XLL: Cross-Layer Logging for Data Deduplication in Consensus-Based Storage

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University of Wisconsin – Madison

NSDI, May 2026

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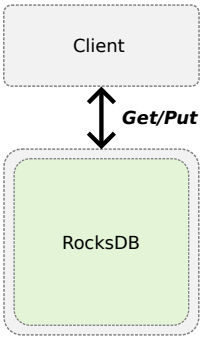
Abstractions Help Us Build Large Systems

Goal: Build a key-value service



Properties:

- ✓ Key-value interface
- ✓ Persistent
- ✓ Crash consistent

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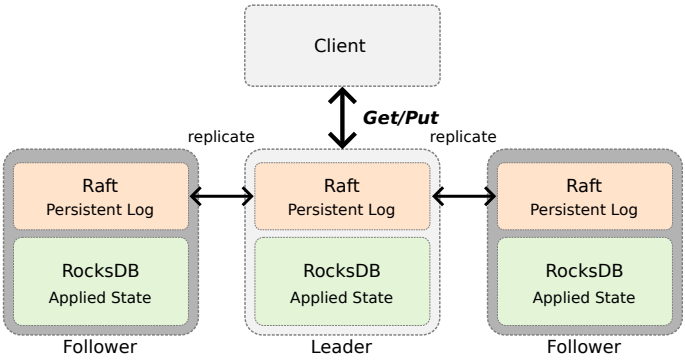
Goal: Build a *replicated* key-value service with state-machine replication



Properties:

- ✓ Key-value interface
- ✓✓ Persistent
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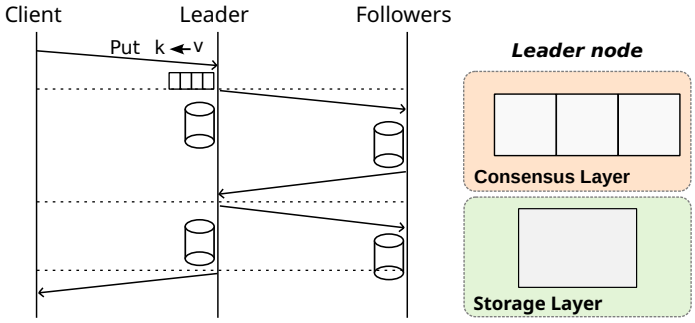
Layered systems duplicate functionality

Data Duplication in Consensus and Storage Layers

State machine replication: commands are proposed, committed, and applied



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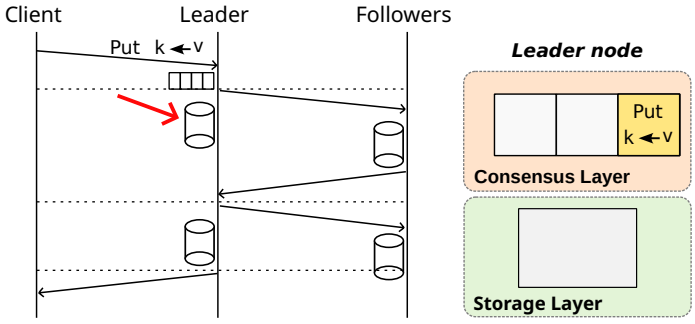

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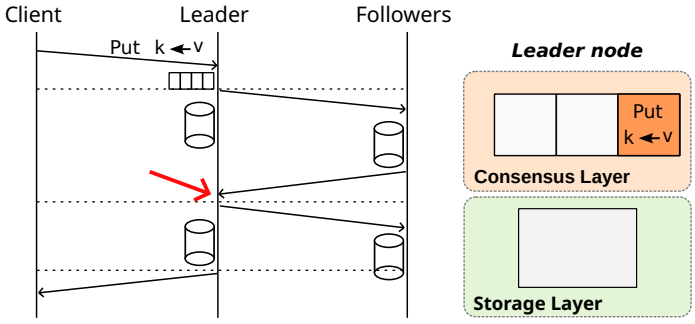

