ISTANBUL TECHNICAL UNIVERSITY
FACULTY OF COMPUTER AND INFORMATICS

EMBEDDED GRAPH DATABASE MANAGEMENT SYSTEM

Graduation Project Final Report

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Department: Computer Engineering
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Statement of Authenticity

I hereby declare that in this study

1. all the content influenced by external references is cited clearly and in detail,
2. and all the remaining sections, especially the theoretical studies and implemented software/hardware that constitute the fundamental essence of this study is originated from my own authenticity.

İstanbul, May 2023

Kağan Hüseyin Erol

EMBEDDED GRAPH DATABASE MANAGEMENT SYSTEM

(SUMMARY)

A graph database is any storage system that uses graph structures with vertices called as nodes and their respective edges, to represent and store data. Graph databases provide insights and advantages on complex and dynamic relationships in highly interconnected data, one of the important business trends of today.

Nowadays, they have helped solve important problems in the areas of social networking, master data management, geospatial, recommendations, and more. The essential factor for increased focus on graph databases is the commercial success of companies such as Facebook, Google, and Twitter, all of whom have centered their business models around graph technologies. Graph databases and graph technology contain features inherent to traditional relational databases such as ACID compliancy and availability.

To better understand relationships between customers, elements in a social network, or genes and proteins, the ability to comprehend and analyze vast graphs of highly interconnected data is crucial. For that purpose, graph database management systems enable storing, processing, and analyzing such large, evolving, and interconnected datasets.

The aim of this project is to develop an embedded graph database management system to provide an embeddable, serverless, and lightweight solution for projects which want to store their data as a graph. This includes implementing a query language for querying graphs and providing the project as a library for achieving embeddability in various applications and languages. The application area is databases, specifically graph databases and embedded databases. This novelty of this project is to implement an embedded database management system similar to the operation of SQLite in relational databases but in the area of graph databases.

Therefore, it is going to utilize the openCypher standards for the graph query language and labeled property graph model for the data model of graphs. The main characteristic and final outcome of the project is a library code used as a graph database management system that can be embedded in other software applications. It can accomplish the essential graph querying operations such as creating and deleting nodes with their respective labels and properties, creating relationships between nodes also with their respective labels and properties, pattern matching, filtering the matched results, and returning the matched results. The library is object-oriented, modular, and designed with considering potential objectives. Such potential objectives are to integrate a robust on-disk data storage strategy, implementation of wrappers to support different languages, an implementation of a more extensive command-line interface, an implementation of an application that can visualize the graph data, and progress towards ACID compliance.

GÖMÜLÜ GRAF VERİTABANI YÖNETİM SİSTEMİ

(ÖZET)

Graf veri tabanı verileri temsil etmek ve depolamak için düğüm olarak adlandırılan noktalar ve bu düğümlere karşılık gelen kenarlar içeren graf yapılarını kullanan herhangi bir depolama sistemidir. Graf veri tabanları, günümüzün önemli iş trendlerinden biri olan yüksek düzeyde birbirine bağlı verilerdeki karmaşık ve dinamik ilişkiler hakkında öngörüler ve avantajlar sağlar.

Günümüzde, sosyal ağ oluşturma, ana veri yönetimi, coğrafi konum, öneriler ve daha pek çok alanda önemli sorunların çözülmesine yardımcı olmaktadırlar. Graf veri tabanlarına ilgiyi artıran temel faktör, iş modellerini graf teknolojileri etrafında toplamış olan Facebook, Google ve Twitter gibi şirketlerin ticari başarısıdır. Graf veri tabanları ve graf teknolojisi, ACID uyumluluğu ve ulaşılabilirliği gibi geleneksel ilişkisel veri tabanlarına özgü özellikler içerir.

Müşteriler arasındaki, bir sosyal ağdaki öğeler arasındaki veya genler ve proteinler arasındaki ilişkileri daha iyi anlamlandırabilmek için, yüksek düzeyde birbirine bağlı verilerin büyük graflarını anlama ve analiz etme yeteneği çok önemlidir. Bu amaçla, graf veri tabanı yönetim sistemleri, bu tür büyük, gelişen ve birbirine bağlı veri kümelerinin depolanmasını, işlenmesini ve analiz edilmesini sağlar.

Bu projenin amacı, projelerinde veya uygulamalarında verileri graf biçiminde depolamak isteyen kullanıcılar için gömülü bir graf veri tabanı yönetim sistemi geliştirmektir. Aynı zamanda grafları sorgulayabilmek için bir sorgu dilinin uygulanmasını ve çeşitli uygulamalarda gömülebilirliğini sağlamak için bir kütüphane sunmayı içerir. Uygulama alanı graf veri tabanları ve gömülü veritabanlar özelinde veri tabanlarıdır. Bu projenin yenilik maksadı, graf veri tabanları alanında SQLite'ın ilişkisel veri tabanlardaki çalışma sistemine benzeyen, gömülü bir veri tabanı yönetim sistemi gerçekleştirmektir.

Bu nedenle, graf sorgulama dili için openCypher standartları ve grafların veri modeli için etiketlenmiş özellikli graf modeli kullanılacaktır. Projenin temel niteliği ve nihai sonucu, diğer yazılım uygulamalarına gömülebilen bir graf veri tabanı yönetim sistemi olarak kullanılan bir kütüphane kodudur. Bu kütüphane, temel graf sorgulama işlemlerini başarıyla gerçekleştirebilir, ilgili etiketleri ve özellikleriyle düğümleri oluşturma ve silme, düğümler arasında ilişkileri ilgili etiketleri ve özellikleriyle oluşturma, örüntü eşleme, eşleşen sonuçları filtreleme ve eşleşen nihai sonucu kullanıcıya döndürme bu özellikler arasındadır. Kütüphane nesne yönelimlidir, modüler bir şekildedir ve potansiyel hedefleri göz önünde bulundurarak tasarlanmıştır. Bu potansiyel hedefler, sağlam bir disk tabanlı veri depolama stratejisi entegrasyonu, farklı dilleri desteklemek için aracı modüllerin uygulanması, daha kapsamlı bir komut satırı arabiriminin uygulanması, graf verilerini görselleştirebilen bir uygulama tasarlanması ve ACID uyumluluğuna doğru ilerlemeyi içerir.

