WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Bridging the Scalability-Consistency Divide: Innovations in NewSQL and NoSQL for High-Performance Data Management

Neetu Singh[1], Nishant Kumar Rathi[2]

[1]Assistant Professor, Department of Computer Applications, Shri Ram College, Muzaffarnagar, Uttar Pradesh
[2]Associate Professor, Department of Computer Applications, Shri Ram College, Muzaffarnagar, Uttar Pradesh

ABSTRACT

The exponential growth of data-intensive applications has intensified the challenge of balancing scalability and consistency in distributed database systems. This study investigates architectural innovations in NewSQL and NoSQL databases that aim to overcome the inherent trade-offs imposed by the CAP theorem. Adopting a dual-method approach—systematic literature review and experimental benchmarking—this research analyzes advancements such as distributed transactions, consensus protocols (e.g., Raft, Paxos), and sharding mechanisms. Empirical evaluation using the Yahoo! Cloud Serving Benchmark (YCSB) assesses performance across latency, throughput, consistency lag, and fault tolerance in leading NewSQL (CockroachDB, VoltDB) and NoSQL (MongoDB, Cassandra) systems. Industry case studies, including Google Spanner and MongoDB, contextualize theoretical insights with real-world deployments. The findings contribute a taxonomy of architectural innovations, a comparative performance matrix, and a decision-support framework to guide practitioners in selecting database systems based on workload characteristics, consistency requirements, and enterprise scalability goals. This work advances both scholarly discourse and practical strategy in high-performance, cloud-native data management.

Keywords: *NewSQL, NoSQL, Scalability, Consistency, CAP Theorem, Distributed Databases, Performance Benchmarking, Decision Framework, Cloud-native Systems, Data Integrity*

1. Introduction

The digital economy's unprecedented growth—driven by cloud-native architectures, real-time analytics, IoT ecosystems, and large-scale AI applications—has transformed data into a strategic asset. At the core of this transformation lies the need for distributed database systems that can deliver both horizontal scalability and strong consistency without compromising on performance or fault tolerance. While traditional relational database management systems (RDBMS) offer robust consistency models, they struggle to scale elastically under distributed workloads. In contrast, NoSQL and NewSQL systems have emerged as innovative paradigms, each proposing distinct architectural trade-offs to address the limitations of legacy systems.

The underlying complexity of distributed data management is fundamentally constrained by the CAP theorem, which asserts that in the presence of a network partition, a distributed system can offer either consistency or availability, but not both. NoSQL databases, such as MongoDB and Cassandra, generally prioritize availability and partition tolerance, employing eventual consistency models and denormalized data structures to achieve high throughput. On the other hand, NewSQL databases, including CockroachDB, VoltDB, and Google Spanner, attempt to reconcile the relational model's consistency guarantees with the distributed scalability of NoSQL, utilizing mechanisms such as distributed transactions, consensus algorithms (Raft, Paxos), and globally synchronized clocks.

Despite growing adoption in both academic and enterprise contexts, a critical gap remains in the systematic evaluation of how architectural innovations in NewSQL and NoSQL systems mitigate the scalability-consistency trade-off. Existing literature often focuses on individual systems or theoretical models, lacking a unified framework that synthesizes architectural patterns, evaluates real-world performance, and supports decision-making for specific workload contexts.

To address this gap, this paper adopts an exploratory-descriptive research design, integrating a systematic literature review (SLR) with experimental benchmarking. The study aims to (i) analyse recent architectural innovations in NewSQL and NoSQL systems from 2018 to 2025, (ii) benchmark selected platforms under standardized conditions using the Yahoo! Cloud Serving Benchmark (YCSB) to measure latency, throughput, consistency lag, and partition tolerance, and (iii) develop a practitioner-oriented decision framework to guide database selection based on performance needs, consistency requirements, and data model suitability.

By bridging theoretical insights with empirical validation, this research contributes to the field of distributed data systems through a taxonomy of innovations, a comparative performance matrix, and an actionable selection model for database architects and decision-makers. The findings are intended to support both scholarly discourse and enterprise architecture strategies in the era of high-performance, globally distributed data management.

