Implementing Linearizability at Large Scale and Low Latency

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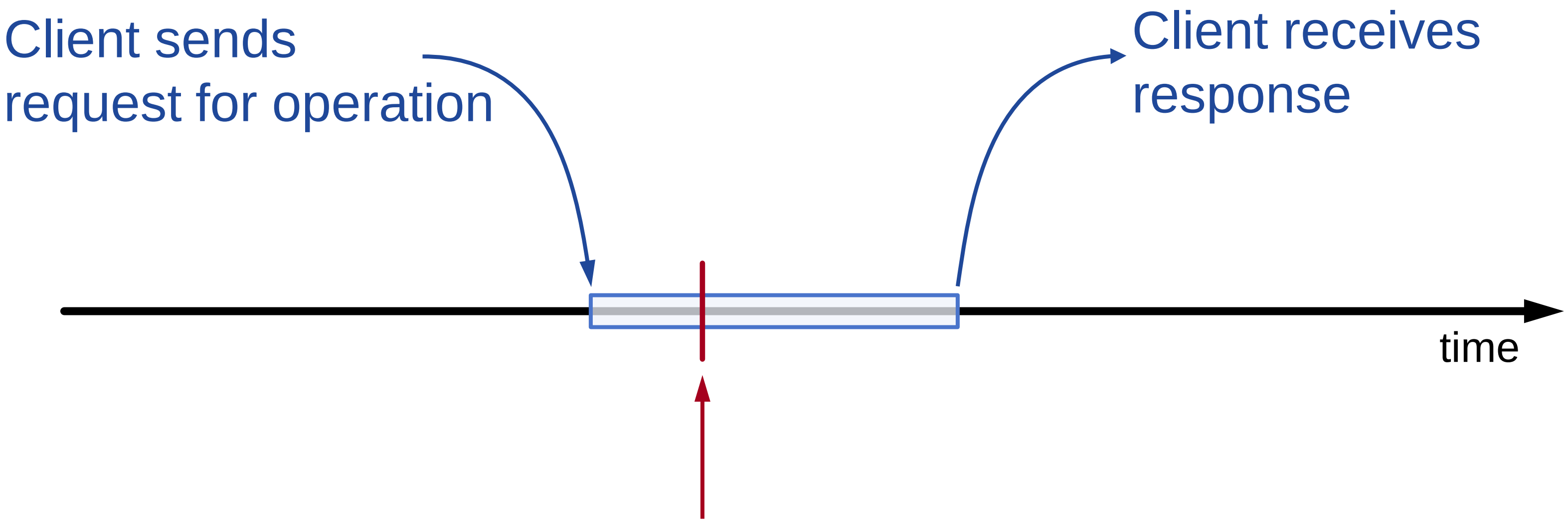
Overview

- **Goal:** take back consistency in large-scale systems
- **Approach:** distinct layer for linearizability
- **Reusable Infrastructure for Linearizability (RIFL)**
  - At-least-once RPC ➔ exactly-once RPC
  - Records RPC results durably
  - To handle reconfiguration, associates metadata with object
- **Implemented on distributed KV store, RAMCloud**
  - Low latency: **< 5% (500ns)** latency overhead
  - Scalable: supports states for 1M clients
- **RIFL simplified implementing transactions**
  - Simple distributed transaction commits in ~**22 μs**
  - Outperforms H-Store

What is Linearizability?

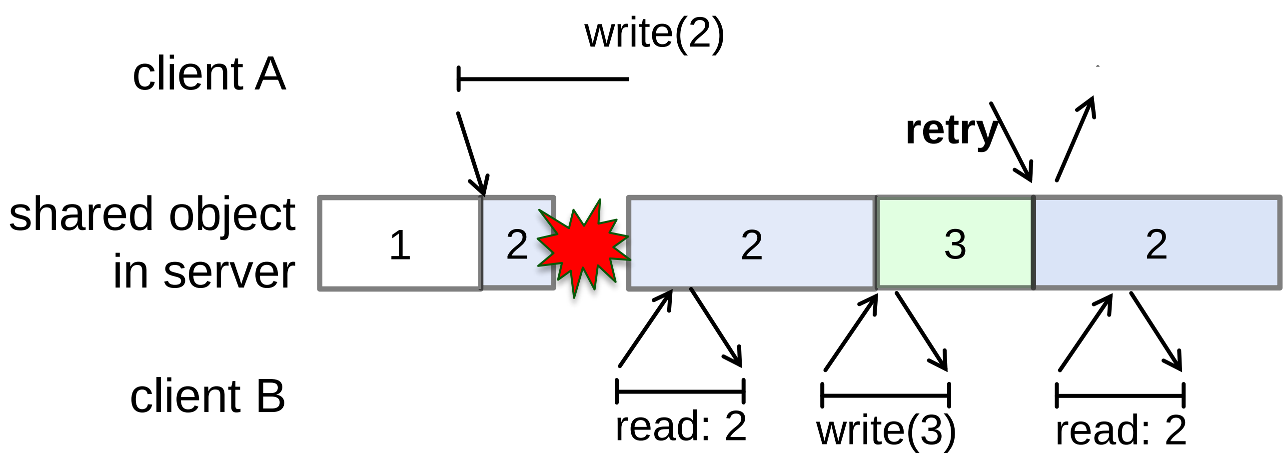


Behaves as if executing exactly once and instantaneously

Strongest form of consistency for concurrent systems

What is Missing from Existing Systems?

