applications, provides insights on fault tolerance and replication strategies.	High implementation complexity. this project simplifies sharding, replication, and fault tolerance.

Proposed Methodology
The proposed system is a **distributed computing framework** that uses a tree-based architecture to process and query large-scale data across multiple companies efficiently. The system divides the data into **shards** based on a **Company ID** and ensures isolation and security while enabling shared usage of computational resources. The workflow involves three key stages: **query submission**, **query routing and execution**, and **result aggregation**.

1.Architecture of system:
The complete architecture of this distributed computing and shared resource system, breaking it down layer by layer from top to bottom.

1. User Interface & Query Routing Layer
   - Users submit queries along with their Company ID to the Query Router (API)
   - The Query Router acts as the entry point and handles initial request processing
   - Query results are returned to users through the same router


User
Submit Query (with Company ID)
Return Query Result
Query Router (API)
Validate &amp; Route Query
Query Processor (Optimizer)
Final Results
Optimized Query with Company ID
Head Node (Coordinator)
Route Query
Aggregate Results
Aggregate Results
Route Query
Intermediate Node 1
Intermediate Node N
Route Query
Return Results
Route Query
Return Results
Route Query
Return Results
Leaf Node 1 (which executes the query on data container)
Leaf Node 2 (which executes the query on data container)
Leaf Node N (which executes the query on data container)
Query Data
Query Data
Query Data
Data Container Company(A)
Data Container Company(B)
Data Container Company(C)
Retrieve Data
Retrieve Data
Retrieve Data
Data Bank (Ocean of Data)

Architectural Diagram of distributed computing and shared resource

2. Query Processing Layer
   - The Query Processor (Optimizer) receives queries for validation and optimization
   - It performs two key functions:
   - Validates the incoming query for correctness and security
   - Optimizes the query for efficient execution across the distributed system
   - The processor then passes the optimized query with the Company ID to the Head Node
3. Coordination Layer (Head Node)
   - The Head Node acts as the central coordinator for the entire system
   - Key responsibilities include:
   - Query distribution across intermediate nodes
   - Result aggregation from multiple nodes
   - Load balancing and resource management
   - Orchestrating the overall query execution flow
4. Intermediate Node Layer
   - Multiple intermediate nodes (Node 1 to Node N) form a middle tier
   - These nodes:
   - Receive routed queries from the Head Node
   - Further distribute queries to appropriate leaf nodes
   - Aggregate results from leaf nodes
   - Send consolidated results back to the Head Node
   - They provide scalability and help in managing the distributed architecture
5. Leaf Node Layer
   - Leaf nodes are the actual query execution points
   - Each leaf node:
   - Receives specific query portions to execute
   - Interacts directly with data containers
   - Processes queries against the assigned data
   - Returns results to their parent intermediate node
6. Data Container Layer
   - Organized in groups of three containers per leaf node
   - Each container is company-specific (Company A, B, and C)
   - Provides isolated data storage for different companies
   - Ensures data segregation and security
   - Enables parallel data processing across containers
7. Data Bank Layer (Ocean of Data)
   - Forms the foundational storage layer
   - Stores the actual data that containers access
   - Acts as a centralized data repository
   - Provides persistent storage for all company data

This architecture effectively combines distributed computing principles with resource sharing while maintaining security and performance. It's particularly well-suited for multi-tenant environments where different companies need to access and process data simultaneously while keeping their data separate and secure.

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2. Data Partitioning and Storage

- **Data Sharding**:
  Data is partitioned into smaller units called shards. Each shard corresponds to a specific company's data and is uniquely identified using the company's ID. Shards ensure that data is distributed evenly across the leaf nodes to avoid overloading a single node.
  Example:
  - Company A’s data → Shard A1, A2
  - Company B’s data → Shard B1, B2
- **Storage in Leaf Nodes**:
  Shards are stored in **data containers** located on the leaf nodes of the system. Each container isolates data at the storage level using technologies like Docker, ensuring that no company can access another company's data.
- **Data Synchronization**:
  Leaf nodes synchronize with the central data bank periodically to ensure that shards are up-to-date.