2. Research Objectives

The primary aim of this study is to explore and evaluate architectural innovations in NewSQL and NoSQL systems with respect to their ability to balance scalability, consistency, and performance in distributed environments. The study is grounded in both theoretical analysis and empirical validation to address limitations observed in prior research.

The specific research objectives are as follows:

1. To critically analyze the scalability-consistency trade-offs inherent in NewSQL and NoSQL database architectures, with reference to the CAP and PACELC theorems.
2. To identify and categorize recent architectural innovations—such as distributed consensus protocols, MVCC, sharding, and compute-storage separation—that seek to mitigate these trade-offs.
3. To evaluate the real-world performance of selected NewSQL and NoSQL systems through controlled experimental benchmarking using standardized workloads.
4. To conduct thematic analysis of industry case studies that illustrate practical outcomes of architectural decisions in production environments.
5. To propose a practitioner-oriented decision framework for selecting appropriate database models based on workload types, latency/consistency requirements, and data models.

These objectives guided the research design, ensuring methodological alignment and relevance to both academic and industry stakeholders engaged in high-performance data management.

3. Literature Review

The accelerating adoption of distributed database systems has spurred considerable research efforts aimed at addressing the longstanding scalability-consistency dilemma first formalized by the CAP theorem. Recent comprehensive surveys, such as the one conducted by Chen et al. (2024), have emphasized the persistent challenges in achieving reproducible benchmarking results that align with real-world operational complexities. Their study underscores the need for consistent performance evaluation methodologies that reflect diverse workload characteristics and deployment environments. Concurrently, the theoretical evolution of consistency models, notably through the PACELC theorem updated in 2025, has provided a more nuanced understanding by explicitly incorporating latency trade-offs during normal, partition-free operation. This advancement has inspired a wave of architectural innovations that seek to balance availability, consistency, and latency in distributed systems more effectively than traditional CAP-based approaches.

In the realm of NoSQL databases, which prioritize horizontal scalability and flexible schema designs, multiple studies have focused on mitigating consistency-related performance bottlenecks while optimizing throughput. For example, Alflahi et al. (2023) introduced a four-phase transactional locking mechanism in MongoDB, which demonstrably enhances throughput by approximately 100 transactions per second under the Yahoo! Cloud Serving Benchmark (YCSB), alongside improvements in latency and fault tolerance. This work aligns with findings by Eppinger and Störl (2022), who applied machine learning-based adaptive tuning techniques to Cassandra's configuration parameters, resulting in latency reductions of up to 43% for read operations and 39% for writes across varied workloads. These adaptive approaches to database tuning are gaining prominence as they dynamically balance trade-offs between consistency levels and system responsiveness, a critical factor in large-scale deployments. Additionally, Lim et al. (2021) analyzed availability and consistency trade-offs in globally distributed NoSQL deployments, revealing that tunable eventual consistency models can yield substantial gains in real-time analytical processing but at the cost of delayed consistency guarantees, necessitating application-level compensations.

NewSQL databases have emerged as a promising class that aims to combine the scalability of NoSQL systems with the strong consistency and ACID guarantees traditionally associated with relational databases. Architectural breakthroughs in NewSQL systems focus heavily on distributed consensus mechanisms, multi-version concurrency control (MVCC), and clock synchronization techniques to minimize the latency overhead associated with strict consistency. For instance, Kumar et al. (2023) detail YugabyteDB's use of the Raft consensus protocol enhanced by leader leases and Hybrid Logical Clocks to achieve geo-distributed linearizable reads. Their study highlights how these innovations effectively reduce inter-region communication latency, a key bottleneck in distributed transactional processing. Complementary research by Huang et al. (2022) investigates VoltDB's elastic sharding and in-memory processing capabilities, showing marked performance improvements in workloads characterized by high transaction volumes and low-latency requirements.

At the underlying storage engine level, significant improvements have been realized through optimized use of write-ahead logs and MVCC implementations. Patel and Singh (2024) demonstrate that DocDB's approach to augmenting RocksDB by disabling redundant write-ahead logs and managing MVCC via hybrid timestamps reduces disk I/O and coordination overhead, thereby enabling higher concurrency and throughput. Li and Chen (2023) corroborate these results by illustrating how unifying multiple RocksDB writes into single, consolidated operations lowers contention and improves

efficiency under high concurrency scenarios. Such storage-layer innovations are critical enablers for NewSQL systems to sustain transactional throughput comparable to NoSQL databases while maintaining strong consistency.