Contents

1 Introduction and Project Summary

A graph database is a specialized database designed to efficiently manage graph data models based on graph theory principles. It consists of nodes representing entities and edges representing relationships. Relationships in graph databases can be labeled, directed, and assigned properties, and can be either directed or undirected. This allows for flexible and expressive data modeling and querying capabilities. Graph databases leverage the inherent structure of graphs to provide advantages such as efficient traversal and navigation of relationships. By prioritizing relationships and offering labeling and property features, graph databases enable powerful data management and analysis.

Two widely recognized graph data models are the Labeled Property Graph and the Resource Description Framework (RDF). In the Labeled Property Graph model, nodes, relationships, properties, and labels play key roles. Nodes and relationships can be labeled and store properties as key-value pairs, allowing for efficient grouping and detailed information representation. Relationships in this model are always directed, connecting a start node to an end node, enabling rapid traversal through direct storage. In contrast, RDF represents each piece of information as a separate node, offering a different approach to data representation within the graph database context.

Graph databases provide significant benefits for associative datasets and seamlessly integrate with the structure of object-oriented applications. They exhibit natural scalability, effortlessly accommodating large datasets without the need for intricate join operations. The flexibility and schema-less nature of graph databases make them particularly adept at handling ad hoc and evolving data with dynamic schemas. In contrast, relational database management systems tend to excel in operations involving a substantial volume of data elements.

Graph databases offer specialized graph query languages designed specifically for querying graph data. Cypher, which is based on the Labeled Property Graph model, stands out as an expressive, compact, and user-friendly query language, facilitating efficient and intuitive graph querying. SPARQL is tailored for RDF and enables querying of semantic data. Another notable graph query language is Gremlin, which follows an imperative, path-based approach, allowing for powerful graph traversals. Moreover, graph databases and graph technology encompass essential features like ACID compliance for transactional integrity and inherent availability, ensuring robustness and reliability comparable to traditional databases.

Graph databases find widespread applicability across diverse domains due to the inherent interconnectedness of the real world. They offer valuable insights and effective data management solutions in areas such as social networks, IoT and smart homes, and genetic research involving genes and proteins. The commercial triumph of tech giants like Facebook, Google, and Twitter, who have built their business models around graph database technologies, has played a significant role in amplifying the attention and interest in graph databases within the computer world. The ability of graph databases to capture and analyze complex relationships and interconnected data sets makes them indispensable tools for understanding and navigating the intricacies of real-world networks.

This project undertakes the development of an embedded graph database management system, offering a lightweight and serverless solution for projects seeking efficient storage of graph-based data. The project aims to create a programming library that serves as an embedded database system, akin to SQLite but optimized for graph databases, encompassing functionalities comparable to SQLite. A key aspect involves the implementation of a graph query language specifically designed for querying graph data, enabling seamless integration of the embedded database in various applications. The project's scope revolves around databases, with a particular focus on graph databases and embedded databases, aiming to deliver a versatile solution tailored to the specific requirements of graph-based data management.

The project utilizes the openCypher standards for the graph query language and the labeled property graph data model for graphs. The main outcome is a library code serving as a graph database management system that can be seamlessly embedded into other software applications. It accomplishes essential graph querying operations such as creating and deleting nodes with their respective labels and properties, creating relationships between nodes also with their respective labels and properties, pattern matching, filtering the matched results, and returning the matched results, that will serve as the foundation for other objectives. Additional potential objectives include enhancing the functionality of the graph query language, integrating a robust on-disk data storage strategy, implementing language-specific wrappers, creating a more elaborative command-line API, implementing an application that can visualize graph data, and ensuring transactionality through ACID compliance. These objectives can be built upon the developed embedded graph database management system.

The project leverages the openCypher standards for the graph query language and adopts the labeled property graph data model as the foundation for graph representation. The primary deliverable is a library code that acts as a fully embedded graph database management system, seamlessly integrable into diverse software applications. It encompasses essential graph querying operations, including node creation and deletion with corresponding labels and properties, establishment of relationships between nodes along with their labels and properties, pattern matching, filtering the matched results furthermore, and retrieval of the matched results. These core functionalities establish the groundwork for achieving other objectives. Potential additional goals involve enhancing the graph query language's capabilities, incorporating a robust on-disk data storage strategy, developing language-specific wrappers for smoother integration, creating a more comprehensive command-line API, implementing a visualization application for graph data, and ensuring transactionality through adherence to ACID compliance. These objectives can be pursued in a progressive manner, building upon the foundational embedded graph database management system that forms the core of the project.

1.1 Engineering Standards and Multiple Constraints

In the process of designing and implementing the project, adherence to engineering standards and consideration of multiple constraints played a crucial role. By incorporating established engineering practices and guidelines, the project aimed to ensure the reliability, compatibility, and quality of the developed solution.

The project adhered to relevant engineering standards, such as those pertaining to data modeling and query languages for graph databases. Standards, such as openCypher, were utilized to provide a common and interoperable foundation for the graph query language implementation. By aligning with these standards, the project ensured compatibility with existing graph database ecosystems and facilitated seamless integration with other systems and tools.

Additionally, various constraints were taken into account throughout the project lifecycle. For example, the project considered constraints related to cost-effectiveness and efficiency. By developing an embedded graph database management system, the project aimed to provide a lightweight and serverless solution, minimizing resource requirements and operational costs. The constraints of constructability and maintainability were also addressed in the report, facilitating ease of development, maintenance, and future enhancements.

Usability constraints were given importance to ensure that the developed system is user-friendly and intuitive. By incorporating industry-standard query languages, the project aimed to enable developers to seamlessly integrate and utilize the embedded graph database system within their applications.

Moreover, the project acknowledged constraints related to extensibility and interoperability. By implementing the graph query language based on open standards like openCypher, the system ensured comparability with other graph database implementations and planned future enhancements and extensions. This design decision allowed for the seamless integration of the embedded graph database system with a diverse range of software applications and ecosystems.