- **Most systems: at-least-once semantics, not exactly-once**
  - Retry (possibly) failed operations after crashes
  - Idempotent semantics: repeated executions *O.K.?*



- **At-least-once + idempotency ≠ linearizability**
- **Need exactly-once semantics!**

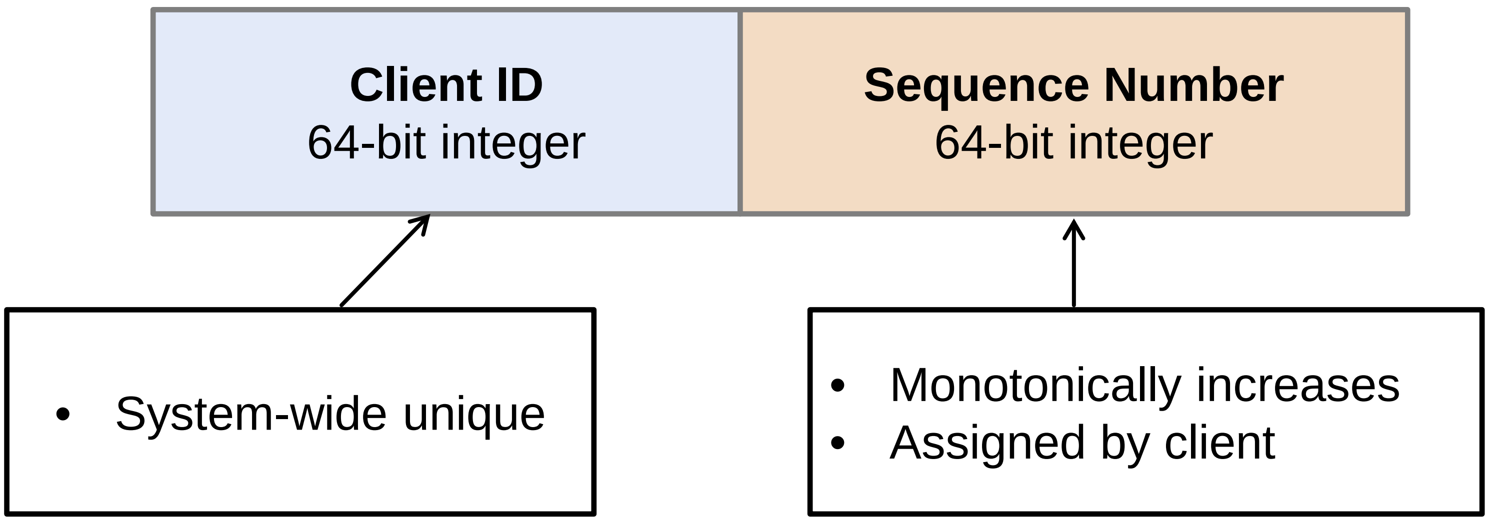
Architecture of RIFL

- **RIFL saves results of RPCs**
- **If client retries,**
  - Don't re-execute
  - Return saved result

➢ **Key problems**
  - Unique identification for each RPC
  - Durable completion record
  - Retry rendezvous
  - Garbage collection

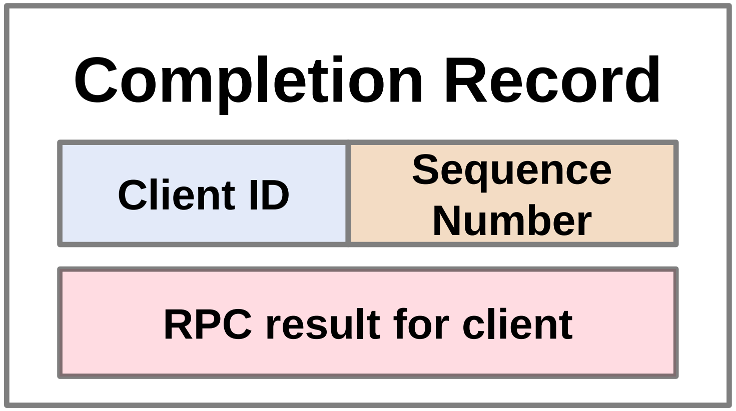
1) RPC Identification

- **Each RPC must have a unique ID**
- **Retries use the same ID**
- **Client assigns RPC IDs**