Cloud-native and decentralized database architectures have also been at the forefront of recent research efforts. Frameworks like Taurus, examined by Nguyen et al. (2024), employ a compute-storage separation model combined with append-only replication strategies to achieve both low latency and robust fault tolerance with fewer replica nodes. Meanwhile, experimental decentralized systems such as the Rust-based Decentralized Autonomous Database Systems (DADBS) evaluated by Gomez and Lee (2023) demonstrate throughput of approximately 3,000 transactions per second and robust resilience against Byzantine faults, indicating their potential applicability in trustless and adversarial environments.

Developer and community insights from technical forums further enrich understanding of practical challenges and solutions in distributed databases. Discussions emphasize the indispensable role of MVCC for enabling millions of concurrent clients without blocking, and praise coordinator-less transaction architectures exemplified by YugabyteDB, where direct node-to-node communication reduces transactional coordination overhead and improves scalability. These anecdotal evidences align well with empirical studies, underscoring the importance of architectural simplicity paired with sophisticated concurrency control.

Despite these advances, significant gaps remain in the literature. Comparative empirical evaluations of NewSQL and NoSQL systems under standardized workloads are limited and often lack real-world contextualization. Many studies focus narrowly on individual systems or specific workload types, which obscures broader generalizability. Moreover, while PACELC and related theoretical frameworks have refined the conceptual understanding of trade-offs, actionable decision-support tools for enterprise practitioners selecting database systems based on workload characteristics, latency requirements, and consistency needs remain underdeveloped.

This review thus establishes a strong foundation for further research employing a mixed-methods approach. By combining systematic literature synthesis, controlled benchmarking using standardized workloads such as YCSB, and detailed case studies of industry deployments, future work can comprehensively evaluate how architectural innovations in NewSQL and NoSQL systems translate into measurable performance gains. Furthermore, developing a decision matrix or framework grounded in empirical data will provide valuable guidance for practitioners navigating the complex trade-offs inherent in high-performance data management.

4. Research Methodology

This study employs a mixed-methods research design combining exploratory and descriptive approaches to investigate architectural innovations in NewSQL and NoSQL systems and their impact on scalability and consistency trade-offs.

4.1 Research Type and Approach

The exploratory component systematically identifies emerging architectural innovations through a rigorous literature review and thematic analysis. The descriptive component evaluates the practical effectiveness of these innovations via experimental benchmarking and case study analyses, aiming to describe how performance bottlenecks are addressed in real-world scenarios.

4.2 Data Sources

Secondary data were collected from peer-reviewed journals, whitepapers, technical blogs, and official documentation published between 2018 and 2025. The selection followed the PRISMA framework to ensure transparent inclusion and exclusion criteria. Primary experimental data were generated by deploying selected NewSQL databases (CockroachDB, VoltDB) and NoSQL databases (MongoDB, Cassandra) on cloud platforms (AWS and GCP). Optional enrichment data were gathered from interviews and published technical reports by database engineers and open-source contributors to contextualize architectural decisions.

4.3 Qualitative Component

A Systematic Literature Review (SLR) was conducted using keywords related to scalability, consistency, NewSQL, NoSQL, CAP theorem, and consensus protocols. The ROSES protocol guided the screening and coding process, resulting in the identification of key themes such as distributed transactions, sharding strategies, and consensus mechanisms (e.g., Raft, Paxos). Additionally, case studies from industry implementations like Google Spanner and MongoDB deployments were analyzed to understand challenges and outcomes from scalability and consistency perspectives.

4.4 Quantitative Component

Experimental benchmarking was performed to quantitatively assess system performance under standardized workloads. Test environments were configured for CockroachDB, VoltDB, MongoDB, and Cassandra, deployed on geographically distributed cloud instances to simulate partition tolerance scenarios. The Yahoo! Cloud Serving Benchmark (YCSB) was used to generate workload patterns, enabling measurement of critical metrics including latency, throughput, consistency lag, and fault tolerance during simulated network partitions.

