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(Review Article)

Innovations in real-time trade execution: database speed, latency and resilience

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Abstract

This comprehensive article examines the technological foundations that enable real-time trade execution in modern financial markets, where performance is measured in microseconds and nanoseconds. The article delves into the sophisticated database architectures that support high-frequency trading environments, highlighting how memory-first designs, zero-copy data streaming, and concurrent write optimization techniques have revolutionized execution speed and market structure. It analyzes how these database innovations directly impact profitability through reduced latency and increased throughput while maintaining the strict consistency guarantees essential for financial transactions. The article extends to distributed replication technologies that enable synchronized order books across geographically dispersed trading venues, creating new capabilities for cross-market strategies. The article further examines emerging technologies including quantum computing applications, photonic interconnects, and computational storage that represent the next frontier in trading infrastructure. Throughout, the article emphasizes the symbiotic relationship between database technology innovation and market evolution, where technological capabilities continuously reshape trading strategies and market structures.

Keywords: High-Frequency Trading; In-Memory Databases; Zero-Copy Architecture; Concurrency Control; Distributed Replication

1. Introduction

In the high-stakes arena of financial trading, technology battles are won or lost in microseconds. Modern financial markets operate at speeds that would have seemed impossible just a decade ago, with trading platforms executing millions of transactions per second across global exchanges. At the heart of this technological arms race lies database technology the often-overlooked foundation that enables the millisecond-critical operations driving today's markets.

The evolution of trading technology has progressed dramatically over recent years, transforming execution speeds and market structure. Contemporary trading systems now routinely process market data with latencies measured in microseconds rather than milliseconds, representing orders of magnitude improvement from earlier generations of technology. This transformation has enabled sophisticated algorithmic trading strategies that depend on rapid data processing and execution capabilities. Market microstructure research has demonstrated that these technological advances have fundamentally altered market dynamics, including price discovery processes, liquidity provision mechanisms, and the nature of market making activities across global exchanges.

The financial implications of advanced database technologies in trading environments extend beyond simple execution speed advantages. Research examining high-frequency trading practices has revealed that technological sophistication creates significant economic advantages for market participants. Researchers investigating market microstructure have documented how speed differentials between market participants influence trading outcomes and market efficiency. Studies published in the Journal of International Financial Markets, Institutions and Money have explored how the

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interplay between algorithmic trading systems and database infrastructure impacts market quality metrics including bid-ask spreads, market depth, and price efficiency during both normal and stressed market conditions [1].

The economic incentives driving technological innovation in trading systems are substantial. A comprehensive analysis published in the Quarterly Journal of Economics has examined the theoretical and practical implications of the "arms race" for trading speed. This research presents a compelling economic framework that explains why continuous limit order book markets naturally produce strong incentives for speed competition among traders. The work explores how microscopic time advantages translate into meaningful economic advantages through mechanisms including latency arbitrage opportunities that exist in fragmented markets. These speed-driven advantages create what economists characterize as a positional externality that motivates continued investment in faster database and execution technologies [2].

The architecture supporting modern trading platforms has evolved significantly to meet these performance demands. Trading database systems increasingly employ memory-first designs with specialized data structures optimized for concurrent access patterns. These systems utilize techniques including non-blocking algorithms, lock-free data structures, and custom memory management to minimize contention in high-throughput scenarios. Leading implementations leverage hardware-specific optimizations including NUMA-aware memory allocation, CPU cache-conscious data layouts, and direct mapping of market data structures to specialized networking hardware. These architectural approaches allow systems to maintain consistency guarantees while processing millions of market data updates per second with sub-microsecond internal latencies.

The networking infrastructure connecting these database systems has similarly transformed. Modern trading networks employ field-programmable gate arrays (FPGAs) and application-specific integrated circuits (ASICs) to process market data with deterministic latency profiles. These specialized hardware components integrate with memory-mapped communication mechanisms that minimize context switching and interrupt handling overhead. The resulting data pipelines enable market data to flow from exchange gateways into trading database systems with end-to-end latencies measured in single-digit microseconds during normal operations.

This technological foundation powers the millisecond-critical operations driving contemporary financial markets. The database systems at the core of this infrastructure continue to evolve, incorporating innovations from distributed systems research, memory architecture advances, and specialized hardware acceleration techniques. These systems represent the cutting edge of database technology, operating at performance levels that push the boundaries of what's possible with current computing paradigms.