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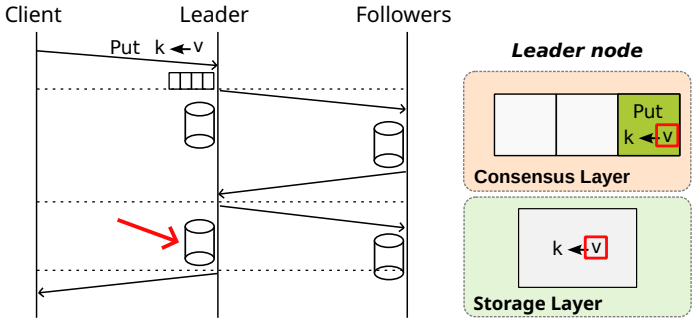

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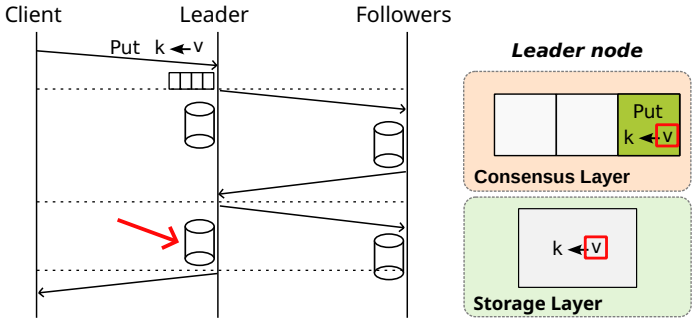

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The problem: **Cross-layer data duplication**

Our Contribution

Our solution: Cross-layer logging with XLL

- Cross-layer data duplication
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- Practice
  - XLL: shared library append-only log links to storage application
  - TiKV-XLL: cross-layer data deduplication in a production-quality system

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- Practice
  - XLL: shared library append-only log links to storage application
  - TiKV-XLL: cross-layer data deduplication in a production-quality system
- Evaluation
  - 5.5$\times$ higher write throughput
  - 73% lower write amplification
  - Preserve read performance
  - Preserve persistence and crash recovery semantics

Outline

Remainder of the talk

- Rethinking data organization in a replicated persistent key-value store
- High performance in practice
  - Reading from the log
  - Crash recovery
- Evaluation
- Conclusion

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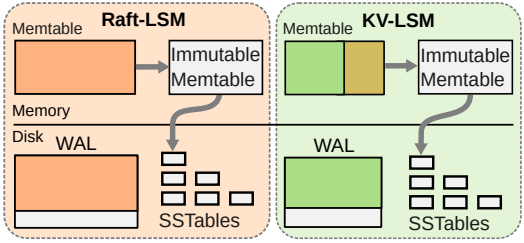
Design: Data organization with cross-layer logging

TiKV – Raft and Key-Value Storage



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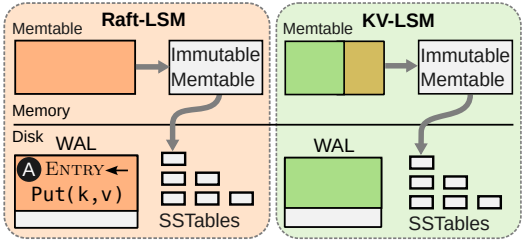

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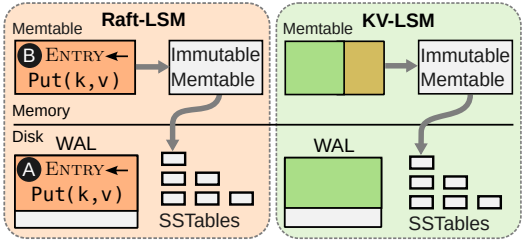

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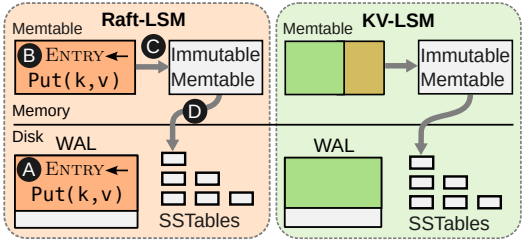