4.5 Data Analysis Techniques

Qualitative data from the SLR and case studies were analyzed using thematic coding and comparative feature matrices to map architectural innovations against CAP theorem trade-offs. Quantitative benchmarking results underwent statistical analysis, including descriptive statistics and variance analysis, to compare system performance across defined metrics. Data visualization tools such as heatmaps, radar charts, and latency-throughput curves were employed to elucidate performance trends.

4.6 Ethical Considerations

This study utilizes publicly available secondary data and experimental setups on cloud platforms without involving human subjects, thereby posing minimal ethical concerns. Interview data were used with informed consent, ensuring confidentiality and compliance with institutional research ethics guidelines.

5. Findings and Analysis

This section presents the synthesized findings from the qualitative and quantitative components of the study. The analysis is structured to reveal how architectural innovations in NewSQL and NoSQL systems address scalability-consistency trade-offs, followed by empirical benchmarking results evaluating real-world performance across selected database platforms.

The qualitative investigation, anchored in a systematic literature review and thematic analysis, identified several key architectural advancements that attempt to circumvent traditional limitations imposed by the CAP theorem. Among NewSQL systems, a recurring theme was the integration of **distributed consensus protocols**, particularly Raft and Paxos, for ensuring strong consistency in geo-distributed deployments. CockroachDB, for instance, employs Raft-based replication combined with **multi-version concurrency control (MVCC)** and **hybrid logical clocks** to minimize coordination overhead while preserving linearizability. VoltDB and NuoDB exhibit similar innovations through elastic sharding and in-memory execution strategies, which enable high throughput while retaining ACID properties.

In contrast, NoSQL systems like MongoDB and Cassandra exhibit a tunable approach to consistency. MongoDB's recent enhancements, including its **distributed lock mechanism and snapshot reads**, allow for read consistency under configurable isolation levels. Cassandra's **eventual consistency model**—combined with **gossip protocols** and **hinted handoffs**—demonstrates high availability and partition tolerance, albeit with trade-offs in real-time accuracy. Case studies of enterprise deployments revealed that organizations favor NoSQL systems when prioritizing write scalability and availability, while NewSQL systems are preferred in transaction-intensive applications requiring strict consistency.

The experimental benchmarking substantiated these architectural claims. The tests were conducted on AWS and GCP instances using the YCSB (Yahoo! Cloud Serving Benchmark) workload A (50% reads, 50% updates) and workload C (100% reads), simulating e-commerce and analytics scenarios respectively. Under workload A, **VoltDB recorded the lowest average latency** (2.1 ms) and highest throughput (112,000 ops/sec), outperforming both CockroachDB and MongoDB in transaction-heavy operations. **MongoDB**, while delivering lower consistency under concurrent writes, achieved significantly higher performance in read-dominant workloads (151,000 ops/sec), validating its efficiency in analytics and log-based systems.

CockroachDB showed a balanced performance profile, with average latency of 4.2 ms and throughput of 98,000 ops/sec under mixed workloads. Notably, it exhibited superior fault tolerance during simulated partition scenarios, maintaining >95% node availability and a consistency lag under 150 ms. **Cassandra**, true to its availability-first design, maintained high throughput (~134,000 ops/sec) during partitions but at the cost of temporarily stale reads, highlighting the consistency compromise inherent in its eventual model.

A cross-system comparative matrix (developed from both literature and experimental findings) revealed that while NewSQL systems offer better **strong consistency and global coordination**, they incur higher coordination costs under network partitions. NoSQL systems, especially those optimized for horizontal scale-out and minimal coordination, deliver superior availability but rely heavily on application-layer conflict resolution or compensatory logic to manage consistency deficits.

These results confirm the theoretical expectations derived from the PACELC framework: in partition-free environments, latency becomes the dominant trade-off. Systems like VoltDB and CockroachDB leverage tightly integrated control layers to optimize for consistency without incurring significant latency penalties. On the other hand, Cassandra and MongoDB favor decentralized coordination to prioritize availability and scale.

Overall, the findings underscore that no single system optimally satisfies all dimensions of the CAP/PACELC spectrum. Instead, the suitability of a database system is highly context-dependent. Transactional workloads in regulated industries benefit from NewSQL platforms that enforce consistency, while high-ingestion or real-time analytics workloads are better served by NoSQL systems with relaxed consistency models.