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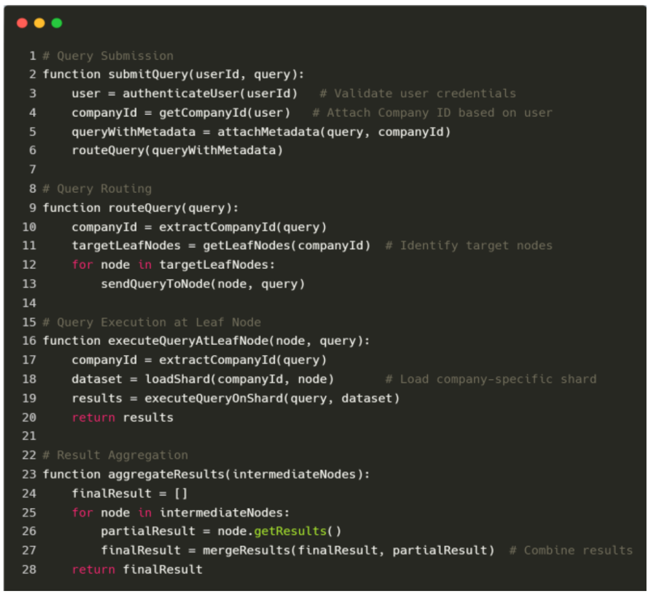
3. Query Workflow

- **Step 1: Query Submission**:
  A user submits a query through an API, which authenticates the user and attaches metadata (e.g., Company ID).
- **Step 2: Query Routing**:
  The query is validated and routed by the **query router** to the relevant leaf nodes based on the attached Company ID.
- **Step 3: Query Execution**:
  At the leaf nodes, the query is executed on the company-specific shard. Results are returned to intermediate nodes for aggregation.
- **Step 4: Result Aggregation**:
  Intermediate nodes aggregate results from multiple leaf nodes and forward the combined results to the head node, which sends the final output back to the user.

4.Pseudocode

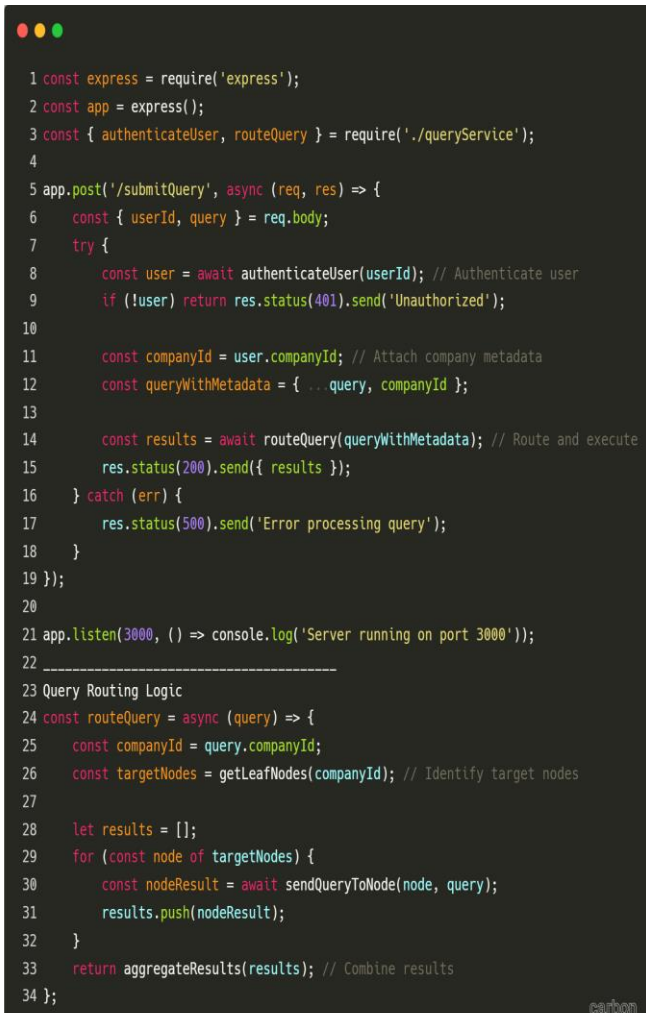
Query work flow pseudo code



```
# Query Submission
function submitQuery(userId, query):
    user = authenticateUser(userId)   # Validate user credentials
    companyId = getCompanyId(user)   # Attach Company ID based on user
    queryWithMetadata = attachMetadata(query, companyId)
    routeQuery(queryWithMetadata)

# Query Routing
function routeQuery(query):
    companyId = extractCompanyId(query)
    targetLeafNodes = getLeafNodes(companyId)  # Identify target nodes
    for node in targetLeafNodes:
        sendQueryToNode(node, query)

# Query Execution at Leaf Node
function executeQueryAtLeafNode(node, query):
    companyId = extractCompanyId(query)
    dataset = loadShard(companyId, node)       # Load company-specific shard
    results = executeQueryOnShard(query, dataset)
    return results

# Result Aggregation
function aggregateResults(intermediateNodes):
    finalResult = []
    for node in intermediateNodes:
        partialResult = node.getResults()
        finalResult = mergeResults(finalResult, partialResult)  # Combine results
    return finalResult
```