Throughout the project, various constraints were carefully evaluated, and trade-offs were made to achieve a high-quality solution that meets the desired needs and specifications. The iterative nature of the engineering design process enabled the consideration of different constraints at each stage, trying to ensure that the final solution strikes a balance between functionality, performance, maintainability, and compatibility.

In summary, the project embraced engineering standards and navigated multiple constraints to develop a lightweight embedded graph database management system. By aligning with established standards, considering various constraints, and making informed trade-offs, the project aimed to deliver a solution that not only meets the requirements but also ensures compatibility, usability, and extensibility.

2 Comparative Literature Survey

In the rapidly evolving landscape of Database Systems, Graph Databases have emerged as a compelling solution, specifically tailored for managing data with intricate graph structures comprising nodes and edges. The significance of graph databases is underscored by their ability to efficiently store, process, and query graph-based data, leading to their increasing adoption across various domains. This comparative literature survey aims to explore, to analyze, and to compare with the final design the key aspects of graph databases, encompassing a comprehensive examination of their characteristics, a comparative evaluation of different graph database systems, an investigation into Graph Query Languages for effective data retrieval, an in-depth exploration of the Labeled Property Graph Model, and a thorough exploration of storage strategies for graph data. By delving into these interconnected subjects, this survey seeks to shed light on the potential of graph databases as a sophisticated and robust solution, addressing the growing demands of modern data management and unlocking new opportunities for data analysis and decision-making processes.

2.1 Literature Survey

In his study, Pokorny [1] critically examines the advancements, limitations, and potential future approaches within the realm of graph databases. The research highlights three key focal points of graph databases: the efficient processing of highly connected data, the flexibility offered by graph-based data models, and the exceptional performance achieved through local reads via graph traversal. However, when compared to traditional relational database management systems (RDBMS), potential users may encounter challenges in identifying the most suitable use cases for each product.

One current limitation and an area with potential for advancement lies in the utilization of graph databases for large-scale, unstructured datasets. Addressing this challenge will require a reevaluation of existing designs to ensure efficient handling of such datasets. Moreover, as emerging technologies like the Internet of Things (IoT) and Smart Homes gain traction, new application areas for graph databases are expected to emerge. This calls for future considerations and revisions of previous designs to accommodate the evolving landscape and cater to these emerging domains.

By critically assessing these aspects, Pokorny's research provides valuable insights into the current state of graph databases, their limitations, and potential areas for improvement. This analysis contributes to the broader understanding of graph database technologies and paves the way for future advancements and innovations in this rapidly evolving field.

Recognizing these powers and restrictions is of capital importance as the project is based on Graph Database Model. Before going into further detail, a comparison of current Graph Database systems should be surveyed.

In line with prior research, Besta et al. [2] have undertaken a comprehensive survey to establish a taxonomy of contemporary graph databases, shedding light on their design-related challenges. This pioneering study stands as the first dedicated exploration of the system aspects of graph databases, encompassing crucial topics such as data organization, distribution strategies, language support, and transactional capabilities. By delving into these

key areas, the research not only provides valuable insights into the current landscape of graph databases but also contributes significantly to the understanding and advancement of this field. The taxonomy developed in the study serves as a valuable resource for researchers and practitioners, offering a structured framework for classifying and analyzing various graph database systems based on their fundamental characteristics and features.

This paper offers a wealth of information and in-depth analysis concerning the intricate design aspects of graph databases, thereby providing valuable insights that inform the design choices made for the current project. A key aspect highlighted is the influence of the supported conceptual graph model on query language support. Systems aligned with the RDF model typically offer support for SPARQL, while those centered around the Labeled Property Graph model tend to prioritize query languages such as Cypher or Gremlin. Notably, a significant observation is that there is currently a dearth of graph databases that prioritize embeddability, which distinguishes this project from existing solutions. By focusing on the development of a lightweight and embedded graph database management system, this project provides a solution to fill this gap within the graph database ecosystem.

Several other studies [3], [4], [5], [6] contribute to the comparison and understanding of graph databases. However, it becomes apparent that the term "graph database" can be ambiguous, as its interpretation varies across different studies. For instance, some studies, like [3], view it as a database model, while others, like [4], treat it as a database management system. The historical perspective offered in [3] may be seen as outdated, as it primarily surveys older studies and fails to mention popular data models or query languages. Conversely, the same researcher presents a more contemporary examination of graph database systems in [4]. The research discussed in [5] focuses on comparing graph databases, considering factors such as flexibility, scalability, and the capabilities of the query language. Meanwhile, McColl et al. [6] concentrate on comparing open-source graph databases, taking into account performance metrics and emerging trends in the realm of big data. These diverse studies contribute to a comprehensive understanding of graph databases and provide valuable insights for the current research.

While a canonical graph representation has yet to emerge, as highlighted in [2], it becomes evident that graph databases utilizing the Labeled Property Graph data model have gained prominence in terms of prevalence, timeliness, and, to some extent, performance. Considering this outcome, the project's selection of the query language was primarily narrowed down to Cypher and Gremlin before delving into further research on Graph Query Languages. Eventually, the openCypher standards were chosen as the foundation for implementing the graph query language, considering its widespread adoption and compatibility with the LPG data model. By leveraging openCypher, this project aims to provide a standardized and expressive query language for seamless integration with its graph database system.

The paper [7] provides a comprehensive analysis of the fundamental features that form the basis for querying graph data, including graph database models, pattern matching, and data navigation. By examining recent developments in the field, the paper offers an insightful overview and categorization of these features. This research serves as a valuable resource for understanding the advancements in graph data querying and provides a framework for the project's exploration of relevant concepts and techniques. By leveraging the insights from [7], the project can align with the latest trends and advancements in the field of graph

database querying, ensuring that it incorporates state-of-the-art methodologies in its design and implementation.