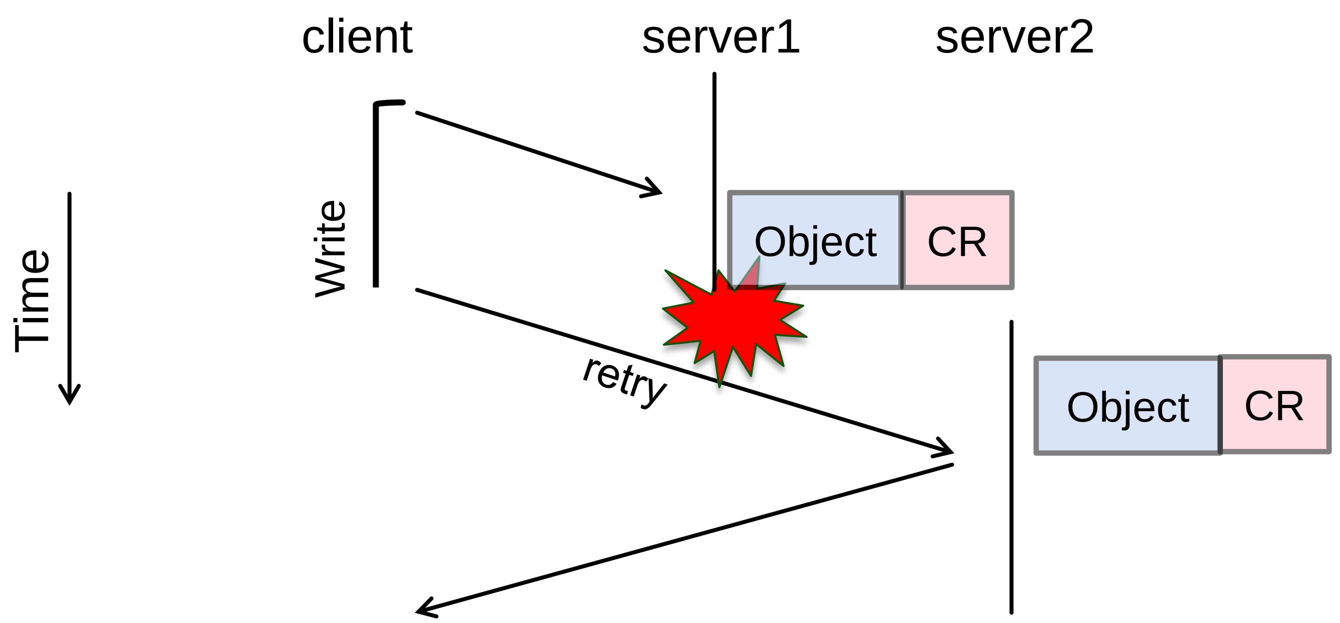
2) Durable Completion Record

- Written when an operation completes
- Same durability as object(s) being mutated
- Atomically created with object mutation



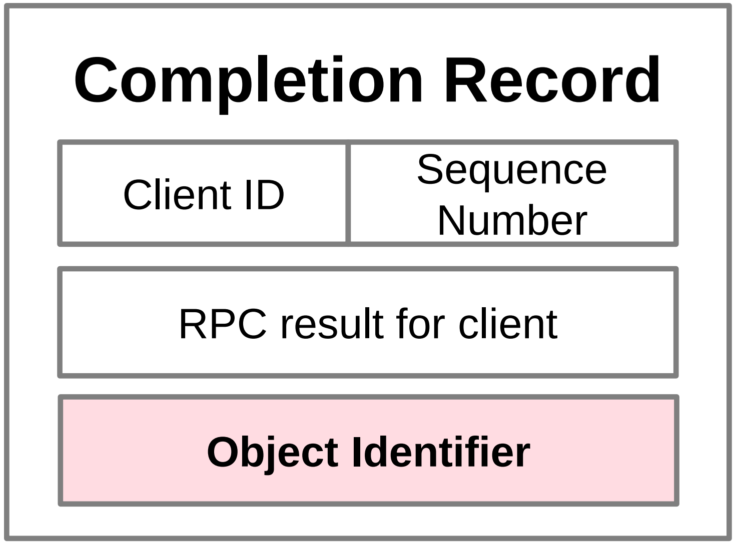
3) Retry Rendezvous

- Data migration is popular in large systems (eg. crash recovery)
- Retries must find completion record



3) Retry Rendezvous (cont.)

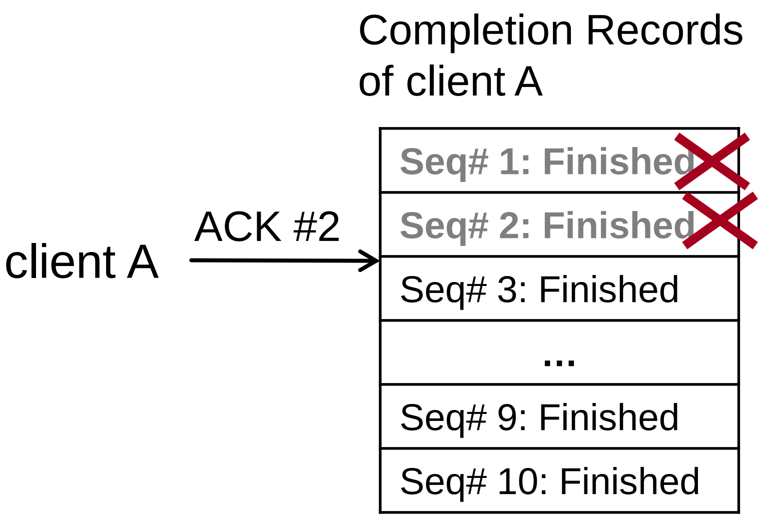
- **Associate each RPC with a specific object**
- **Completion record follows the object during migration**



4) Garbage Collection

- **Lifetime of completion record ≠ lifetime of object value**
- **Can't GC if client may retry later**
- **Server knows a client will never retry if**

