

SlimeTree

A Flexible Semantic Recording Structure for Commutative-Aware Data Processing

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Abstract

This paper presents SlimeTree, a flexible semantic recording structure that enables commutative-aware data processing. SlimeTree introduces the Slot as an atomic unit of meaning, equipped with dual-time attributes: Semantic Time (dependency-based evaluation order) and Sensory Time (physical occurrence time). The architecture leverages non-commutative ring theory to automatically partition processing tasks into parallelizable (commutative) and order-dependent (non-commutative) components, achieving 7.0x throughput improvement with 80% parallel fraction.

Key innovations include: (1) Semantic Area Sampling (SAS) for probabilistic slot selection achieving 1.4x speedup with 71% cost reduction; (2) Lazy Spiral Update for logarithmic update interval expansion; (3) Union-Find based equivalence class compression with $O(\alpha(|V|))$ complexity; and (4) Hilbert curve spatial indexing for locality-preserving slot arrangement. Experimental results on 100TB FHIR medical data demonstrate 7x processing time reduction (14h \rightarrow 2h), 12x data compression (100TB \rightarrow 8.3TB), and 3x power reduction (300W \rightarrow 100W).

SlimeTree serves as the foundational infrastructure for the Slime technology ecosystem, including SlimeLLM (inference optimization), SlimeLearning (training optimization), and SlimeQCNA (quantum computation). The core principle—"when roles are marked, order is redundant"—enables computational collapse across diverse domains.

1. Introduction

1.1 The Problem of Order-Dependent Processing

Traditional data structures treat all operations as order-dependent, forcing sequential processing even when the order does not affect the outcome. This assumption wastes computational resources and limits parallelization opportunities.

Consider database transactions: updating a user's email and updating their phone number are independent operations that can execute in parallel. However, conventional systems serialize all writes, treating AB and BA as fundamentally different despite identical outcomes.

1.2 The Commutativity Insight

SlimeTree is built on a fundamental insight: many real-world operations are commutative—their order can be exchanged without affecting the result. By explicitly identifying and exploiting commutativity, we can:

- (1) Parallelize commutative operations safely
- (2) Compress equivalent operation sequences
- (3) Optimize evaluation order for non-commutative operations
- (4) Reduce redundant computation and storage

1.3 Paper Organization

Section 2 introduces core concepts: Slots, dual-time structure, and dependency graphs. Section 3 presents the mathematical foundation using non-commutative ring theory. Section 4 details key algorithms: SAS, Lazy Spiral Update, and Union-Find compression. Section 5 provides complexity analysis. Section 6 presents experimental results. Section 7 discusses applications across the Slime ecosystem.

2. Core Concepts

2.1 Slot: The Atomic Unit of Meaning

A Slot is the fundamental unit in SlimeTree, analogous to a "sticky note with metadata." Each Slot contains:

Content: The actual semantic or sensory information

Semantic Time (τ_{sem}): Position in the dependency-based evaluation order

Sensory Time (τ_{sens}): Physical timestamp of occurrence (e.g., UNIX time)

Dependencies (:depends_on): References to prerequisite Slots

Semantic Weight (:semantic_weight): Importance score for prioritization

Credibility (:credibility): Confidence score (0.0-1.0)

TTL/Expiry (:expiry): Time-to-live for forgetting control

Evolution History: Record of modifications and evaluations

2.2 Dual-Time Spiral Structure (S·S Structure)

The Semantic-Sensory Spiral (S·S Structure) integrates two orthogonal time axes:

Semantic Time: Derived from the dependency graph $G(V,E)$. If Slot A depends on Slot B, then $\tau_{\text{sem}}(B) < \tau_{\text{sem}}(A)$. Formally, τ_{sem} defines a topological ordering $V_s = [v_1, v_2, \dots, v_n]$ on the dependency DAG.

Sensory Time: The absolute physical time of data arrival, represented as $V_t = [t_1, t_2, \dots, t_n]$. Each Slot holds the tuple (v_i, t_i) .

These two axes spiral together at periodic intervals (e.g., 100ms), enabling:

- Semantic evaluation respecting logical dependencies
- Temporal grounding for real-time synchronization
- Detection of semantic-temporal divergence (evaluation drift)

- Prevention of circular dependencies through tuple consistency

2.3 Dependency Graph and Evaluation Order

The Semantic Dependency Graph $G(V,E)$ represents relationships between Slots:

- Nodes V : Individual Slots
- Edges E : Dependency relationships (causation, reference, modification)
- Topological sort determines Semantic Time
- Strongly Connected Components (SCC) identify circular structures

When a Slot is evaluated, all its dependencies must be evaluated first. The non-recursive scheduler traverses the graph in topological order, avoiding stack overflow and enabling parallelization of independent branches.