In the study conducted by Holzschuher et al. [8], a thorough comparison of Cypher, Gremlin, SQL, and Native Access in Neo4j was carried out, focusing on their performance in highly interconnected data scenarios, resembling use cases found in social networks. The findings indicate that graph query languages, such as Cypher and Gremlin, outperform SQL in these contexts. Specifically, Cypher was found to be more intuitive for developers with prior SQL experience and demonstrated strong performance across various cases. However, Native Access in Neo4j was deemed irrelevant to the project and thus not included in the comparison. These insights provide valuable guidance for the project's selection of a suitable graph query language, highlighting the strengths of Cypher and its compatibility with developers familiar with SQL.

In the studies presented by [9] and [10], novel and standardized graph query languages based on the property graph model are proposed. [9] introduces a new query language called PGQL, which critiques the imperative nature of Gremlin, deeming it more suitable for expressing graph analysis algorithms rather than general querying in large-sized graphs. However, it is noted that newer versions of Cypher have addressed some of these concerns. On the other hand, [10] proposes a query language named G-CORE, aiming to serve as a foundation for future advancements in graph querying. G-CORE emphasizes the principles of composability, allowing graphs and their mental models to act as input and output components and highlighting the significance of paths as first-class citizens, which is a highly valued feature in graph databases. These studies contribute to the evolving landscape of graph query languages, offering alternative options and highlighting key considerations for the project's choice of query language.

In the study [11], the focus is on Cypher, which is recognized as one of the most widely used graph query languages in the field and is designed specifically for the property graph data model. The paper highlights that Cypher benefits from openCypher, which provides comprehensive documentation and standards for the language. This openness enables independent implementations and fosters a collaborative environment for the advancement of Cypher. The study suggests that Cypher's compatibility with newer standardized versions and its openness to independent strategies make it a favorable choice for long-term support in the project. The findings of [11] contribute to the decision-making process by emphasizing the suitability of Cypher as a reliable and evolving graph query language for this project.

In Angles' study [12], a mathematical definition of the property graph data structure is provided, along with the introduction of a graph query language that bears resemblance to SPARQL and Cypher. The paper offers valuable insights by establishing a formal connection between the data model and the query language, which enhances the understanding of query semantics. This formal perspective aids in comprehending the underlying principles of the graph query language and its relationship to the property graph data structure. However, it is important to note that although Angles' work presents a more comprehensive version of property graphs, the focus of this research lies outside the scope of labeled property graphs. Nevertheless, the study serves as a relevant reference for understanding the fundamental aspects of query languages and their association with graph data structures.

Donkers' study [13] provides a comparative analysis between RDF and labeled property graphs using a dataset specifically related to smart homes. The results indicate that RDF

performs better than labeled property graphs for small queries and proves to be more suitable in the context of smart homes. However, the research also highlights that labeled property graphs exhibit greater intuitiveness when dealing with complex queries on highly interconnected data. This investigation offers an intriguing perspective on the application of graph databases within the Internet of Things (IoT) domain, which was previously identified as a potential area of future application in [1]. By exploring the performance and usability aspects of graph databases in the context of IoT data, Donkers' research contributes to a deeper understanding of the strengths and limitations of RDF and labeled property graphs, thereby shedding light on their applicability in real-world scenarios such as smart homes.

Steinhaus et al. [14] present an innovative approach to storing graph data on disk with the introduction of G-Store, a lightweight disk-based storage manager. The paper outlines a placement strategy for efficiently organizing vertices and edges, along with a storage algorithm designed to optimize data placement on disk. Additionally, the authors provide a programming interface for integration with the storage manager. Although the current state of this project incorporates a simple on-disk data storage through serialization of the graph data to binary, the insights and techniques presented in this study offer valuable considerations for potential integration of detailed on-disk storage capabilities. By leveraging the strategies and algorithms proposed by Steinhaus et al., the project could benefit from enhanced data storage efficiency, improved performance, and the ability to handle larger datasets while ensuring optimal disk utilization.

2.2 The Labeled Property Graph Model

The Labeled Property Graph (LPG) model is a comprehensive and intuitive data model that represents structured data in graph databases. It provides a flexible and efficient way to store and query data by capturing the relationships between entities, their attributes, and the semantics associated with them.

In graph theory, a property graph can be described as a type of graph that has specific characteristics. It is a graph with directed edges, where both vertices and edges can have properties assigned to them. The property graph allows for multiple edges between the same pair of vertices (multigraph), and it also allows vertices to have edges that connect to themselves (self-edges). In the context of the property graph, we use the term "node" to refer to a vertex in the graph, and the term "relationship" to refer to an edge between two vertices.

At the core of the LPG model are three fundamental components: nodes, relationships, and properties.

Nodes serve as the building blocks of the graph and represent entities or objects. Each node is assigned a unique identifier and can be labeled to indicate its type or category. These labels help classify nodes into distinct groups, enabling efficient querying and retrieval of specific types of entities. For instance, in a social network graph, nodes can represent users, posts, comments, or even broader concepts like communities or topics.

Relationships are edges that establish connections or associations between nodes. They describe how entities are related to each other. Relationships in the LPG model are directed and have a specific relationship type that characterizes the nature of the connection. By defining relationships, the LPG model captures the semantic meaning and context of the connections between entities. For example, in a social network graph, relationships could

represent friendships, follows, shares, or likes. Each relationship also has a starting node (the source node) and an ending node (the target node), indicating the directionality of the connection.

Properties provide additional information and attributes associated with nodes and relationships. They are represented as key-value pairs and describe various characteristics of entities or connections. Properties can be used to store and query attributes such as names, ages, locations, timestamps, or any other relevant data that enriches the understanding of the graph. The LPG model allows nodes and relationships to have different sets of properties, facilitating the representation of diverse data types and enabling rich metadata about the entities and connections in the graph.

These basic elements provide us with the necessary foundation to build complex and meaningful models. While diagrams are useful for illustrating graphs in a general sense, they lack the functionality required for working with databases. To effectively create, manipulate, and query data within a database, we rely on a dedicated query language. To interact with and query data stored in a graph database using the LPG model, specialized graph query languages like Cypher (used in Neo4j) or Gremlin (used in Apache TinkerPop) are commonly employed. These query languages provide expressive ways to traverse the graph, retrieve specific patterns of nodes and relationships, and perform aggregations or analytics on the data.