1. Client acknowledges receipt of RPC result



4) Garbage Collection

- **Lifetime of completion record ≠ lifetime of object value**
- **Can't GC if client may retry later**
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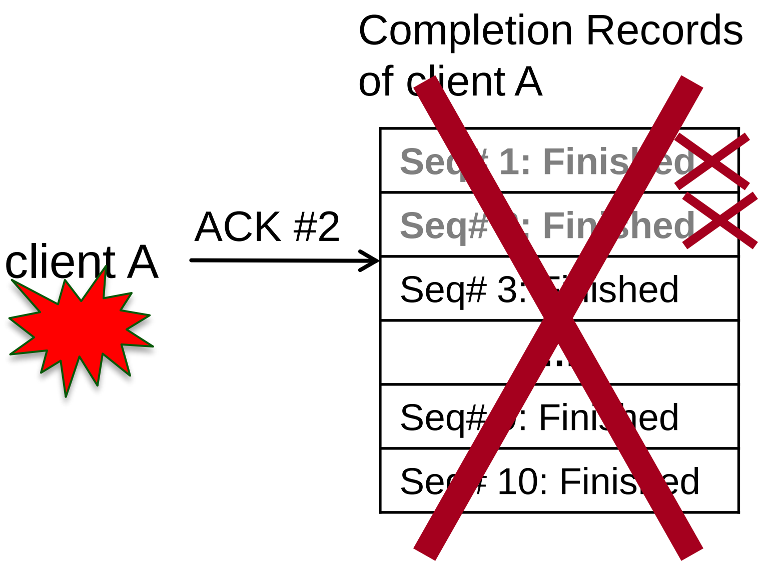
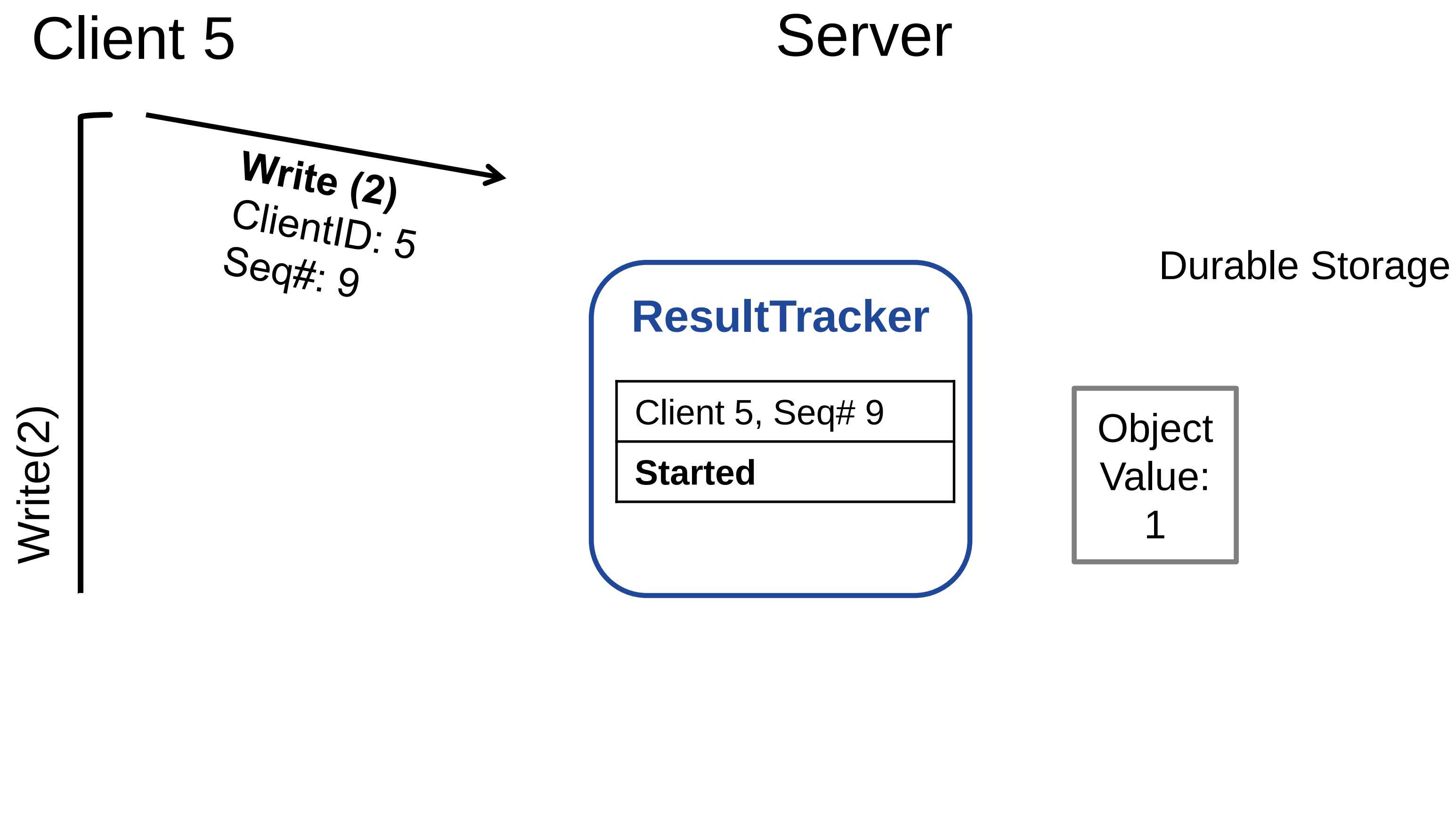
1. Client acknowledges receipt of RPC result
2. Detect client crashes with lease.