2. The Millisecond Imperative

For high-frequency trading firms and major financial institutions, latency isn't just a technical metric—it's directly correlated with profitability. In modern financial markets, the relationship between execution speed and trading outcomes has become increasingly quantifiable, with empirical research demonstrating clear economic advantages for participants with superior technology infrastructure. Advanced market monitoring systems have documented trading environments where competitive advantages are measured in microseconds or even nanoseconds, fundamentally altering the competitive landscape for market participants across asset classes.

The economic value of latency reduction has been thoroughly examined in contemporary trading literature. Industry analysts have demonstrated that low-latency trading encompasses any strategy relying on speed advantages to capitalize on market inefficiencies. These approaches require sophisticated infrastructure connecting traders directly to exchanges with minimal delay, enabling execution speeds measured in microseconds rather than milliseconds. Technical evaluations highlight how each component in the trading stack—from network connections to server hardware and software configurations—must be optimized to achieve competitive performance. As market participants continue to invest in technology infrastructure, minimum viable latency thresholds have steadily decreased across all major markets. These developments have created an environment where trading firms must continuously upgrade their database technologies and execution systems to maintain competitive positioning in time-sensitive trading strategies [3].

This speed imperative has fundamentally reshaped the regulatory frameworks governing algorithmic trading activities. Comprehensive regulatory technical standards have been established to address the risks associated with high-speed algorithmic trading systems. These standards mandate specific testing and governance requirements for trading algorithms and electronic trading systems. Regulatory frameworks require trading firms to implement robust controls that ensure their automated systems cannot create disorderly market conditions or operate contrary to the rules of trading venues. These regulations specifically address the need for pre-trade risk controls, real-time monitoring systems, and post-trade verification procedures. The regulatory standards further require that systems be designed with appropriate technical and operational safeguards to handle peak message volumes and maintain operational resilience under stressed market conditions. These requirements directly influence database system design decisions, particularly regarding capacity management, exception handling procedures, and failover capabilities [4].

The millisecond imperative extends beyond simple database query performance, encompassing the entire trade execution lifecycle. Contemporary trading platforms integrate specialized hardware, custom networking protocols, and purpose-built database technologies to minimize latency across every component of the execution pathway. These systems employ techniques including kernel bypass networking, remote direct memory access (RDMA), and field-programmable gate array (FPGA) accelerated data processing to reduce end-to-end latency. The most advanced implementations utilize co-located servers with direct exchange connectivity, custom application-specific integrated circuits (ASICs) for market data processing, and memory-mapped communication channels between system components. This technological foundation enables leading high-frequency trading firms to consistently achieve round-trip execution times measured in single-digit microseconds during normal market conditions.

The pursuit of latency reduction has catalyzed innovation across multiple technology domains, with specialized database systems playing a central role in this evolution. These innovations include memory-optimized data structures designed specifically for market data processing, novel concurrency control mechanisms that minimize contention in high-throughput scenarios, and sophisticated query optimization techniques tailored to common trading algorithm patterns. The resulting systems represent the cutting edge of database technology, incorporating advances in computer architecture, networking protocols, and distributed systems design to achieve performance characteristics that would have seemed impossible just a decade ago.