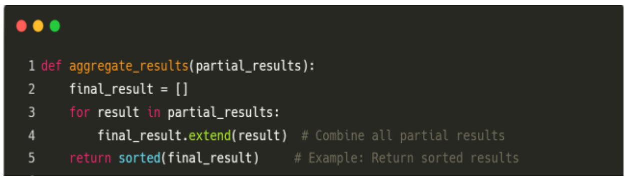
Code Snippet

API Endpoint for Query Submission (Node.js + Express)



```
const express = require('express');
const app = express();
const { authenticateUser, routeQuery } = require('./queryService');

app.post('/submitQuery', async (req, res) => {
    const { userId, query } = req.body;
    try {
        const user = await authenticateUser(userId); // Authenticate user
        if (!user) return res.status(401).send('Unauthorized');

        const companyId = user.companyId; // Attach company metadata
        const queryWithMetadata = { ...query, companyId };

        const results = await routeQuery(queryWithMetadata); // Route and execute
        res.status(200).send({ results });
    } catch (err) {
        res.status(500).send('Error processing query');
    }
});

app.listen(3000, () => console.log('Server running on port 3000'));
_______________________________________
Query Routing Logic
const routeQuery = async (query) => {
    const companyId = query.companyId;
    const targetNodes = getLeafNodes(companyId); // Identify target nodes

    let results = [];
    for (const node of targetNodes) {
        const nodeResult = await sendQueryToNode(node, query);
        results.push(nodeResult);
    }
    return aggregateResults(results); // Combine results
};
```

Result Aggregation Logic (Python)



```
def aggregate_results(partial_results):
    final_result = []
    for result in partial_results:
        final_result.extend(result)  # Combine all partial results
    return sorted(final_result)     # Example: Return sorted results
```

5.Key Features of the Proposed System

1. **Scalability**:
   New leaf nodes can be added to handle increased data volume.
2. **Data Isolation**:
   Each company's data is securely isolated in separate shards and containers.
3. **Resource Sharing**:
   Shared infrastructure reduces redundancy and cost.
4. **Efficiency**:
   Parallel query execution across leaf nodes ensures faster responses.

6. Scalability and Resource Sharing

- **Dynamic Scaling**:
  New leaf nodes can be added dynamically to handle increased data volumes or user queries.
- **Shared Resources**:
  All companies share the same infrastructure (nodes and computational resources), reducing operational costs.
- **Efficient Resource Utilization**:
  Idle resources can be reallocated to handle queries from other companies during non-peak times.

This methodology ensures efficient and secure data querying by combining techniques like sharding, distributed query execution, and result aggregation. By sharing computational resources and scaling dynamically, the system provides a cost-effective solution for handling large datasets across multiple companies. It is particularly suited for environments where companies rely on massive data processing without the overhead of dedicated infrastructure.

Results: The proposed distributed computing system successfully addresses the challenges of managing and querying large-scale datasets across multiple companies in a secure and cost-effective manner. Key outcomes of the implementation include:

1. **Scalability**: The system supports dynamic scaling by adding new leaf nodes to accommodate growing data volumes and user queries. This ensures that the system can grow alongside the needs of businesses.
2. **Data Isolation**: By partitioning data into shards based on the Company ID, the system guarantees that each company's data is isolated and secured, ensuring confidentiality and integrity.
3. **Resource Sharing**: The system leverages shared computational resources, which significantly reduces infrastructure costs for each company while maintaining high performance and security.
4. **Query Optimization**: Through intelligent query routing and parallel execution, the system delivers faster query responses, even for large and complex datasets.

5. **Efficient Resource Utilization**: Idle resources are dynamically reallocated across companies, enhancing resource utilization and reducing operational waste.

Conclusion: The distributed computing system with shared resources provides a robust solution for efficiently handling large datasets in a multi-tenant environment. Its tree-based architecture ensures both data security and high performance while optimizing resource usage. The system's scalability, query optimization, and cost-effectiveness make it particularly suited for SaaS platforms and big data analytics. By offering a cost-effective alternative to dedicated infrastructure, it empowers companies to manage and query large datasets efficiently without the high operational costs associated with traditional systems.

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