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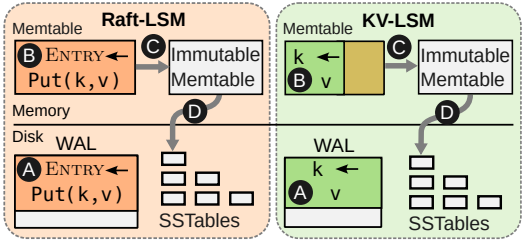

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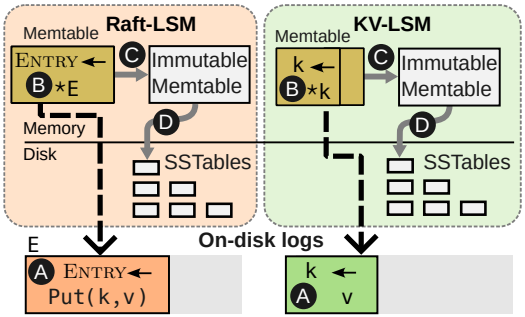
Four physical writes for v. Can we write v once?

Design: Data organization with cross-layer logging

Intermediate Step – Key-value separation

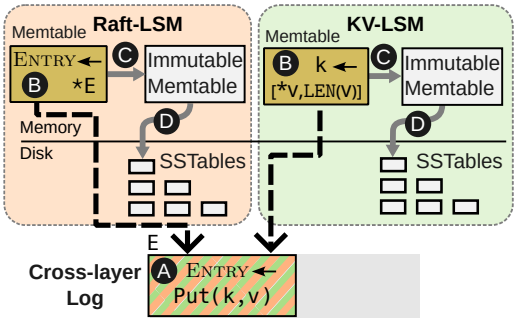


- Data payloads stored in *external logs*
- Keys and references stored in LSM tree
  - Wisckey
  - BadgerDB
  - Titan
- External logs act as WAL
- Key-value separation does not solve cross-layer duplication (v written twice)

- Ⓐ: Persistent write to on-disk log, log byte-offset stored in LSM

Design: Data organization with cross-layer logging

XLL: Cross-Layer Log



- Store single copy of payload in XLL
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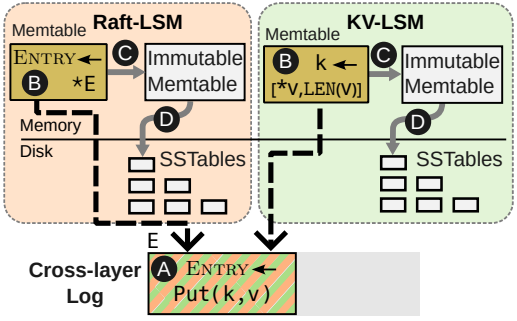

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Problem: *How to reference the payload v?*

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Practical Design Challenges

This talk:

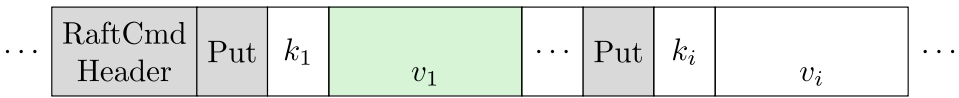
- Efficient reads from XLL
- Crash recovery

More in the paper:

- Append-only writes
- Garbage collection from log
- Range scans

Challenge 1: Efficient Reads

Problem: Distributed system: Raft entries are sent and written in wire format (Protobuf)
Raft entry: Fixed-size header followed by put ops *key* and *value*



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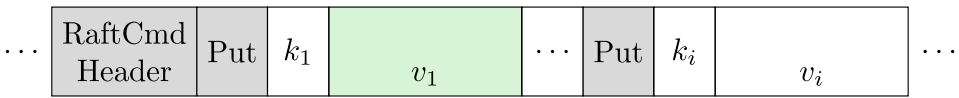

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Variable-width integers encode the length of fields in the buffer

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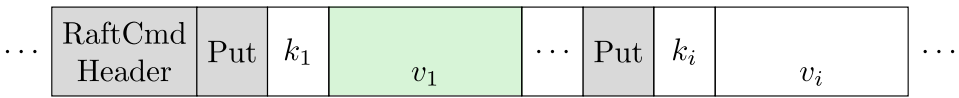