Linearizable RPC in Action



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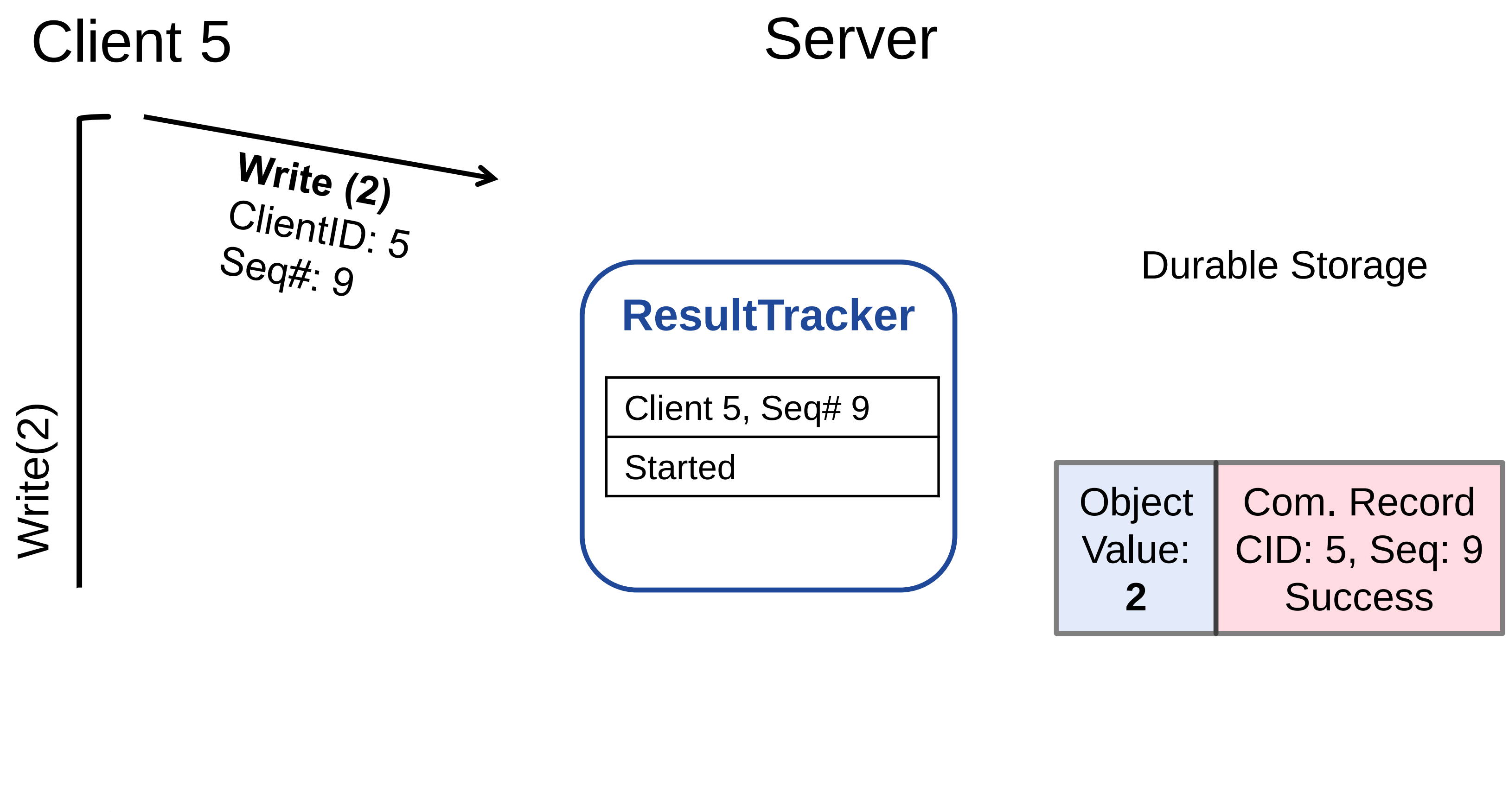