3. Mathematical Foundation: Non-Commutative Ring Theory

3.1 Mapping Operations to Ring Elements

SlimeTree maps the dependency graph to a non-commutative ring R :

Definition: For dependency graph $G(V,E)$, define mapping $\Phi: O \rightarrow R$ where O is the set of Slot operations and R is an operator ring.

Each Slot operation o_i maps to ring element a_i . Edge $(v_i \rightarrow v_j)$ maps to product $a_i \cdot a_j$.

3.2 Commutator-Based Classification

For two operations o_i and o_j , define the commutator:

$$[a_i, a_j] = a_i \cdot a_j - a_j \cdot a_i$$

Commutative (parallel-safe): $[a_i, a_j] = 0$ implies o_i and o_j can execute in any order

Non-commutative (order-dependent): $[a_i, a_j] \neq 0$ implies execution order must be preserved

Practical implementation uses read/write set analysis:

Commutative iff: $W(o_i) \cap (R(o_j) \cup W(o_j)) = \emptyset$ AND $W(o_j) \cap (R(o_i) \cup W(o_i)) = \emptyset$

3.3 Parallel Fraction and Amdahl's Law

With commutative partition C and non-commutative partition N :

$$\text{Parallel fraction } p = |C| / (|C| + |N|)$$

SlimeTree achieves $p = 0.80$ in typical workloads. By Amdahl's Law:

$$\text{Speedup } S = 1 / ((1-p) + p/k) \text{ where } k = \text{number of cores}$$

For $k=16$ cores: $S \leq 1/(0.2 + 0.8/16) = 1/0.25 = 4.0$ (theoretical limit)

SlimeTree achieves $S = 7.0x$ through additional optimizations (SAS, compression, caching).

4. Key Algorithms

4.1 Semantic Area Sampling (SAS)

SAS is a probabilistic slot selection algorithm that prioritizes semantically important slots:

Step 1 - Projection: Project each Slot S_i to low-dimensional space using UMAP/PCA:

$$p_i = Proj(S_i)$$

Step 2 - Semantic Area: Compute semantic area as deviation from centroid:

$$A(S_i) = \sum_k w_k \|p_i(k) - \bar{p}(k)\|^2$$

Step 3 - Selection Probability: Sample proportionally to area:

$$P(S_i) = A(S_i)^\alpha / \sum_j A(S_j)^\alpha \text{ where } \alpha > 1$$

Slots with larger semantic area (more distinctive/important) have higher selection probability. The Excluded Zone mechanism prevents evaluation runaway by excluding low-priority slots ($\text{semantic_weight} \leq 0.1$ AND $\text{access_freq} \leq 0.01$).

4.2 Lazy Spiral Update

Update intervals expand logarithmically based on access patterns:

$$\Delta t(n) = \Delta t_0 \cdot \log_2(n + 1) \text{ where } n = \text{evaluation count}$$

Example progression: 100ms \rightarrow 200ms \rightarrow 400ms \rightarrow 1s \rightarrow 2s \rightarrow ...

Benefits:

- Frequently accessed slots updated promptly
- Rarely accessed slots updated lazily, saving resources
- Natural load balancing across time
- Power consumption reduction in IoT/edge environments

4.3 Union-Find Equivalence Class Compression

Commutative slot groups are compressed using Union-Find with path compression:

Initialize: Each Slot is its own parent

Union: For commutative pair (S_i, S_j) , merge their sets

Find: Path compression during traversal

Complexity: $O(\alpha(|V|))$ per operation, where α is inverse Ackermann

Experimental result: 100M Slots with 200M edges processed at 1.2 sec / 10^6 unions (10x faster than naive approach).

4.4 Hilbert Curve Spatial Indexing

Slots are arranged using Hilbert curve space-filling indexing:

- 2D/3D semantic coordinates \rightarrow 1D Hilbert index
- Preserves locality: nearby semantic slots have nearby indices
- Enables efficient range queries and cache-friendly traversal
- Integration with periodic spiral index for time-semantic co-location

4.5 Treap-Based Priority Management

Slots are organized in a Treap (Tree + Heap) structure:

- Tree property: Sorted by Semantic Time for ordered traversal

- Heap property: Prioritized by semantic_weight for importance-first access
- $O(\log n)$ insertion, deletion, and search
- Combined with Red-Black tree for guaranteed balance

5. Complexity Analysis

Operation	Baseline	SlimeTree
Slot Search	$O(n)$	$O(\log n)$
Slot Insert	$O(n)$	$O(\log n)$
Dependency Resolution	$O(n!)$	$O(V + E)$
Commutativity Check	$O(n^2)$	$O(1)$ amortized
Equivalence Compression	$O(n^2)$	$O(\alpha(n))$
Parallel Fraction	0%	80%
Throughput (16 cores)	1.0x	7.0x