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Naive read: read and deserialize entire entry

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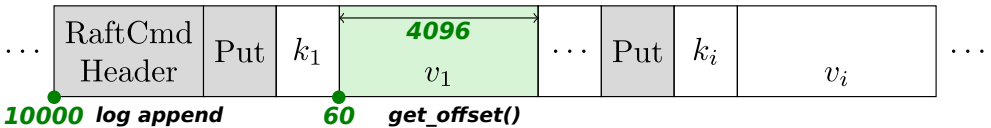

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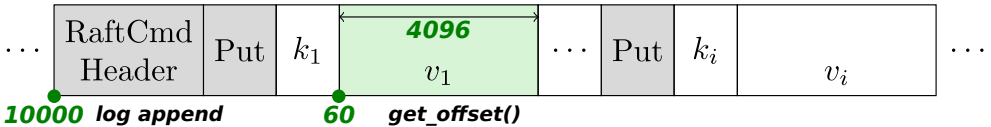

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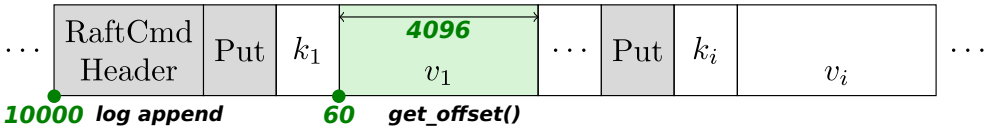

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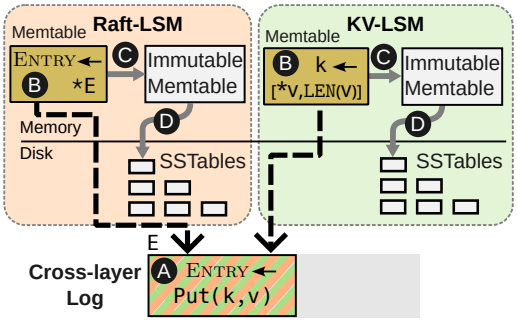
`pread(log, offset, length)` directly reads values from XLL

Challenge 2: Persistence and Crash Recovery



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KV-LSM data is *only* memory-durable between memtable flushes

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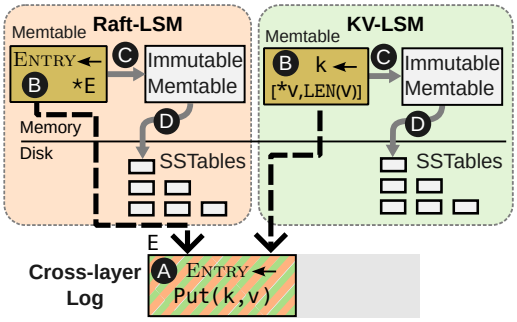

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Problem: *How to recover key-value data following a crash?*

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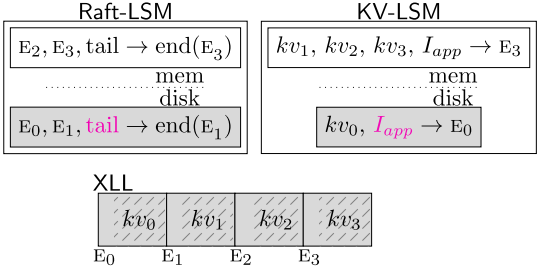

Consensus-directed crash recovery

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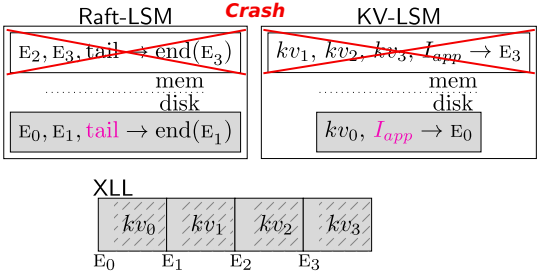

