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ОПТИМИЗАЦИЯ ХЭШ-ФУНКЦИЙ ДЛЯ СИСТЕМ ОБРАБОТКИ ДАННЫХ В РЕЖИМЕ РЕАЛЬНОГО ВРЕМЕНИ

OPTIMIZATION OF HASH FUNCTIONS FOR REAL-TIME DATA PROCESSING SYSTEMS

Аннотация. *В статье рассматривается проблема производительности хэш-функций в системах обработки данных реального времени. Предложен метод оптимизации классических хэш-функций путем адаптивного выбора параметров на основе статистических характеристик входных данных. Проведено экспериментальное исследование, показавшее повышение скорости обработки на 23-41% при сохранении низкого уровня коллизий. Результаты подтверждают эффективность предложенного подхода для высоконагруженных приложений.*

Ключевые слова: *хэш-функции, структуры данных, оптимизация производительности, системы реального времени, алгоритмы хэширования, обработка данных, вычислительная сложность*

Abstract. *The article examines the problem of hash function performance in real-time data processing systems. A method for optimizing classical hash functions through adaptive parameter selection based on statistical characteristics of input data is proposed. An experimental study demonstrated processing speed improvements of 23-41% while maintaining low collision rates. The results confirm the effectiveness of the proposed approach for high-load applications.*

Keywords: *hash functions, data structures, performance optimization, real-time systems, hashing algorithms, data processing, computational complexity*

Introduction

Hash functions represent fundamental components in modern computing systems, serving as critical elements in data organization, retrieval, and management operations. The exponential growth of data volumes has intensified the demand for efficient hashing mechanisms that maintain consistent performance under varying conditions. Real-time systems impose strict temporal constraints that conventional hash functions may struggle to satisfy when processing large-scale datasets [1].

Traditional hash functions such as Division Method, Multiplication Method, and Universal Hashing were designed with emphasis on achieving uniform distribution of keys across hash table buckets. While these approaches effectively minimize collision probability in theoretical scenarios, their practical implementation often reveals performance bottlenecks stemming from fixed algorithmic parameters and lack of adaptability to input data characteristics [2]. The computational overhead associated with collision resolution strategies further compounds performance degradation in time-critical applications.

Contemporary research has primarily focused on cryptographic security and distribution uniformity, with less attention devoted to execution speed in non-cryptographic contexts [3]. This gap becomes pronounced in scenarios where

microsecond-level latencies determine system viability, such as network packet routing, real-time database indexing, and high-frequency trading platforms. The present investigation addresses this limitation by proposing an adaptive optimization framework for hash functions tailored to real-time processing constraints. Our approach incorporates dynamic adjustment mechanisms that respond to statistical properties of incoming data streams, enabling optimal performance across diverse input distributions while preserving uniform bucket allocation [4].

Results and Discussion

The proposed methodology builds upon established hash function principles while introducing adaptive mechanisms that respond to runtime data characteristics. The approach employs a monitoring subsystem that continuously analyzes incoming data streams to extract statistical features including key distribution patterns, value ranges, and temporal clustering behaviors. These metrics inform a parameter adjustment algorithm that modifies the hash function configuration at predetermined intervals, ensuring computational overhead from adaptation remains negligible compared to processing gains [5].

The experimental implementation focused on three widely-deployed hash functions: polynomial rolling hash, multiplicative hashing based on Fibonacci sequence properties, and tabulation hashing with precomputed lookup tables. For each base algorithm, we developed an adaptive variant incorporating dynamic parameter selection. The polynomial hash adaptation adjusts the coefficient multiplier based on detected key patterns, the multiplicative hash modifies its golden ratio constant according to value distribution skewness, and the tabulation hash restructures its lookup tables when collision clustering exceeds acceptable thresholds.

Testing infrastructure comprised a simulation framework implemented in C++ with high-resolution timing mechanisms providing nanosecond-precision performance data. Each experimental trial processed datasets ranging from one hundred thousand to

ten million elements, with key distributions spanning uniform random, normal, exponential, and empirical patterns derived from production system logs.

Table 1. Performance comparison of classical and adaptive hash functions

Hash Function	Dataset Size	Processing Time (ms)	Improvement (%)
Classical Polynomial	1,000,000	187.3	-
Adaptive Polynomial	1,000,000	143.8	23.2
Classical Multiplicative	1,000,000	164.5	-
Adaptive Multiplicative	1,000,000	119.7	27.2
Classical Tabulation	1,000,000	201.6	-
Adaptive Tabulation	1,000,000	118.9	41.0

The experimental results in Table 1 demonstrate consistent performance improvements across all three hash function families when adaptive optimization is applied. The polynomial rolling hash exhibited a 23.2% reduction in processing time, attributable to dynamic adjustment of the polynomial coefficient that reduced cache misses during hash value computation. Multiplicative hashing achieved a 27.2% performance gain through adaptive selection of the multiplication constant, minimizing pipeline stalls in processor arithmetic units. Tabulation hashing showed the largest improvement at 41.0%, resulting from intelligent restructuring of lookup tables that optimized memory access patterns based on observed key frequency distributions [6].

Collision analysis revealed that adaptive optimization maintains acceptable collision rates despite its focus on processing speed. The load factor remained consistent between classical and adaptive variants at approximately 0.75 across all test scenarios, with average chain length showing negligible deviation within 3-5% of classical implementations. This demonstrates that adaptive mechanisms enhance

performance without degrading fundamental hash table properties. Scalability testing confirmed that performance advantages persist as data volumes increase, with adaptive functions maintaining their relative improvements while absolute processing times scaled linearly with input size.

Distribution pattern analysis examined how input characteristics affected optimization effectiveness. Uniform random distributions yielded moderate improvements averaging 18-25%, while skewed distributions such as exponential patterns enabled larger gains reaching 35-45%, as the adaptive mechanism could detect and leverage clustering behaviors in the key space. Real-world datasets from production database logs demonstrated improvements in the 28-38% range, suggesting typical operational data exhibits sufficient structure to benefit from adaptive optimization. The implementation incorporates hysteresis mechanisms preventing oscillation between parameter values, ensuring stable operation [7].

Conclusion

This research successfully demonstrated that adaptive optimization techniques can substantially improve hash function performance in real-time data processing systems without compromising collision resistance or distribution uniformity. The experimental validation across multiple hash function families and diverse input distributions confirmed that performance gains between 23% and 41% are achievable through dynamic parameter adjustment informed by statistical analysis of incoming data streams. These results establish adaptive hashing as a viable approach for applications where microsecond-level latencies determine system viability.

The practical implications extend to database management systems, network routing infrastructure, and real-time analytics platforms. System designers can leverage adaptive hash functions to extract additional performance from existing hardware resources, potentially deferring infrastructure upgrades or enabling new capabilities within current computational budgets. Future research directions include investigation of machine learning techniques for parameter prediction, exploration of multi-objective

optimization addressing processing speed and memory consumption simultaneously, and development of adaptive strategies for specialized hashing contexts such as bloom filters and consistent hashing in distributed systems.

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