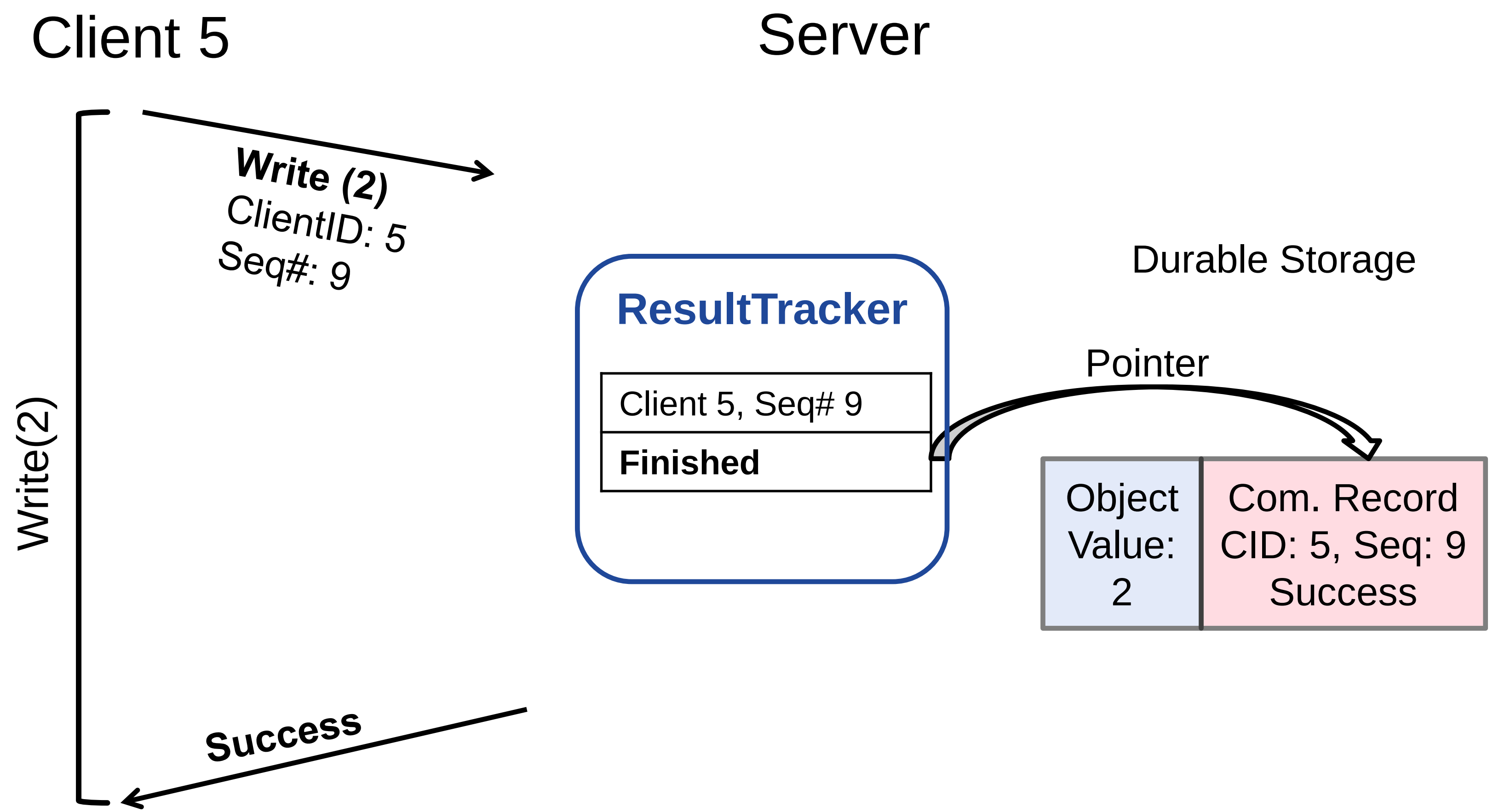
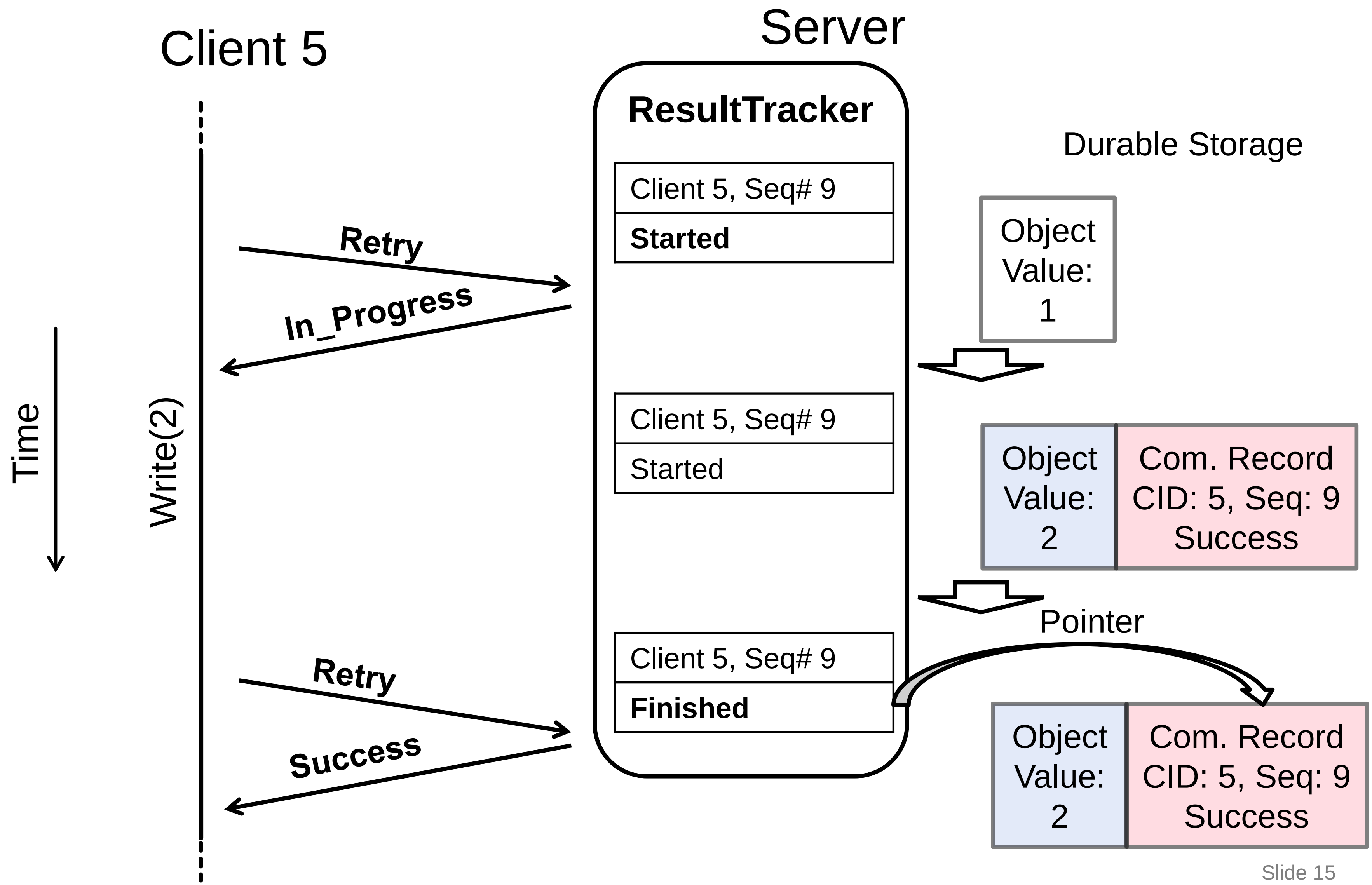