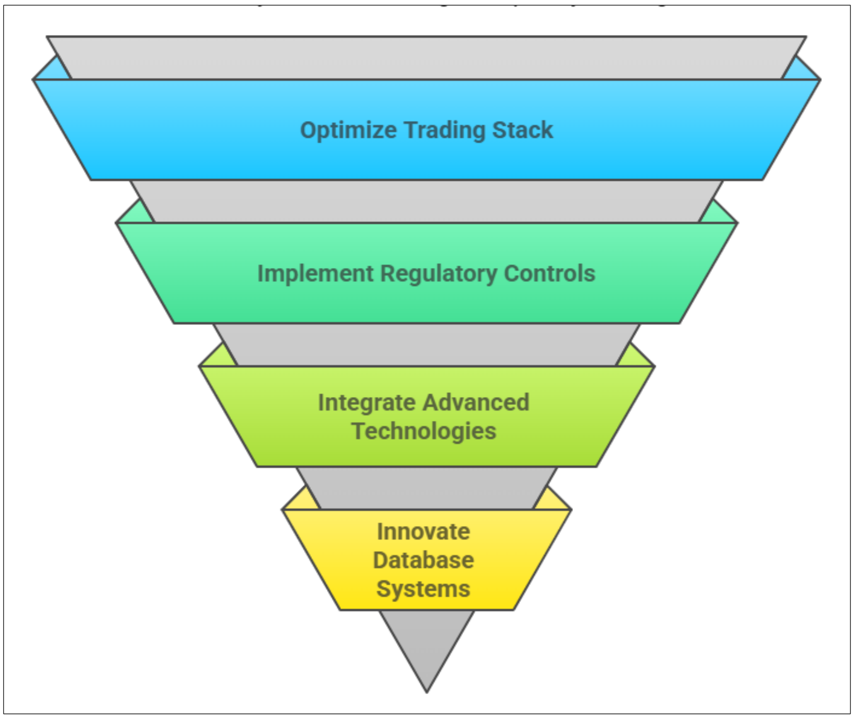

Figure 1 Latency Reduction in High-Frequency Trading [3, 4]

3. Memory-First Architecture: Breaking the Storage Bottleneck

Traditional disk-based database systems face fundamental physical limitations in read/write speeds. Modern trading platforms have largely migrated to memory-first architectures that maintain primary datasets entirely in DRAM, with disk relegated to persistence and recovery functions. This architectural transition represents one of the most significant developments in trading infrastructure over the past decade, enabling performance characteristics that would be physically impossible with conventional storage technologies.

The transition to memory-first architectures has been driven by the inherent physical constraints of mechanical storage systems. Comprehensive surveys of in-memory big data management and processing technologies have identified the fundamental advantages of memory-centric designs in latency-sensitive applications. These analyses document how in-memory database systems (IMDS) consistently outperform disk-based alternatives across multiple performance dimensions, with particular advantages in transaction processing scenarios requiring minimal latency. The research specifically examines how in-memory systems handle concurrent access patterns characteristic of trading applications, where thousands of processes may simultaneously require access to shared market data structures. These systems incorporate sophisticated memory management techniques including custom allocators, pointer swizzling mechanisms, and hardware-conscious data layouts that minimize memory access latency. The performance advantages are particularly pronounced in trading scenarios involving complex join operations and analytical queries that would require costly disk I/O operations in traditional architectures [5].

Memory-first systems typically employ sophisticated data structures optimized for parallel access patterns and concurrent operations. Technical documentation and architectural analyses of production in-memory database implementations have revealed how these systems achieve exceptional performance through specialized data organization techniques. Leading commercial implementations organize data in hybrid formats that combine the advantages of both row and column storage models. These architectures frequently employ dual-format approaches where data is maintained in both traditional row format for transaction processing and compressed columnar format for analytical operations. The columnar structures enable advanced optimization techniques including SIMD vector processing, single-instruction processing of multiple column values, and predicate evaluation pushdown that dramatically improve query performance. These architectural approaches are particularly valuable in trading systems that must simultaneously support both high-volume transaction processing and complex analytical queries for risk assessment and strategy optimization [6].

