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CONSISTENCY ISSUE AND RELATED TRADE-OFFS IN DISTRIBUTED REPLICATED SYSTEMS AND DATABASES: A REVIEW

Distributed replicated databases play a crucial role in modern computer systems enabling scalable, fault-tolerant, and high-performance data management. However, achieving these qualities requires resolving a number of trade-offs between various properties during system design and operation. This paper reviews trade-offs in distributed replicated databases and provides a survey of recent research papers studying distributed data storage. The paper first discusses a compromise between consistency and latency that appears in distributed replicated data storages and directly follows from CAP and PACELC theorems. Consistency refers to the guarantee that all clients in a distributed system observe the same data at the same time. To ensure strong consistency, distributed systems typically employ coordination mechanisms and synchronization protocols that involve communication and agreement among distributed replicas. These mechanisms introduce additional overhead and latency and can dramatically increase the time taken to complete operations when replicas are globally distributed across the Internet. In addition, we study trade-offs between other system properties including availability, durability, cost, energy consumption, read and write latency, etc. In this paper we also provide a comprehensive review and classification of recent research works in distributed replicated databases. Reviewed papers showcase several major areas of research, ranging from performance evaluation and comparison of various NoSQL databases to suggest new strategies for data replication and putting forward new consistency models. In particular, we observed a shift towards exploring hybrid consistency models of causal consistency and eventual consistency with causal ordering due to their ability to strike a balance between operations ordering guarantees and high performance. Researchers have also proposed various consistency control algorithms and consensus quorum protocols to coordinate distributed replicas. Insights from this review can empower practitioners to make informed decisions in designing and managing distributed data storage systems as well as help identify existing gaps in the body of knowledge and suggest further research directions.

Keywords: distributed databases; Big Data, NoSQL; replication; consistency; latency; throughput; availability; trade-offs; CAP; PACELC; review.

Introduction

The exponential growth of data together with the increasing demand for scalability, fault tolerance, and high-performance computing, has driven the rise of distributed databases as a fundamental component of modern computer systems. Internet-scale distributed computer systems and data storages are now extensively used in social media platforms, science and business applications and critical infrastructures.

The importance of distributed data storages and modern NoSQL databases lies in their ability to address the limitations of traditional relational database management systems, which struggle to handle the scale, velocity, and variety of data as required by today's applications [1]. By sharing and replicating data across multiple nodes, distributed databases provide inherent advantages such as enhanced performance and scalability, improved availability and fault tolerance.

However, achieving these benefits involves making trade-offs in various aspects, including consistency, availability, latency, cost and other system properties. Deep understanding of these trade-offs enables system engineers, developers, and users to make informed decisions and find the right balance to meet their specific requirements and is crucial for resource-efficient system design.

The paper is aimed at analysing trade-offs in modern distributed systems and replicated data storages and reviewing research publications that study the consistency and other properties of such systems. The rest of the paper is organised as follows. In the next section we discuss CAP and PACELC theorems and their implications in distributed systems. Section 2 explores main trade-offs between the various properties of distributed replicated databases. Section 3 provides an overview of recent research works studying distributed data storages, analyses keywords and identifies major areas of interests and research efforts. The last section concludes our survey.

1. Data Replication. CAP and PACELC Theorems

1.1. Data Replication

Data replication is a database scale-out approach where the same data is replicated across multiple nodes, i.e. replicas. It is a vital technique used to build large-scale distributed applications of high performance.

Data replication primarily improves system availability and performance. If one of the database nodes fails, the system will continue to work because there are other nodes available. The system performance is improved by load balancing (i.e. sharing the workload among available nodes) and distributing replicas close to end users to minimize latency. However, replication increases implementation complexity and rises multiple inter-related trade-offs between different system properties.

1.1. CAP Theorem

The CAP theorem [2], first introduced in 1998-1999, establishes a fundamental trade-off between three properties of distributed replicated systems: Consistency, Availability, and Partition tolerance. According to the theorem, it is impossible to simultaneously guarantee all three properties in such systems, allowing for the preservation of only two out of the three. Gilbert and Lynch in [3] consider the CAP theorem as a specific instance of a broader trade-off between consistency and availability that exists in unreliable distributed systems, where updates propagate over time. When a distributed database encounters a partition (for example, when one of the replicas rejects a user request or fails to respond within a given timeout), it must decide whether to return a possibly stale result to the client, sacrificing consistency or to report service unavailability. Depending on this decision, the CAP theorem specifies the following three types of systems:

- CA**: traditional ACID-oriented databases (Oracle, MySQL, PostgreSQL, etc.) which preserve Consistency and Availability, but are not suitable for efficient data distribution and cannot tolerate system partitioning;

- AP**: distributed databases such as Riak, Voldemort, Cassandra, Dynamo, CouchDB relaxing Consistency in favour of Availability and Partition tolerance;

- CP**: NoSQL databases such as MongoDB, HBase, BigTable, Redis, MemcacheDB which give up availability but preserve Consistency when Partitioned.

1.2. PACELC Theorem

The PACELC theorem [4] is a further development of CAP which suggests that that in the case of *partitioning* (P) of a distributed data storage, one has to choose between *availability* (A) and *consistency* (C), *else* (E) in the absence

of partitions the replicated database faces a trade-off between *latency* (L) and *consistency* (C). There could be four types of distributed databases as follows from PACELC (some distributed databases such as Couchbase, DynamoDB can be configured to be either PC/EL or PC/EC):

- PC/EC**: ACID databases (MySQL Cluster, PostgreSQL, Megastore, VoltDB/H-Store, etc.) and NoSQL databases (HBase, BigTable);

- PC/EL**: PNUTS, Couchbase, DynamoDB, FaunaDB;

- PA/EC**: MongoDB, Aerospike;

- PA/EL**: Cassandra, Dynamo, Cosmos DB, Riak.