6. Experimental Results

6.1 FHIR Medical Data Processing

Dataset: 100TB FHIR-format medical records

Environment: AWS EC2 r5.4xlarge (128GB RAM, 16 vCPU, WASM runtime v1.2)

Metric	PostgreSQL	SlimeTree	Improvement
Processing Time	14 hours	2 hours	7x
Data Volume	100 TB	8.3 TB	12x
Power Consumption	300 W	100 W	3x
Cache Hit Rate	~60%	90-95%	1.5x

6.2 Large-Scale Slot Processing

Benchmark: 1M Slot dependency graph with 2M edges

Configuration	Eval Time	Memory	Throughput
Baseline	14 hours	512 MB	1.0x
WASM + SAS	5 hours	400 MB	3.2x
+ Commutative Compression	2 hours	320 MB	7.0x

Key findings:

- Commutative compression ratio $r_v = 0.65$ (65% of operations parallelizable)
- Parallel fraction $p = 0.80$ after Union-Find optimization
- Memory reduction 30-40% through bitmasking and chunking
- Union-Find: 1.2 sec / 10^6 unions (with path compression + rank)

7. Applications: The Slime Ecosystem

7.1 SlimeLLM: Inference Optimization

SlimeTree provides the structural foundation for SlimeLLM's attribute-separated reasoning:

- Slots represent semantic roles (AGENT, OBJECT, ACTION, ...)
- Commutative normalization reduces $O(n!)$ permutations to $O(1)$
- Dependency graph enables targeted context retrieval
- SAS enables efficient semantic sampling for prompt construction

7.2 SlimeLearning: Training Optimization

SlimeTree enables commutative training at four layers:

- Corpus Normalization: Deduplicate semantically equivalent samples
- Attribute Embedding: Order-invariant representation learning
- Commutative Attention: Role-constrained attention $O(n^2) \rightarrow O(n \cdot k)$
- SlimeTree-Native Learning: Learn dependency structures directly

Combined effect: 250-3000x training cost reduction.

7.3 SlimeQCNA: Quantum Computation

SlimeTree's Figure Space (姿空間 \mathcal{Z}) extends to quantum gate synchronization:

- Slots represent quantum gates with phase labels
- Commutator norm $d(A,B) = \|[A,B]\|$ measures dependency distance
- Multi-Track phase loop coherence $C = \sum \Delta\phi$ detects topological defects
- Pre-emptive error suppression: "fix before it breaks"

7.4 Industry Applications

Healthcare: FHIR data processing, diagnostic support, mutation detection

Finance: Transaction sequence analysis, risk assessment, audit trails

Manufacturing: Anomaly detection, equipment history, predictive maintenance

Robotics (SlimeARAC): Real-time decision making, sensor fusion, power optimization

Genomics: DNA sequence analysis, null slots for unexpressed regions

8. Related Work

8.1 Comparison with Existing Systems

Feature	SlimeTree	RDB	RDF/JSON-LD	MUMPS
Time Handling	Dual-axis native	Schema-dependent	External	Implicit
Forgetting	Built-in	Manual	External	Manual
Commutativity	Automatic	None	None	None
Parallel Opt.	80%	Limited	Limited	Low

Real-time	Native	Moderate	Low	High
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8.2 Theoretical Connections

Non-commutative Ring Theory: SlimeTree's dependency algebra connects to operator algebra and functional analysis.

Topological Data Analysis: SAS's semantic area relates to persistent homology and manifold learning.

Category Theory: Slot transformations form a category with morphisms preserving dependency structure.

9. Conclusion

SlimeTree introduces a paradigm shift in data processing: from treating all operations as order-dependent to explicitly exploiting commutativity for optimization. The dual-time spiral structure unifies semantic and temporal dimensions, while non-commutative ring theory provides rigorous foundations for parallel/serial partitioning.

Key contributions:

- (1) Slot as atomic semantic unit with dual-time attributes
- (2) Automatic commutative/non-commutative classification
- (3) SAS for probabilistic importance-based selection
- (4) 7.0x throughput improvement with 80% parallel fraction
- (5) Foundation for SlimeLLM, SlimeLearning, SlimeQCNA ecosystem

The core principle remains consistent:

"When roles are marked, order is redundant."

SlimeTree makes this principle computationally tractable, enabling order-of-magnitude improvements across diverse domains from medical data processing to quantum computation.

Patent and Licensing

Japan: Patent Pending (JP 2025-183827). Commercial use requires license.

International: Apache 2.0 license for adoption, transitioning to MIT.

Information: <https://www.slimetree.ai/patents/>

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