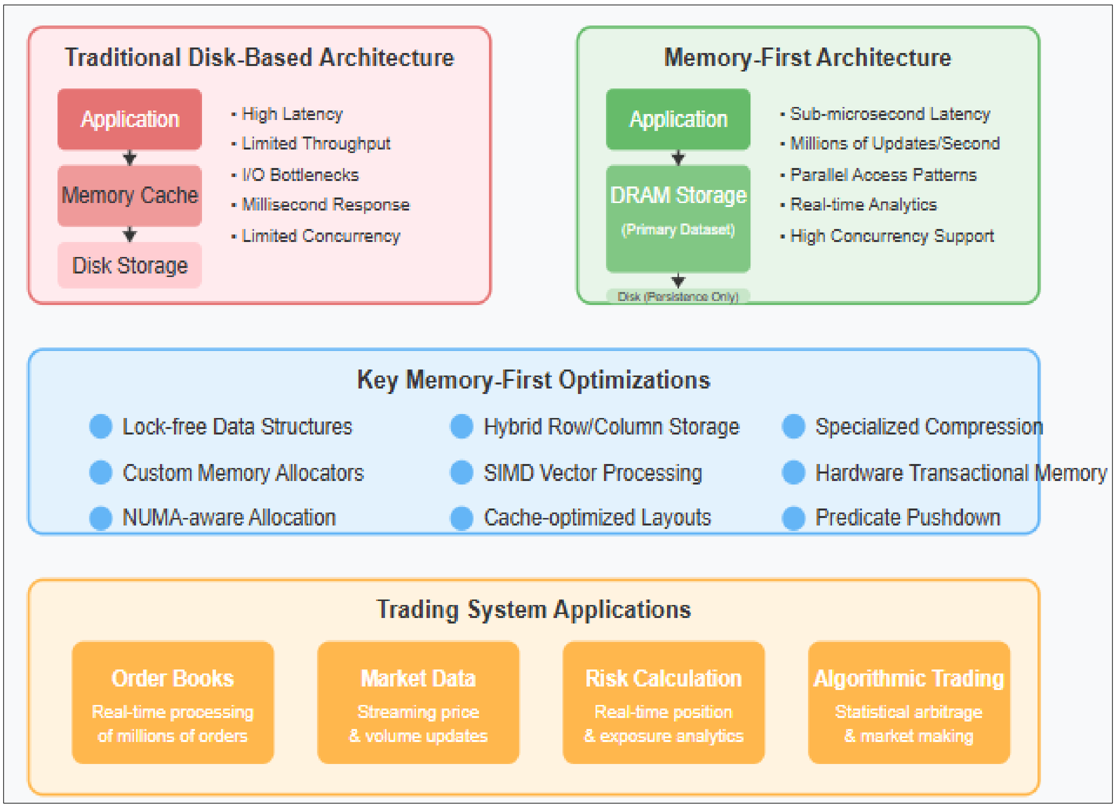

Figure 2 Memory First Architecture in Trading Systems [5, 6]

The adoption of memory-first architectures has transformed the operational characteristics of trading systems across global markets. Contemporary trading platforms now routinely maintain complete order books, position inventories, and market data histories in memory for immediate access. These systems achieve consistent sub-microsecond internal latencies while processing millions of updates per second during normal market conditions. The performance envelope has expanded to the point where leading implementations can complete complex risk calculations, determine optimal order parameters, and execute transactions within microseconds of receiving market data updates. This performance profile enables sophisticated trading strategies including statistical arbitrage, market making, and high-frequency directional trading that would be impossible with traditional disk-based architectures.

The in-memory database systems supporting modern trading platforms incorporate numerous technical innovations beyond simple storage medium changes. These systems employ specialized compression techniques that maximize effective memory capacity while maintaining decompression performance compatible with latency requirements. They implement sophisticated memory management strategies including NUMA-aware allocation, large page support, and cache-optimized data layouts that minimize CPU stalls during critical processing. The most advanced implementations further leverage hardware features including transactional memory, vector processing extensions, and specialized memory controllers to achieve performance characteristics that approach theoretical hardware limits.

4. Zero-Copy Data Streaming: Eliminating Transfer Overhead

Traditional data pipelines incur significant overhead through repeated serialization, deserialization, and memory copying as data moves between system components. Zero-copy architectures eliminate these inefficiencies by allowing different processes to access the same memory regions without duplicating data. This architectural approach has proven particularly valuable in trading systems, where minimizing data transfer overhead directly translates to improved execution latency.

The technical foundations of zero-copy architectures have been extensively examined in systems research literature. Groundbreaking research on protected dataplane operating systems has demonstrated how specialized system architectures can achieve exceptional performance for network-intensive applications. These studies document how conventional operating systems introduce substantial overhead through context switching, interrupt processing, and buffer management operations. By implementing a specialized dataplane operating system that provides direct access to hardware resources, researchers have demonstrated dramatic performance improvements for networked applications. Experimental evaluations have shown how these architectures achieve up to 10x higher throughput and 18.2x lower latency compared to conventional implementations when processing high-volume network traffic. These performance characteristics are directly applicable to trading systems that must process market data feeds with minimal latency while maintaining strict security and isolation guarantees. The architectural principles established in this research have influenced the design of numerous high-performance trading systems that employ similar dataplane separation techniques to minimize processing overhead [7].

In practice, implementing zero-copy architectures requires sophisticated technological approaches spanning both hardware and software domains. Seminal research on parallel software routers has established fundamental techniques for high-performance packet processing that have been widely adopted in trading system design. This work demonstrates how general-purpose multi-core processors can achieve network processing performance previously possible only with specialized hardware. The research specifically examines how parallel processing techniques, memory access patterns, and inter-core communication mechanisms influence overall system performance under high packet rates. Experimental evaluations document how these architectures can achieve packet processing rates exceeding 35 Gbps using commodity hardware, with linear scaling as additional processing cores are added. These techniques have been adapted for market data processing in trading systems, where similar parallelization approaches enable platforms to handle extreme message volumes during market volatility events. The research further establishes design principles for memory management and inter-process communication that minimize overhead in data-intensive applications, directly applicable to zero-copy implementation in trading infrastructure [8].