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In-memory state lost on crash

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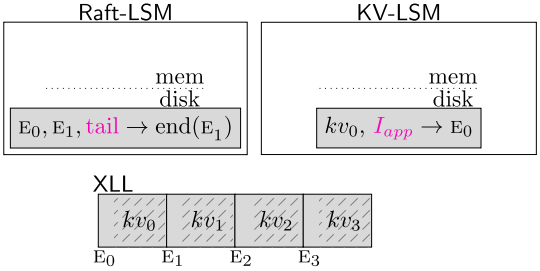

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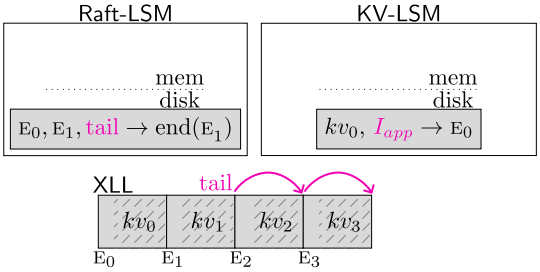
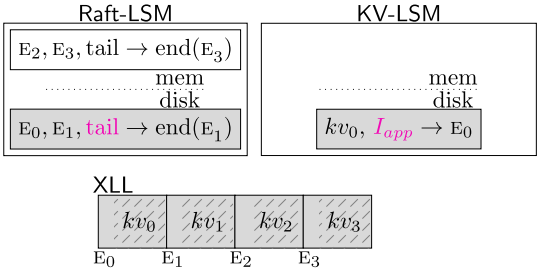


Consensus-directed crash recovery

Phase one: use Raft log tail to recover Raft entries

Challenge 2: Persistence and Crash Recovery



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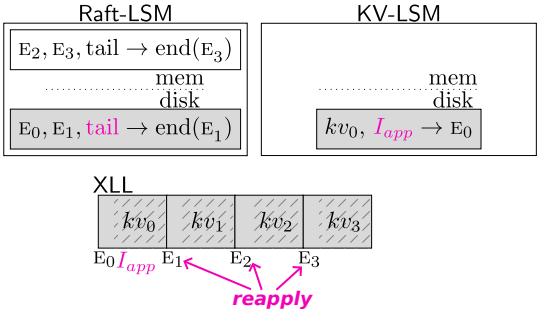

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Phase two: re-apply Raft commands from old applied index

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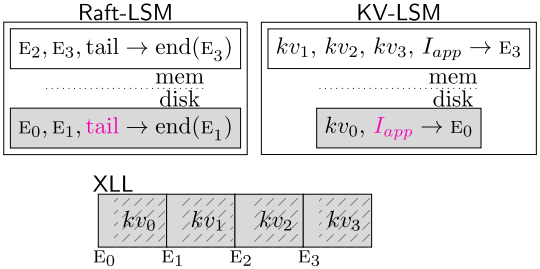

Consensus-directed crash recovery

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Evaluation: Key Questions

- How do XLL writes affect end-to-end latency for consensus operations?
- Does XLL lower write amplification compared to other layered storage systems?
- How does XLL perform in key-value workloads?

(Much more in paper, including garbage collection, crash recovery, read/write scalability)

Evaluation: Experimental Setup

Experiment configuration

Systems:

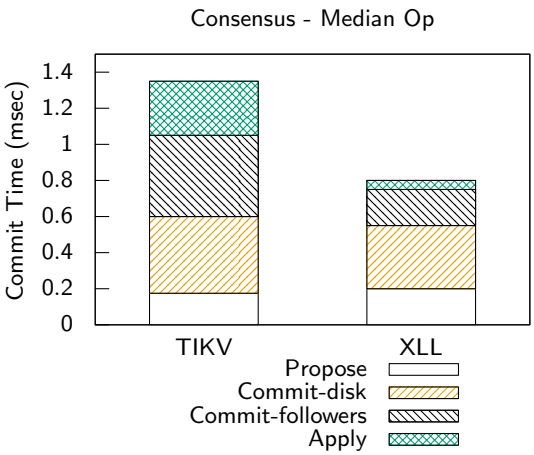
- TiKV
- XLL-SO (Separation Only)
- XLL

Three-node raft cluster:

- 32-core AMD 9354P
- 192GB Memory (KV Service run in 32GB cgroup)
- 800GB NVMe SSD
- 100Gb network

TiKV-SO separates keys from values, but does not deduplicate values

Evaluation: Consensus End-to-End Latency

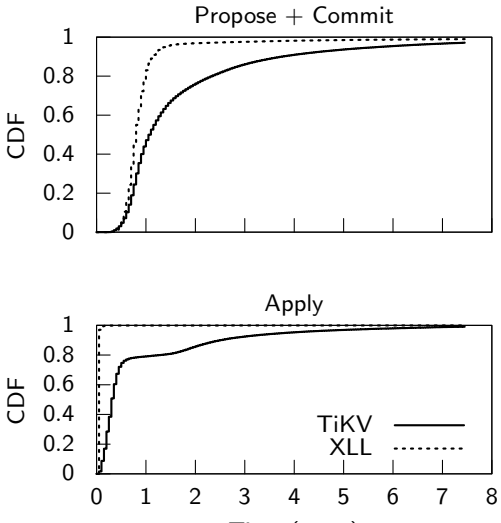


Measure Raft execution phases on leader
16KB writes on a 50GB database

Median op

- **Commit** is faster:
  KV-separation ⇒ quicker disk + quorum
- **Apply** is dramatically faster: KV-LSM just records the locator — no value re-write

Evaluation: Consensus End-to-End Latency



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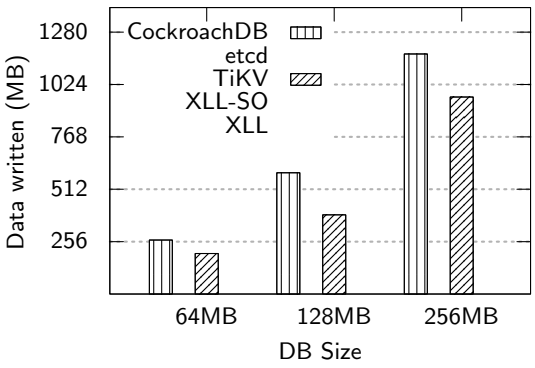
Tail latency

- **Apply** nearly instantaneous

Evaluation: Write Amplification



Foreground bytes written during small-DB loads (1KB records, `strace`)

- TiKV, CockroachDB: 3–4× amplification (2x WAL, 2x LSM)

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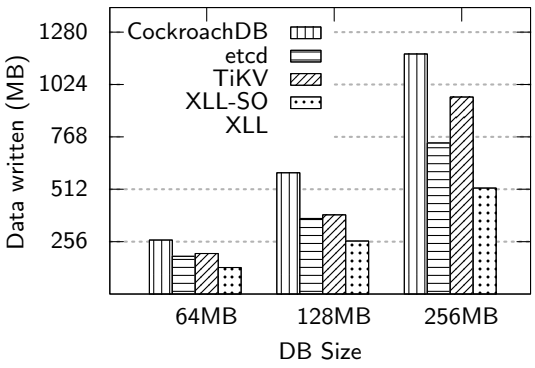

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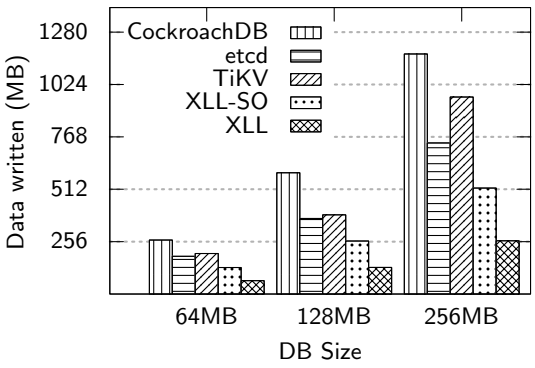