Linearizable RPC in Action



Handling Retries



Performance of RIFL in RAMCloud

- **Achieved linearizability without hurting performance of RAMCloud**
  - Minimal overhead on latency(< 5%) and throughput (~0%)
  - Supports state for 1M clients

Why RAMCloud?

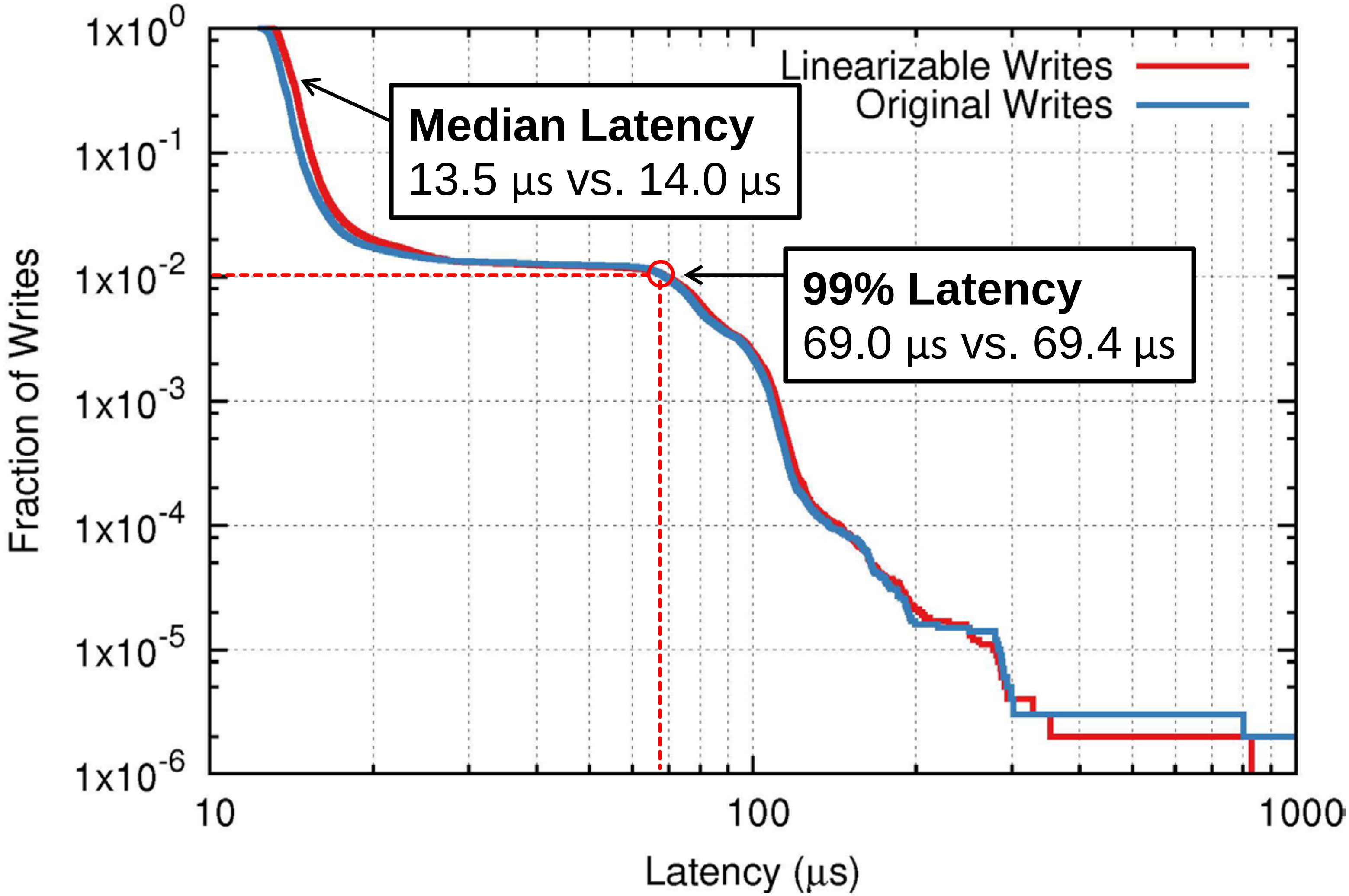
- **General-purpose distributed in-memory key-value storage system**
- **Durability:** 3-way replication
- **Fast recovery:** 1~2 sec for server crash
- **Large scale:** 1000+ servers, 100+ TB
- **Low latency:** 4.7 μs read, 13.5 μs write (100B object)