The performance impact of zero-copy architectures extends beyond simple latency reduction to encompass broader system efficiency improvements. By eliminating redundant copy operations, these systems substantially reduce memory bandwidth consumption, a critical resource in high-throughput trading applications. The reduced CPU overhead similarly allows more computational resources to be directed toward core trading functions including strategy evaluation, risk assessment, and order generation. These efficiency improvements enable trading systems to process higher message volumes without proportional increases in hardware requirements, creating both operational and economic advantages for trading firms employing these technologies.

Modern trading platforms increasingly combine zero-copy architectures with complementary technologies to achieve comprehensive performance improvements. These integrated approaches combine kernel bypass networking, shared memory interprocess communication, and hardware-accelerated processing to minimize latency across the entire trade execution pathway. The most sophisticated implementations employ specialized hardware including field-programmable gate arrays (FPGAs) and application-specific integrated circuits (ASICs) that implement critical data transformation functions in hardware, further reducing processing overhead. These technologies collectively enable leading trading systems to maintain end-to-end latencies measured in single-digit microseconds even under extreme load conditions, creating meaningful competitive advantages in time-sensitive trading strategies.

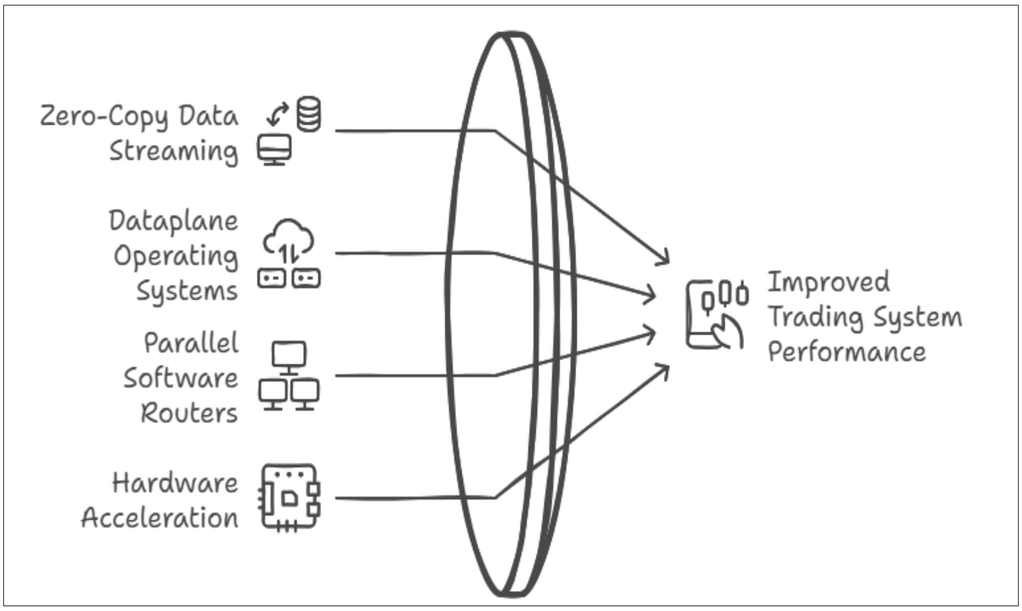

Figure 3 Achieving Peak Trading Performance [7, 8]

5. Concurrent Write Optimization: Beyond Traditional ACID

Trading databases face the dual challenge of requiring both absolute consistency and extraordinary throughput for write operations. Traditional ACID (Atomicity, Consistency, Isolation, Durability) implementations often create contention points that limit scaling. This fundamental tension between consistency requirements and performance objectives has driven significant innovation in database concurrency control mechanisms for trading applications.

The evolution of concurrency control mechanisms in transaction processing systems has been extensively documented in database research literature. Groundbreaking research on fast serializable multi-version concurrency control for main-memory database systems has established fundamental techniques that dramatically improve transaction processing performance. This work presents a sophisticated approach that combines precision locking with optimistic validation to minimize contention in high-throughput scenarios. The researchers introduce innovative techniques including a hybrid timestamp allocation mechanism that eliminates centralized bottlenecks, a precision locking scheme that minimizes false conflicts, and optimized version management that reduces overhead for both readers and writers. Experimental evaluations demonstrate how these techniques enable main-memory database systems to process more than 100,000 transactions per second while maintaining serializable isolation guarantees—the strictest ACID compliance level. This performance profile is particularly significant for trading systems that must combine high throughput with absolute consistency guarantees to maintain transactional integrity across distributed operations. The architectural principles established in this research have been widely adopted in modern trading platforms that employ similar hybrid concurrency control mechanisms to achieve exceptional performance while maintaining strict correctness guarantees [9].