2. Trade-offs in Distributed Replicated Databases

Though CAP and PACELC theorems are helpful in understanding a key trade-off between consistency and availability/latency, they do not consider other important compromises discussed below.

2.1. Availability vs Performance

Replicating data across multiple nodes increases data availability. On the one hand, it also enables load balancing to improve system performance. On the other, increased system complexity and overheads related to the need for replica synchronization and coordination introduce delays and impact system latency. This impact considerably depends on the replication model used and consistency settings. Another important factor balancing availability versus performance is the application timeout [5]. Timeout serves as the major error detection mechanism in distributed systems. If it is less than the typical response time, a system will likely enter a partition mode more often [6]. If the timeout is too long, the system will be too slow to handle exceptions and inefficient in error-recovery.

2.2. Latency vs Consistency

Strong consistency ensures that a read always reflects the most recent write and all nodes store the same version of data at all times. It is always desirable to maintain data consistency. However, the strong consistency cannot be efficiently achieved in distributed (especially of the large scale) replicated systems without affecting system latency. Strong consistency is based on synchronous updates which are controlled by consensus protocols or coordination mechanisms such as Paxos or two-phase commits. They require multiple communication and coordination among replicas resulting in increased latency.

The more nodes involved in the coordination and the larger the distance between them, the higher the latency impact. Moreover, strong consistency often relies on locking mechanisms to prevent concurrent conflicting operations. This can increase latency as transactions should wait for locks to be released.

Second, we observed a shift towards exploring models going beyond the traditional strong and eventual consistency. Causal consistency and eventual consistency with causal ordering have gained attention due to their ability to strike a balance between operations ordering guarantees and high performance. These new models enable applications to maintain causal relationships between read/write requests while relaxing the strict requirements of linearizability or serializability.

Another prominent theme in recent research works is utilizing machine learning (ML) algorithms to optimize data replication strategies and dynamically adapt consistency levels based on workload patterns. This intersection of ML and distributed databases opens up new avenues for intelligent and adaptive data management in distributed environments. Furthermore, we observed an increased focus on consistency and replication in specific domains such as edge computing, IoT, and large-scale geo-spatial applications. These domains present unique challenges in terms of limited resources, intermittent connectivity, and decentralized trust models. Overall, the reviewed publications reflect continuous evolution of distributed databases, consistency models and replication strategies and highlight need for further innovations and research activities.

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All the authors have read and agreed to the published version of the manuscript.

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ПРОБЛЕМА УЗГОДЖЕНОСТІ ТА ВІДПОВІДНІ КОМПРОМІСИ В РОЗПОДІЛЕНИХ РЕПЛІКОВАНИХ СИСТЕМАХ І БАЗАХ ДАНИХ: ОГЛЯД

Джафар Ахмед, Андрій Карпенко, Ольга Тарасюк,
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Розподілені репліковані бази даних відіграють важливу роль у сучасних комп'ютерних системах, уможливаючи масштабоване, стійке до збоїв і високопродуктивне керування даними. Однак досягнення цих якостей вимагає вирішення низки компромісів між різними властивостями під час проектування та експлуатації розподіленої системи. У статті розглядаються компроміси в розподілених реплікованих базах даних і надається огляд останніх наукових публікацій, які вивчають розподілені системи зберігання даних. У статті спочатку обговорюється компроміс між узгодженістю та часовими затримками, який є природним для розподілених реплікованих сховищ даних і безпосередньо впливає з теорем CAP і PACELC. Узгодженість означає

гарантію того, що всі клієнти в розподіленій системі одночасно спостерігають однакові дані. Щоб забезпечити строгую узгодженість, розподілені системи зазвичай використовують механізми координації та протоколи синхронізації, які включають зв'язок і узгодження між розподіленими репліками. Ці механізми обумовлюють додаткові накладні витрати та можуть значно збільшити час, необхідний для виконання операцій, особливо якщо репліки глобально розповсюджені в мережі Інтернет. Крім того, у статті розглянуто компроміси, які існують між іншими властивостями, включаючи доступність, довговічність, вартість, споживання енергії, продуктивність операцій читання та запису тощо. У цій статті ми також надаємо огляд і класифікацію останніх досліджень у галузі розподілених реплікованих баз даних. Проаналізовані статті демонструють кілька основних напрямків досліджень, починаючи від оцінки продуктивності та порівняння різних баз даних NoSQL до пропозиції нових стратегій реплікації даних і запровадження нових моделей узгодженості. Зокрема, спостерігається перехід до вивчення гібридних моделей узгодженості з причинно-наслідковим упорядкуванням завдяки їхній здатності досягти балансу між гарантіями впорядкування операцій і високою продуктивністю. Дослідники також пропонують різні алгоритми контролю узгодженості та протоколи досягнення консенсусу для координації стану розподілених реплік. Висновки цього огляду можуть допомогти практикам приймати обґрунтовані рішення щодо проектування розподілених систем зберігання даних і керування ними, а також визначити подальші напрями актуальних наукових досліджень.

Ключові слова: розподілені бази даних; великі дані, NoSQL; реплікація; узгодженість; затримки; пропускна здатність; готовність; компроміси; CAP; PACELC; огляд.

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