The LPG model's flexibility and adaptability make it well-suited for a wide range of applications and domains. It accommodates dynamic changes to the graph structure and allows for the addition or removal of nodes, relationships, and properties without requiring a rigid predefined schema. This characteristic makes the LPG model particularly valuable when dealing with evolving or heterogeneous data sources.

In summary, the Labeled Property Graph model offers a comprehensive and versatile approach to representing structured data in graph databases. By organizing data into nodes, relationships, and properties, it enables efficient storage, retrieval, and analysis of complex relationships and attributes within the graph. The model's flexibility and support for dynamic changes make it well-suited for various domains, making it a valuable tool for data management and analysis.

2.3 OpenCypher Query Language

OpenCypher is an open-source implementation specification of the Cypher Query Language, specifically designed for graph databases. It provides a standardized way to express graph queries and manipulations, enabling users to retrieve and manipulate data stored in graph databases, offering a powerful tool for graph data analysis. OpenCypher Implementers Group [15] provided the reference for the Cypher Query Language specifications.

The syntax of OpenCypher is designed to be intuitive and familiar, resembling SQL (Structured Query Language). It borrows its structure from SQL — queries are built up using various clauses. These clauses are a collection of operations which are similar to SQL statements in terms of operability and comprehensibility. This similarity allows users who are already familiar with SQL to quickly grasp OpenCypher concepts and query graph data effectively. However, OpenCypher is tailored to work with graph data and includes graph-specific constructs and operations.

OpenCypher allows users to express complex graph patterns, filter and aggregate data, and perform graph traversals and joins. It supports a wide range of graph operations and functions, providing powerful capabilities for querying and analyzing graph data. It has gained popularity as a common query language for graph databases. It provides a standardized and expressive way to interact with graph data, making it easier for developers and analysts to work with graph databases and perform complex graph queries.

One of the key features of OpenCypher is its ability to express complex graph patterns. Using the *MATCH* clause, users can specify patterns of nodes and relationships they want to match in the graph. The pattern consists of nodes, relationships, and their connections, forming a graph-shaped query. By matching this pattern, you can retrieve the desired data from the graph. This pattern matching capability is crucial for querying graph data effectively. For example, a *MATCH (n:Person)-[r:WROTE]->(m:Book)* query could specify that a *Person* node is connected to a *Book* node through a *WROTE* relationship, enabling the retrieval of authors and their associated books. Once the *MATCH* clause is executed, the query engine will traverse the graph, matching the specified pattern, and retrieve the desired data. The matched nodes and relationships can then be used in subsequent clauses like *RETURN*, *WHERE,* and more, to further filter, aggregate, or manipulate the data.

OpenCypher not only allows querying existing data but also provides operations to create and delete graph elements. The *CREATE* operation in OpenCypher enables the creation of nodes and relationships within the graph. Using the *CREATE* clause, users can specify the structure of new graph elements. For example, to create a new *Person* node with properties like *name* and *age*, the following syntax can be used: *CREATE (p:Person {name: 'Arda', age: 18})*. Similarly, relationships can be created between existing or newly created nodes. For instance, to create a *FRIEND* relationship between two *Person* nodes identified by their properties, the following syntax can be used: *CREATE (p1:Person {name: 'Ahmet'})-[:FRIEND]->(p2:Person {name: 'Semih'})*. The *DELETE* operation in OpenCypher allows users to remove nodes and relationships from the graph. Users can specify which elements should be deleted based on specific conditions. For example, to delete a node with a specific property value, the following syntax can be used: *MATCH (p {name: 'John'}) DELETE p*. These *CREATE* and *DELETE* operations in OpenCypher allow users to modify the graph structure by adding or removing graph elements, enabling users to maintain the integrity and relevance of the graph over time.

Properties play an essential role in OpenCypher. Both nodes and relationships can have properties associated with them, represented as key-value pairs. Properties provide additional information and attributes about graph elements. Users can filter and retrieve specific graph elements based on property values, allowing for more precise querying. For example, a *MATCH (n:Person {name: 'Arda'}) WHERE n.age < 21* query could retrieve all *Person* nodes who have a *name* property equal to "Arda" and an *age* property smaller than 21.

Labels and relationship types are fundamental concepts in OpenCypher. Labels are used to categorize nodes, representing different types or classes of entities. By assigning labels to nodes, users can organize and group them based on their characteristics or roles in the domain. Relationship types capture the semantics or meaning of the connections between nodes. These concepts enable users to filter and retrieve specific types of nodes and define

constraints on the relationships they want to match in the graph. For the examples above, it can be said that *Person* and *Book* are labels, meanwhile *WROTE* is a relationship type.

The *RETURN* clause in OpenCypher specifies what data should be returned as the query result. It allows users to define node and relationship variables, property values, or expressions to be included in the result. This flexibility enables users to retrieve specific information from the graph and perform various calculations or aggregations on the data. For example, a *MATCH (person:Person {name: 'Ahmet'})-[:FRIEND_OF]-(friend:Person) RETURN friend.name, friend.age* query result will include the names and ages of all the friends of persons named 'Ahmet' in the graph.

OpenCypher includes a wide range of graph operations and functions. Users can apply filtering conditions on the matched graph elements using the *WHERE* clause. It allows you to further refine your query by specifying criteria that the graph elements must meet in order to be included in the result. Users can use various comparison operators to filter the data based on property values or other criteria. It's important to note that the *WHERE* clause is optional in OpenCypher. If no *WHERE* clause is provided, the query will match all the graph elements specified in the *MATCH* clause without any additional filtering.

OpenCypher also provides additional features such as the *OPTIONAL MATCH* clause, which allows users to specify optional graph patterns in the query. The *MERGE* clause is used to combine pattern matching and creation in a single operation. It allows you to specify a pattern to match in the graph, and if the pattern is not found, it creates it. The *WITH* clause facilitates pipelining query results, enabling intermediate calculations and transformations. Aggregation functions such as *COUNT*, *SUM*, *MIN*, *MAX*, and *AVG* allow for data summarization and analysis. Path expressions enable users to traverse paths in the graph, exploring connected data and navigating through the graph structure. Sorting, pagination, subqueries, and other SQL-like features are also supported in OpenCypher, enhancing its versatility and usefulness in various scenarios.