Modern trading databases increasingly incorporate innovative storage engine designs that fundamentally rethink write processing mechanisms. Seminal research on log-structured merge trees has established architectural patterns that remain foundational in contemporary high-performance database systems. This pioneering work describes how log-structured merge trees maintain multiple component data structures organized in a hierarchical structure, with recent updates stored in memory-resident components that periodically merge with larger disk-resident structures. The architecture specifically addresses the performance challenges of maintaining indexes in write-intensive applications by transforming random access patterns into sequential operations that align with storage device characteristics. The researchers analyze how this approach dramatically improves write throughput while maintaining acceptable read performance through techniques including bloom filters and fractional cascading. The work further examines how these structures can be optimized for specific workload characteristics through careful tuning of component sizes, merge policies, and compaction strategies. These architectural approaches have proven particularly valuable in market data systems that must capture high-volume update streams while supporting efficient queries across both recent and historical data a common requirement in algorithmic trading applications [10].

Beyond these architectural innovations, trading database systems employ numerous complementary techniques to optimize write performance while maintaining consistency guarantees. Hardware transactional memory (HTM) implementations leverage specialized CPU features to support speculative execution of transactions, committing results only when conflict detection mechanisms verify operation safety. Advanced timestamp management strategies including hybrid logical clocks and timestamp oracle services enable globally consistent ordering without centralized synchronization points. Sophisticated partitioning schemes direct transactions to specific processing nodes based on data affinity patterns, minimizing cross-partition operations that would require distributed coordination. These technologies collectively enable trading systems to achieve remarkable performance characteristics while maintaining the strict consistency guarantees required for financial applications.

The impact of these concurrent write optimization techniques extends beyond simple throughput improvements to encompass broader system capabilities. By minimizing contention in write processing, these architectures enable trading systems to maintain consistent performance even during extreme market conditions where transaction volumes can spike by orders of magnitude. The reduced coordination overhead similarly enables more sophisticated transaction processing models that support complex multi-step trading operations while maintaining atomicity guarantees. These capabilities create meaningful competitive advantages for trading firms that can execute complex strategies with minimal latency, particularly during volatile market conditions where execution speed directly impacts trading outcomes.

6. Real-Time Replication: Distributed Order Books

Market fragmentation and regulatory requirements have driven the need for distributed databases that maintain consistent views across multiple locations. Synchronized order books across exchange points are now commonplace, requiring sophisticated replication techniques. This distributed data management challenge has become increasingly critical as trading operations expand across global markets with stringent consistency requirements.

The evolution of consensus algorithms for latency-sensitive financial applications has been extensively documented in distributed systems research. Comprehensive analyses of practical consensus implementations have examined how systems optimize replication protocols for the specific requirements of trading applications. These studies document how conventional consensus implementations often prioritize throughput over latency, creating performance characteristics incompatible with trading applications that require both strong consistency and microsecond-scale responsiveness. The research specifically explores optimization techniques including leader lease management, streamlined commit protocols, and network-aware quorum selection that substantially reduce commit latency in distributed environments. Experimental evaluations demonstrate how these optimized implementations achieve consensus latency measured in single-digit milliseconds even in geographically distributed deployments spanning multiple regions. These performance characteristics are particularly valuable for trading systems that must maintain consistent order book views across execution venues while supporting sub-millisecond trading decisions. The architectural approaches established in this research have influenced numerous commercial database systems that provide strong consistency guarantees with performance characteristics suitable for distributed trading applications [11].

Modern trading platforms increasingly employ sophisticated techniques from distributed systems research to maintain consistency across geographically dispersed operations. Detailed technical analyses have examined how conflict-free replicated data types (CRDTs) provide mathematical guarantees regarding eventual consistency without requiring synchronous coordination between replicas. These studies document how CRDTs enable distributed systems to progress independently while automatically resolving conflicts through well-defined merge operations, dramatically reducing coordination overhead compared to traditional replication approaches. The research specifically explores specialized CRDT implementations for financial data structures including order books, position inventories, and trading limits that maintain both consistency guarantees and performance characteristics compatible with trading applications. Experimental evaluations demonstrate how these implementations achieve update latencies measured in microseconds for local operations while guaranteeing eventual global consistency without explicit coordination. These properties make CRDT-based architectures particularly valuable for multi-region trading operations that must maintain global consistency while providing minimal latency for local operations—a common requirement in follow-the-sun trading environments [12].