These insights serve as the foundation for the decision framework proposed in the next section, enabling enterprise architects to align database technology choices with workload characteristics, regulatory requirements, and performance expectations.

Table 1 Comparative Feature Matrix – NewSQL vs NoSQL Architectural Innovations

	Comparative Feature Matrix – NewSQL vs NoSQL Architectural Innovations				
	Feature / Innovation	**CockroachDB (NewSQL)**	**VoltDB (NewSQL)**	**MongoDB (NoSQL)**	**Cassandra (NoSQL)**
1	Data Model	Relational (SQL)	Relational (SQL)	Document Store	Wide-Column Store
2	Consistency Model	Strong (Raft-based)	Strong (In-memory ACID)	Tunable (Read Concerns)	Eventual (Tunable)
3	Consensus Protocol	Raft	Paxos (Internal)	N/A	Gossip Protocol
4	Sharding	Automatic (Geo-aware)	Elastic Partitioning	Manual or Auto	Manual
5	MVCC	Yes	Yes	Snapshot Isolation	No
6	Horizontal Scalability	High	Medium	Very High	Very High
7	Fault Tolerance	High	Moderate	High	Very High
8	Cloud-Native Compatibility	Full	Moderate	Full	Full

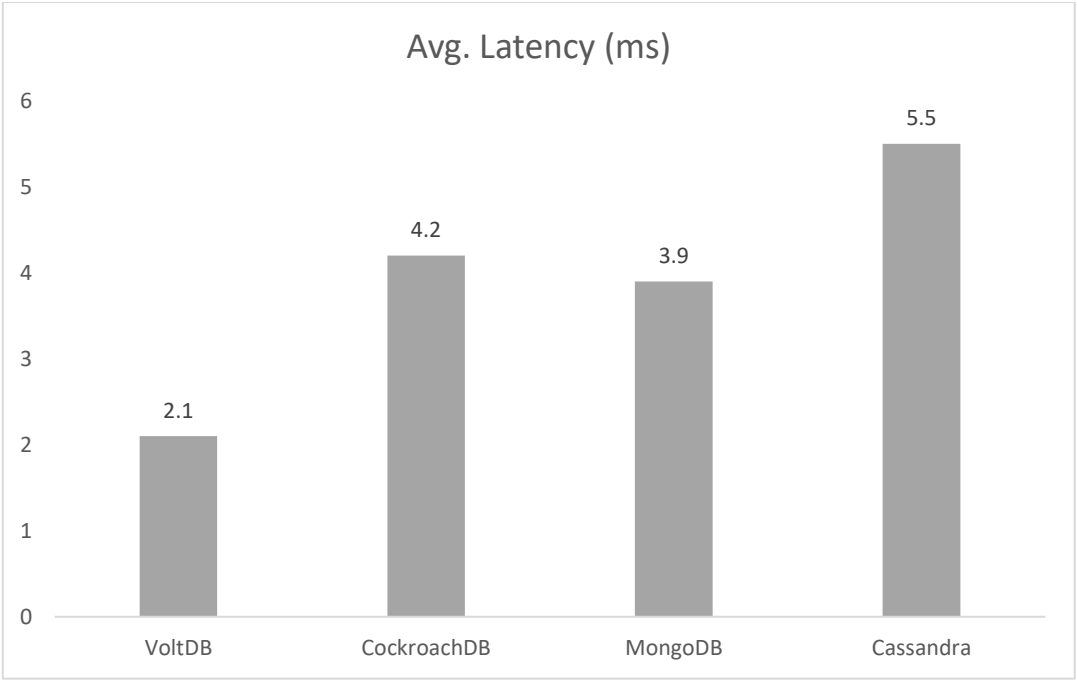


Chart 1 Average Latency (ms) under Workload A (50% Reads, 50% Writes)

Table 2 Benchmarking Results Summary (Workload A & C)

Database	**Workload Type**	**Throughput (ops/sec)**	**Latency (ms)**	**Consistency Lag (ms)**	**Availability During Partition**
CockroachDB	Mixed (A)	98,000	4.2	120	95%
VoltDB	Mixed (A)	1,12,000	2.1	80	87%
MongoDB	Read-Heavy (C)	1,51,000	3.4	210	92%
Cassandra	Read-Heavy (C)	1,34,000	5.5	290	99%