It is important to note that the specific capabilities and syntax of OpenCypher may vary slightly depending on the graph database platform you are using. While OpenCypher was initially developed by Neo4j, it has gained widespread adoption across multiple graph database platforms, making it a common and standardized query language for working with graph data.

In conclusion, OpenCypher provides a standardized, expressive, and intuitive query language for graph databases. With its graph-specific constructs and operations, it enables users to efficiently retrieve and manipulate graph data. The familiarity of its syntax, combined with powerful features like pattern matching, property filtering, and aggregation functions, makes OpenCypher a valuable tool for graph data analysis and exploration.

3 Developed Approach and System Model

The output of this project is a code library named *ConstelLite*, which implements a lightweight and embedded graph database management system. This library can be embedded into an application or accessed as a standalone service through the provided command-line interface application named *ConstelLiteShell*, which is implemented to demonstrate such features.

The system is built upon the Labeled Property Graph (LPG) data model, which forms the basis for structuring the main data model. Also, the system adheres to the OpenCypher standards, serving as the underlying logic for implementing the behavior of the graph query language. The system follows a modular and extensible architecture. It consists of core components responsible for graph storage, query execution on graph data, and serialization of graph data for on-disk storage.

To represent and store graph data, the data model employs the *Graph*, *GraphEntity*, *NodeStructure*, and *RelationshipStructure* classes as its primary data structures. Section 3.1 Data Model provides comprehensive details about these classes and their functionality.

The library includes the *GraphEngine* class, acting as a query processing engine responsible for parsing and executing OpenCypher queries. Currently, it supports *CREATE*, *DELETE*, *MATCH*, *WHERE*, and *RETURN* clauses defined in the section 2.3 OpenCypher Query Language. Based on the query requirements, the system can create and delete graph data, traverse the graph, perform pattern matching, apply filtering, and retrieve matched results by utilizing these clauses based on the query requirements. Additionally, the library offers serialization capabilities to save the graph database as a binary file and deserialization to load a specified graph database file from disk.

It is important to note that the implementation of a parser is out of scope for this project. The parser code is automatically generated by a tool called *ANTLR*, which stands for ANother Tool for Language Recognition. *ANTLR* simplifies the creation of language parsers, compilers, interpreters, and other language-related tools [16]. It operates by taking a formal language specification, written in its own syntax called *ANTLR grammar*, and generating a parser based on that specification. The generated parser can then analyze input text according to the defined grammar rules and produce a structured representation of the input. The OpenCypher grammar for the *ANTLR* that used in this project can be found at [15]. The generated classes are *CypherLexer*, *CypherParser*, *CypherListener*, and *CypherBaseListener*. The *CypherLexer* is responsible for breaking down the input text into individual tokens. The *CypherParser* examines the tokens generated by the *CypherLexer* and constructs a parse tree based on the OpenCypher grammar. The parse tree represents the syntactic structure of the query input. *CypherListener* and *CypherBaseListener* provides mechanisms for traversing and listening the parse tree.

In the system, the *GraphCypherListener* class is defined to execute the necessary query behavior for handling *CREATE*, *DELETE*, *MATCH*, *WHERE*, and *RETURN* clauses. It is derived from the *CypherBaseListener* to be able to traverse the parse tree. The base class *CypherBaseListener* offers event-based callbacks for specific tree traversal events. The *GraphCypherListener* class utilizes these callbacks to invoke its behavior for performing necessary processing on the graph database based on the query requirements. For example, the *GraphCypherListener* class implements an *ExitOC_Create()* method to create nodes and

relationships on the graph database based on the query requirements. If a query involves a *CREATE* clause, and when the listener exits the context of the parse tree related to the *CREATE* clause, the *ExitOC_Create()* method will be invoked to carry out its defined behavior. A similar workflow behavior also applies to the DELETE, MATCH, WHERE, and RETURN clauses and their respective methods implemented in the *GraphCypherListener* class.

For serialization and deserialization of graph data, the system utilizes an open-source library called Protobuf-net. This library is a contract based serializer that write data in the *protocol buffers* serialization format engineered by Google. It allows me to define my data model in such contracts, and then use its methods to serialize and deserialize the data into a file in binary format. The system defines the *GraphSerializer* class to wrap these methods with *SerializeGraph()* and *DeserializeGraph()* methods to specify the graph data and the file path. *Protobuf-net* is selected because serialization and deserialization are highly efficient in terms of speed, and the serialized data is small in terms of size.

3.1 Data Model

The data model of the system is a graph database based on the LPG model. In the LPG model, a graph is composed of nodes, relationships, and their associated properties. For a more comprehensive understanding of the LPG model, please refer to Section 2.2 The Labeled Property Graph Model.