Beyond these fundamental techniques, modern trading platforms employ numerous complementary technologies to optimize distributed data management. Gossip-based protocols distribute updates across replicas using epidemic communication patterns that prioritize trading-critical information, ensuring rapid convergence for market-sensitive data while managing communication overhead. Hybrid logical clock implementations combine physical and logical timestamping to establish globally consistent event ordering without requiring synchronized clocks across regions, addressing a fundamental challenge in distributed trading systems. Sophisticated network routing overlays dynamically adjust replication pathways based on observed network conditions, optimizing replication latency even as underlying infrastructure performance fluctuates. These technologies collectively enable trading systems to maintain consistency guarantees across distributed environments while providing performance characteristics compatible with latency-sensitive trading operations.

The impact of these distributed replication techniques extends beyond simple consistency maintenance to enable sophisticated cross-regional trading strategies. By providing consistent views across geographically dispersed locations, these systems enable trading firms to identify and exploit market inefficiencies that exist between different venues. The reduced coordination overhead similarly allows more complex, multi-venue transaction patterns that would be impractical with conventional replication approaches. These capabilities create meaningful competitive advantages for trading firms that can execute coordinated strategies across global markets with minimal latency, particularly during market conditions where regional variations create temporary arbitrage opportunities.

7. The Quantum Horizon: What's Next for Trading Databases

As current technologies approach fundamental physical limits, research is already underway on the next generation of database systems for trading applications. Quantum computing applications for specific portfolio optimization problems are in early experimentation phases, though general-purpose quantum databases remain theoretical. This emerging technological frontier presents both challenges and opportunities for the future evolution of trading infrastructure.

The potential application of quantum computing technologies to financial problems has been extensively examined in research literature. Comprehensive analyses have explored how quantum algorithms might address computational challenges in portfolio optimization, risk assessment, and market simulation that remain intractable for classical computing approaches. These studies document how quantum optimization algorithms including quantum approximate optimization algorithm (QAOA) and quantum annealing techniques could potentially solve complex portfolio construction problems with exponentially lower computational requirements than classical alternatives. The research specifically investigates how these approaches might be applied to practical trading scenarios including optimal execution strategies, risk-constrained portfolio rebalancing, and derivative pricing models. Experimental evaluations using current quantum computing platforms demonstrate promising results for small-scale problem instances, though significant technological advances will be required before these approaches can be applied to production trading systems. These investigations nevertheless provide valuable insights into how quantum computing might eventually transform specific components of trading infrastructure, particularly for computationally intensive optimization problems currently addressed through approximation techniques [13].

While quantum computing applications remain largely experimental, more immediately applicable innovations are advancing rapidly toward practical deployment in trading systems. Detailed technical analyses have examined how emerging photonic interconnect technologies promise to revolutionize data movement in distributed computing environments. These studies document how silicon photonics and integrated optical communication systems achieve dramatic reductions in both latency and power consumption compared to conventional electronic interconnects. The research specifically explores how these technologies enable inter-node communication with latencies measured in nanoseconds rather than microseconds, representing order-of-magnitude improvements over current interconnect technologies. Experimental evaluations demonstrate how these photonic systems achieve bandwidth exceeding multiple terabits per second while maintaining consistent sub-100 nanosecond latencies even under extreme load conditions. These performance characteristics make photonic interconnects particularly valuable for distributed trading systems that require minimal communication latency between processing nodes, especially in applications including distributed order matching, cross-venue arbitrage, and synchronized risk assessment that depend on rapid inter-node coordination [14].

Beyond these emerging hardware technologies, numerous software innovations promise to reshape trading infrastructure in the near future. Computational storage architectures move processing capabilities directly onto storage devices, enabling filtering, aggregation, and transformation operations to occur without moving data to central processors. These approaches dramatically reduce both latency and bandwidth requirements for operations on large datasets, particularly valuable for historical market data analysis and backtesting applications. Domain-specific languages designed specifically for trading applications enable higher-level expression of trading algorithms, with compilation pipelines that generate optimized database queries and processing operations tailored to specific runtime environments. These technologies collectively represent the next evolutionary wave for trading infrastructure, building upon the foundational capabilities already established in current systems.