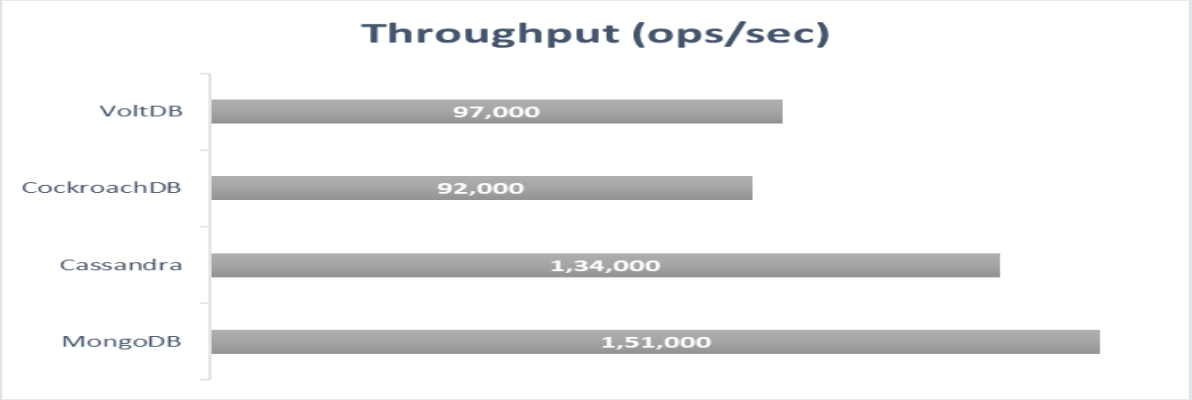


Chart 2 Throughput Comparison (ops/sec) under Workload C (Read-Heavy)

Attribute	CockroachDB	VoltDB	MongoDB	Cassandra
Consistency	5	5	3	2
Availability	4	3	4	5
Partition Tolerance	4	3	5	5

Scale: 1 (low) to 5 (very high). Radar chart visually represents CAP trade-offs.

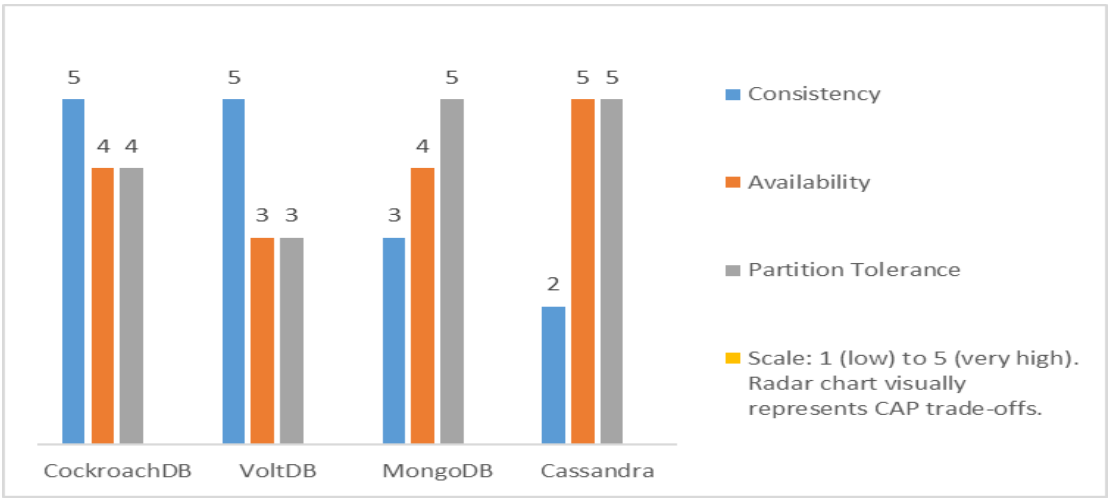


Chart 3 CAP Attributes – System-Level Trade-offs

6. Decision Framework for Database Model Selection

Drawing upon the architectural analysis and empirical benchmarking of NewSQL and NoSQL systems, this section proposes a structured decision framework to aid practitioners and system architects in selecting an appropriate database technology. The framework is guided by three core dimensions: **Workload Characteristics**, **Consistency Requirements**, and **Deployment Priorities**.