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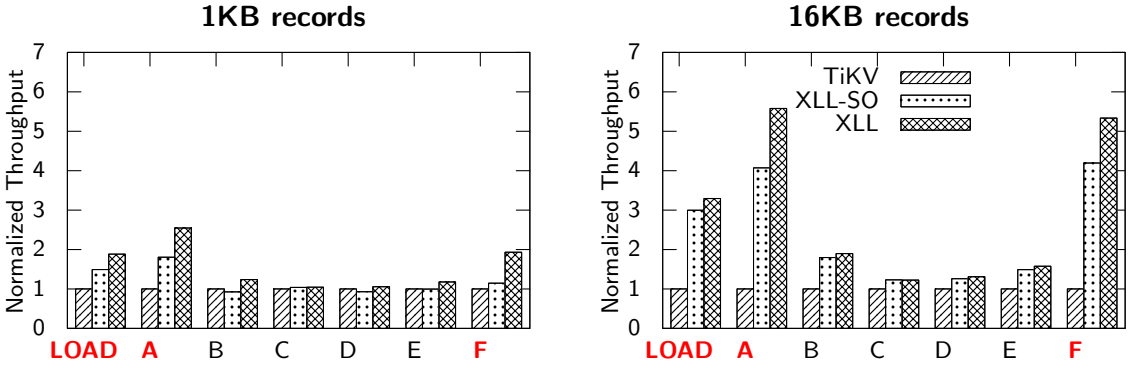
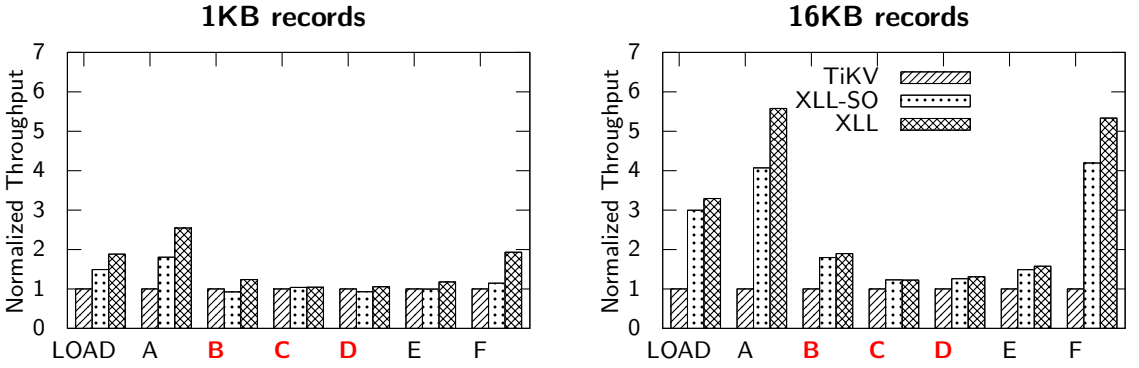
- XLL-SO & etcd: lower — no WALs, but still double-writes values
- **TiKV-XLL: 1–2% overhead**
- 73% reduction vs. TiKV

Evaluation: YCSB



- Throughput normalized to TiKV; 100GB dataset, 32GB page-cache budget
- Write-heavy (Load, A, F): TiKV-XLL up to 5.5× TiKV; clear gap over KV-separation-only
- Read-heavy (B, C, D): matches TiKV-XLL-SO — targeted reads avoid any read penalty

Evaluation: YCSB



- Throughput normalized to TiKV; 100GB dataset, 32GB page-cache budget
- Write-heavy (Load, A, F): TiKV-XLL up to 5.5× TiKV; clear gap over KV-separation-only
- Read-heavy (B, C, D): matches TiKV-XLL-SO — targeted reads avoid any read penalty

Conclusion

Cross-layer data duplication is a pervasive cost in consensus-based storage

XLL – a shared append-only log used by consensus and storage layers

TiKV-XLL: 5.5× write throughput, 73% less write amplification, same crash-consistency guarantees as TiKV

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Cross-layer data duplication is a pervasive cost in consensus-based storage

XLL – a shared append-only log used by consensus and storage layers

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Strict data isolation between system layers is unnecessary and harmful to performance!

Thank you!