The continual evolution of trading database technologies reflects broader innovation patterns within both technology and financial markets. As technological capabilities advance, trading strategies and market structures similarly evolve to leverage these new possibilities. This symbiotic relationship drives ongoing investment in cutting-edge database technologies that might initially appear excessive but quickly become essential competitive requirements as adoption spreads. The future will likely see continued acceleration of this innovation cycle, with emerging technologies including neuromorphic computing, programmable networks, and novel non-volatile memory architectures potentially reshaping trading infrastructure in ways that remain difficult to fully anticipate.

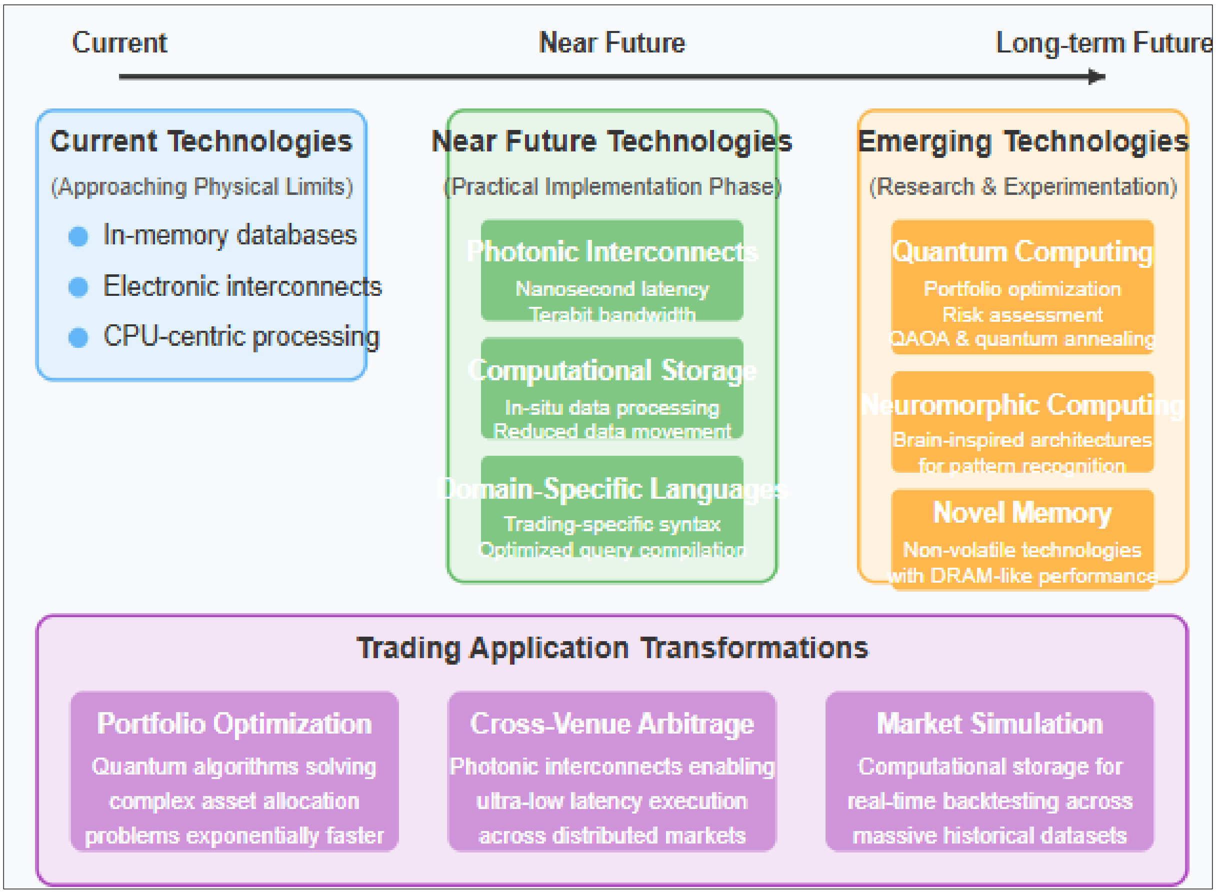

Figure 4 The Quantum Horizon: Next Generation Trading Database Technologies [13, 14]

8. Conclusion

The relentless pursuit of speed and resilience in financial trading continues to drive database innovation. What begins as specialized technology for trading applications frequently finds wider application across other industries with similar demands. As distributed ledger technologies and decentralized finance grow in importance, many of these same innovations are being adapted to solve similar challenges in new contexts. In this environment, the competitive advantage belongs to those who can most effectively leverage database technology not just as infrastructure, but as a strategic asset in the quest for trading performance. The millisecond imperative remains, and the technological response continues to evolve.

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