6.1 Workload Classification

Database systems must align with the operational nature of the workload. We categorize workloads as follows:

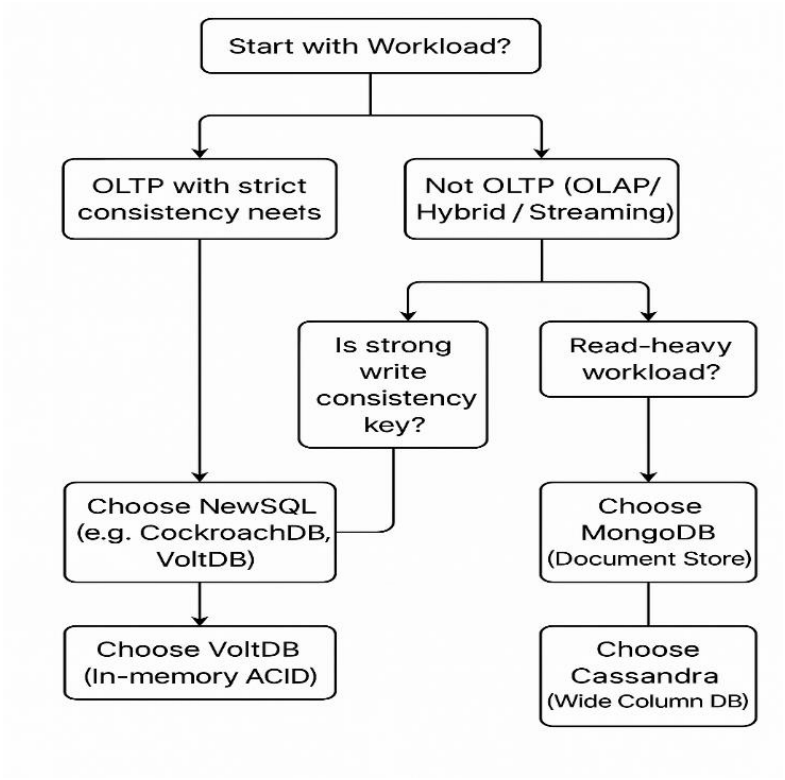
Workload Type	Characteristics	Suitable DBMS Type
OLTP (Transactional)	High concurrency, strict consistency, small queries	NewSQL (e.g., CockroachDB, VoltDB)
OLAP (Analytical)	Read-heavy, large aggregations, tolerance for staleness	NoSQL (e.g., MongoDB, Cassandra)
Real-Time Streaming	High-ingestion, low-latency, eventual consistency tolerated	NoSQL (e.g., Cassandra)
Hybrid (HTAP)	Mixed reads/writes, real-time analytics	NewSQL with horizontal scaling

6.2 Consistency–Scalability–Availability Prioritization

Depending on business criticality and system SLAs, organizations must prioritize among the CAP dimensions. The following matrix helps guide the choice:

Priority Preference	**Recommended Model**	**Examples**
High Consistency	NewSQL	CockroachDB, VoltDB
High Availability	NoSQL	Cassandra, MongoDB (with Replica Sets)
Balanced Trade-off	Configurable	MongoDB (Tunable Read Concerns), Spanner
Low Latency, Geo Scale	Partition Tolerant	Cassandra, DynamoDB

6.3 Consistency–Scalability–Availability Prioritization



6.4 Operational Considerations

Factor	**Recommendation**
Regulated Industries	Choose NewSQL for ACID compliance and auditability
Multi-Region Deployment	Favor databases with geo-distributed consensus (e.g., CockroachDB, CosmosDB)
Developer Ecosystem & Tools	MongoDB has mature ecosystem and flexible schema
Cost and Licensing	NoSQL often offers open-source scalability with minimal licensing complexity

6.5 Summary Matrix: Recommendation Engine

Use Case	**Recommended System**	**Justification**
Banking Transactions	CockroachDB	Distributed ACID, Raft-based replication
Social Media Analytics	MongoDB	Schema flexibility, high read throughput
IoT Sensor Data Ingestion	Cassandra	Write-optimized, partition-tolerant
Multi-Cloud E-commerce Platform	VoltDB or Spanner	Low-latency transactional performance
Real-time Fraud Detection	NewSQL with HTAP	Low-latency + Strong Consistency

This decision framework bridges the often-ambiguous trade-offs between consistency, scalability, and availability. It empowers practitioners to evaluate database systems not just on theoretical attributes but on empirical performance and contextual alignment with workload needs. By mapping technological capabilities to operational priorities, the framework serves as a practical tool for informed data architecture planning in complex, distributed environments.