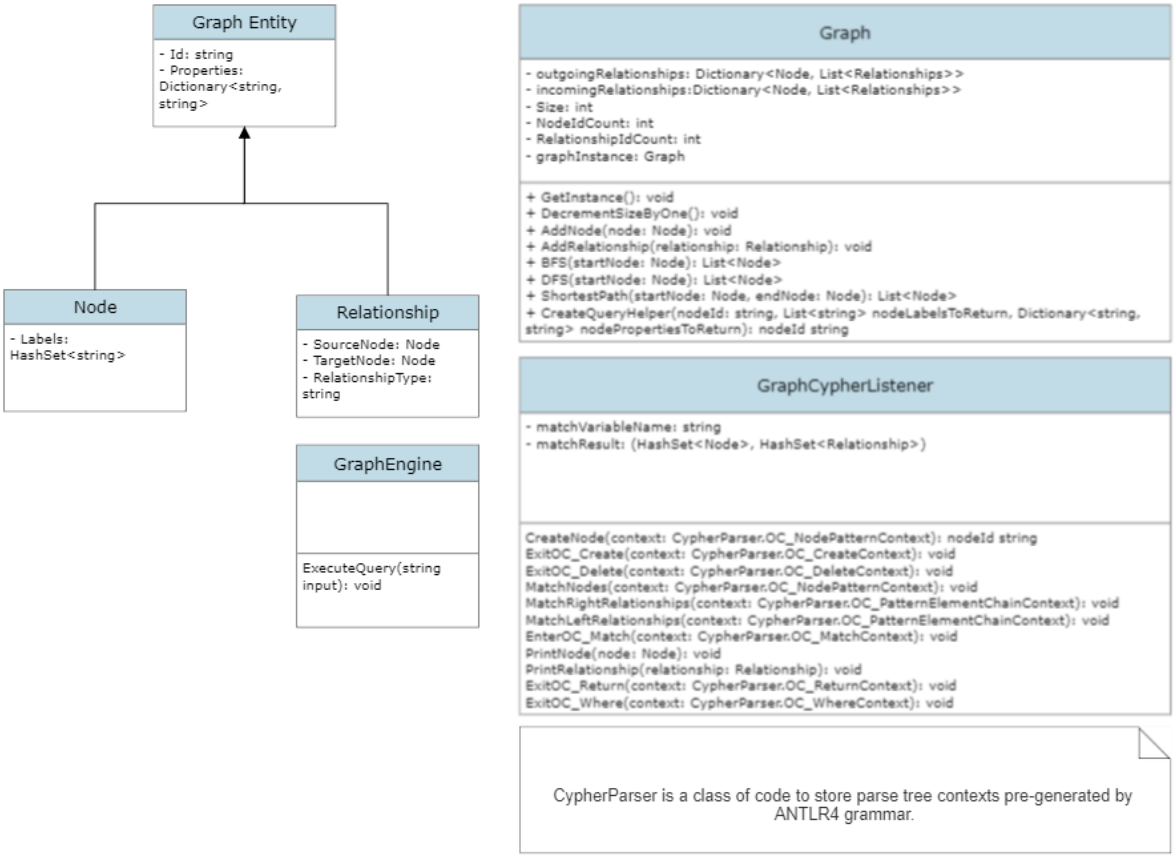
In this model, the following data structures are utilized to organize and represent the graph:

1. *Graph Entity*: This structure represents a graph entity within the graph. It contains an *Id* to uniquely identify the entity. It contains a *Properties* dictionary to store its set of properties. Each property can be uniquely identifiable with their respective property keys.
2. *Node*: This structure represents a node in the graph. A node is a fundamental component of the graph, serving as a vertex. It is a subclass of the *Graph Entity* structure. Along with the attributes inherited from the graph entity, it contains a *Labels* hash set to store its assigned labels. A node can be associated with one or more unique labels. It may also possess zero or more outgoing relationships, which are represented in the *Graph* structure. Similarly, it may have zero or more incoming relationships, also depicted in the *Graph* structure.
3. *Relationship*: This structure represents a directed relationship between two nodes in the graph. It is a subclass of the *Graph Entity* structure. In addition to the attributes inherited from the graph entity, it contains a *SourceNode* node structure pointing to the source node of the relationship, a *TargetNode* node structure pointing to the target node of the relationship, and a *RelationshipType* attribute to store the relationship type. Each relationship is assigned exactly one relationship type.
4. *Graph*: This structure serves as the primary data structure for the graph database. It represents a directed graph with nodes and relationships. It maintains two dictionaries: *outgoingRelationships* and *incomingRelationships*, where each node in the graph maps to a list of outgoing and incoming relationships, respectively. Furthermore, it contains *Size* attribute to store the size of the graph in terms of the number of nodes, *NodeIdCount* attribute to assign unique *Id*s to nodes maintained

inside the graph, and a *RelationshipIdCount* attribute to assign unique *Id*s to relationships maintained inside the graph.

These data structures form the foundation of the graph database based on the LPG model, providing a way to organize and represent the graph data efficiently.

Class Diagrams of the data model are represented as follows:



3.2 Structural Model

Algorithm Definitions:

1. *BFS (Breadth-First Search)*: traverses the graph in a breadth-wise motion, exploring all the neighbors of a node before moving to the next level. It visits nodes at each level before moving to the next level. It is written for future functionality of graph database such as pattern matching relationships between nodes faster.
2. *DFS (Depth-First Search)*: traverses the graph in a depth-wise motion, exploring as far as possible along each branch before backtracking. It visits nodes in depth-first order. It is written for future functionality of graph database such as pattern matching relationships between nodes faster.
3. *Shortest Path*: finds the shortest path between two nodes in terms of the minimum number of edges. It uses Dijkstra's algorithm to compute the shortest path. It is written for future functionality of graph database such as pattern matching relationships between nodes faster.

Pseudocode:

```
BFS(startNode):
```

```
    visited = []
    queue = []

    visited.Add(startNode)
    queue.Enqueue(startNode)

    while queue is not empty:
        currentNode = queue.Dequeue()

        for each outgoing relationship from currentNode:
            neighbor = relationship.EndNode
            if neighbor is not in visited:
                visited.Add(neighbor)
                queue.Enqueue(neighbor)

    return visited

DFS(startNode):
    visited = []
    stack = []

    stack.Push(startNode)

    while stack is not empty:
        currentNode = stack.Pop()

        if currentNode is not in visited:
            visited.Add(currentNode)

            for each outgoing relationship from currentNode:
                neighbor = relationship.EndNode
                stack.Push(neighbor)

    return visited

ShortestPath(startNode, endNode):
    distances = dictionary of node distances (initialized with infinity)
    previous = dictionary of previous nodes (initialized with null)
    unvisited = list of all nodes

    distances[startNode] = 0

    while unvisited is not empty:
        currentNode = node with minimum distance in distances from unvisited

        if currentNode is null:
            break

        unvisited.Remove(currentNode)

        for each outgoing relationship from currentNode:
            neighbor = relationship.EndNode
            distance = distances[currentNode] + 1 // Assuming each edge has weight 1

            if distance < distances[neighbor]:
                distances[neighbor] = distance
                previous[neighbor] = currentNode

    shortestPath = []
    current = endNode

    while current is not null:
```

```
        shortestPath.Insert(0, current)
        current = previous[current]

    return shortestPath
```

4 Experimental Environment and Design

The project incorporates experiments to evaluate the effectiveness and performance of the developed embedded graph database management system. To ensure reliable and reproducible results, a well-defined experimental environment was established.