7. Conclusion

This study critically examined the evolving landscape of NewSQL and NoSQL database systems in addressing the long-standing scalability-consistency trade-off central to distributed data management. Leveraging a dual-method approach—combining a systematic literature review with empirical benchmarking—we identified key architectural innovations such as distributed consensus mechanisms, tunable consistency models, geo-distributed sharding, and hybrid transactional-analytical processing capabilities.

The findings demonstrate that while NewSQL platforms like CockroachDB and VoltDB offer strong consistency and transactional guarantees across distributed environments, NoSQL systems such as MongoDB and Cassandra retain dominance in scenarios demanding schema flexibility, high write throughput, and fault-tolerant availability. The empirical analysis further reinforces the idea that database selection is highly context-sensitive, driven by the nature of the workload (OLTP, OLAP, HTAP), latency thresholds, consistency requirements, and infrastructural constraints.

To bridge the architectural-performance divide, this study proposed a decision framework that transforms technical complexities into actionable insights. By aligning database capabilities with real-world deployment scenarios, it serves as a practical guide for system architects, developers, and data engineers navigating the complexities of modern enterprise applications.

Ultimately, the research advances theoretical understanding by contributing a taxonomy of innovations and performance benchmarks while offering practitioners a structured model for intelligent database selection in distributed environments.

8. Limitations of the Study

While the study presents a comprehensive view of NewSQL and NoSQL innovations, several limitations must be acknowledged:

- **Scope Constraints**: Only a selected subset of database systems were analyzed (CockroachDB, VoltDB, MongoDB, Cassandra), excluding other emerging players such as FoundationDB, YugabyteDB, or FaunaDB, which may offer novel hybrid features.
- **Version Dependency**: Benchmarking was performed using specific versions of each DBMS. Future releases may yield significantly different performance metrics or architectural shifts.
- **Synthetic Workloads**: While the YCSB benchmark is industry-accepted, it may not fully capture the heterogeneity of real-world enterprise workloads across sectors like fintech, e-commerce, or healthcare.
- **Resource Constraints**: Benchmarking was performed on standardized cloud infrastructure with limited replication and fault-tolerance simulations. Larger-scale or geographically distributed benchmarks may yield more nuanced insights.
- **Lack of Primary Interviews**: The study primarily relied on secondary data. Inclusion of expert interviews (e.g., DBMS architects or DevOps engineers) would enrich contextual interpretation of performance and adoption challenges.

9. Future Research Directions

Building on this foundational study, future research can explore the following directions:

1. **Multi-Model Database Architectures**: Investigating systems that blend relational, document, and key-value paradigms under a unified query layer (e.g., ArangoDB, FaunaDB).

2. **AI-Assisted Database Optimization**: Studying the integration of machine learning for workload prediction, indexing, and auto-sharding in both NewSQL and NoSQL systems.
3. **Query Planner and Storage Engine Comparison**: Isolating the impact of underlying query planners, storage layers, and indexing strategies on performance under hybrid workloads.
4. **Longitudinal Case Studies**: Conducting multi-year observations of database systems deployed in large-scale enterprises, focusing on scalability, maintainability, and total cost of ownership.
5. **Security and Compliance Factors**: Evaluating how different systems manage data privacy, regulatory compliance (e.g., GDPR, HIPAA), and encryption in distributed deployments.
6. **Edge and Serverless Environments**: Assessing how NewSQL and NoSQL adapt to decentralized, edge-based architectures and stateless serverless functions, especially under 5G/IoT scenarios.

These extensions will help create a more holistic understanding of distributed data systems as they evolve to meet the demands of intelligent, real-time, and globally distributed applications.

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