The development environment consisted of Microsoft Visual Studio 2019. The programming language of the library is C#. ANTLR is a powerful parser generator for reading, processing, executing, or translating structured text or binary files. From a grammar, ANTLR generates a parser that can build and walk parse trees. It is utilized to create pre-generated parser code from a grammar provided by openCypher to parse inputs from user. Functionality of the code to perform necessary operations is coded by me authentically.

Additionally, the experimental setup included representative datasets from openCypher standards that simulated real-world scenarios on queries. These datasets were carefully selected to cover a wide range of graph sizes and complexities, allowing for comprehensive testing and evaluation of the system's capabilities.

In terms of resource requirements, the project demanded a suitable development machine with adequate processing power, memory, and storage to support the development and testing phases. The machine should meet the minimum system requirements of the chosen development tools, programming languages, and libraries.

Furthermore, the project SpecFlow and its Gherkin structure to utilize various feature-scenario based testing methodologies on graph query language clauses, including unit tests, functional tests, and performance tests. These tests were designed to assess the system's functionality, validate its behavior against predefined requirements, and evaluate its performance under different workloads and data sizes.

By establishing a well-defined experimental environment and considering resource requirements, the project ensures that the evaluation process is conducted in a controlled and reliable manner. This allows for accurate assessment and comparison of the system's performance and functionality.

5 Comparative Evaluation and Discussion

In this section, the system design will be evaluated and compared with approaches found in the literature, focusing on quantitative measurements. The evaluation criteria are based on the goals and evaluation criteria presented in the interim report.

One of the evaluation criteria stated in the interim report was the successful execution of at least five openCypher clauses. I am pleased to report that our system meets this criterion, as it is capable of executing *CREATE*, *DELETE*, *MATCH*, *WHERE*, *RETURN* openCypher clauses effectively. Through testing and verification, it is confirmed that the system can process a wide range of openCypher queries accurately and efficiently.

Another evaluation criterion was the implementation of at least one wrapper for a programming language. In the project, we have successfully implemented a wrapper in C#, providing a convenient REPL (Read-Eval-Print Loop) interface. This wrapper utilizes the library DLL, which contains the essential functionality of our embedded graph database management system. The C# wrapper allows developers to interact with the graph database using familiar programming constructs and seamlessly integrate it into their C# applications.

By meeting these evaluation criteria, our system demonstrates its capability to execute openCypher queries and provides a user-friendly programming interface. We have achieved the intended goals set forth in the interim report and created a system that aligns with the design objectives.

In conclusion, our system design has met the evaluation criteria outlined in the interim report, successfully executing openCypher queries and implementing a programming language wrapper. This establishes a solid foundation for future enhancements and opens up possibilities for further quantitative evaluations, ensuring the continued improvement and refinement of our embedded graph database management system.

6 Conclusion and Future Work

The project at hand focuses on the development of an embedded graph database management system, offering a lightweight and serverless solution for projects that require efficient graph-based data storage. By adopting the openCypher standards for the graph query language and leveraging the labeled property graph data model, the system aims to provide a flexible and expressive platform for managing graph data effectively.

The primary objective is to create a library code that seamlessly integrates into other software applications, enabling developers to harness the power of graph databases within their projects. To achieve this, the project will initially concentrate on implementing fundamental graph querying operations, including node and relationship creation, deletion, and pattern matching. These core functionalities serve as the building blocks for subsequent objectives and pave the way for advanced data manipulation and analysis.

Looking towards future enhancements, one potential avenue is to enrich the functionality of the graph query language. By expanding its capabilities and expressive power, the system can accommodate more intricate queries and complex data transformations. This could involve incorporating features like aggregations, advanced filtering mechanisms, and support for graph algorithms, empowering users to perform sophisticated analysis and gain deeper insights from their graph data.

Furthermore, integrating a robust on-disk data storage strategy can significantly enhance the system's scalability and performance. Drawing insights from the lightweight disk-based storage manager proposed by Steinhaus et al. [14], the project can devise efficient placement strategies for vertices and edges, optimize storage algorithms, and develop a programming interface for seamless interaction with the storage manager. By efficiently managing the on-disk data, the system can handle larger datasets, enable faster data retrieval, and provide improved resilience and durability.

To enhance usability and streamline integration with different programming languages, language-specific wrappers can be developed. These wrappers would provide developers with idiomatic interfaces to interact with the embedded graph database system, abstracting away low-level implementation details and offering a more intuitive and seamless experience. This expansion would ensure wider adoption and make the system accessible to developers from diverse backgrounds and language preferences.

Improving the user experience is also essential, and one way to achieve this is by creating a more elaborate command-line API. By enriching the command-line interface with comprehensive commands, options, and intuitive syntax, users can easily perform various graph-related tasks, such as data management, querying, and visualization, in a more efficient and user-friendly manner.

Additionally, the project can explore the implementation of visualization capabilities, enabling users to gain visual insights into their graph data. By integrating graph visualization libraries or building a dedicated visualization module, users can interactively explore the graph structure, analyze relationships, and identify patterns and clusters. Visualizations provide an intuitive means of understanding complex graph data, facilitating decision-making and discovery of meaningful information.

Lastly, ensuring transactionality through ACID compliance is crucial for maintaining data integrity and consistency. Future work can involve implementing transaction support within the embedded graph database system, allowing users to execute multiple operations atomically and providing mechanisms for rollback and recovery in case of failures. This would guarantee the reliability and consistency of the data, especially in scenarios where data modifications need to be performed as a cohesive unit.

By considering these future possibilities and extensions, the project can evolve into a comprehensive and versatile embedded graph database solution. It can cater to diverse application domains, offering extended functionality, scalability, and ease of use. This would empower developers and users to leverage the full potential of graph databases, enabling advanced data analysis, insights generation, and decision-making based on rich and interconnected graph data.

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