- **RIFL is implemented on top of RAMCloud**
  - Core: 1200 lines of C++ for infrastructure
  - Per operation: 17 lines of C++ to make an operation linearizable

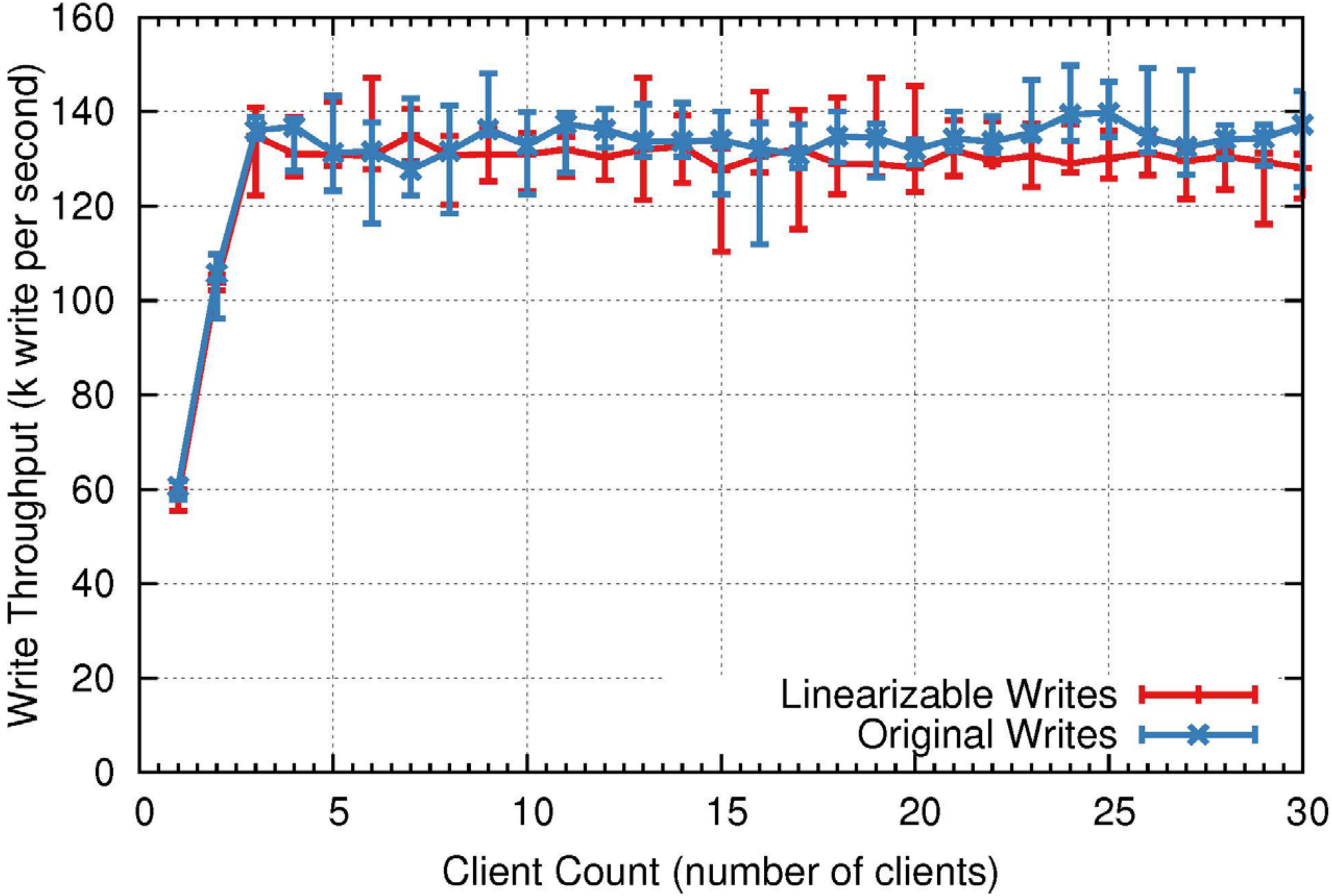
Experimental Setup

- **Server: Xeon 4 cores at 3 GHz**
- **Fast Network**
  - Infiniband (24 Gbps)
  - Kernel-bypassing transport (RAMCloud default)

Impact on Latency

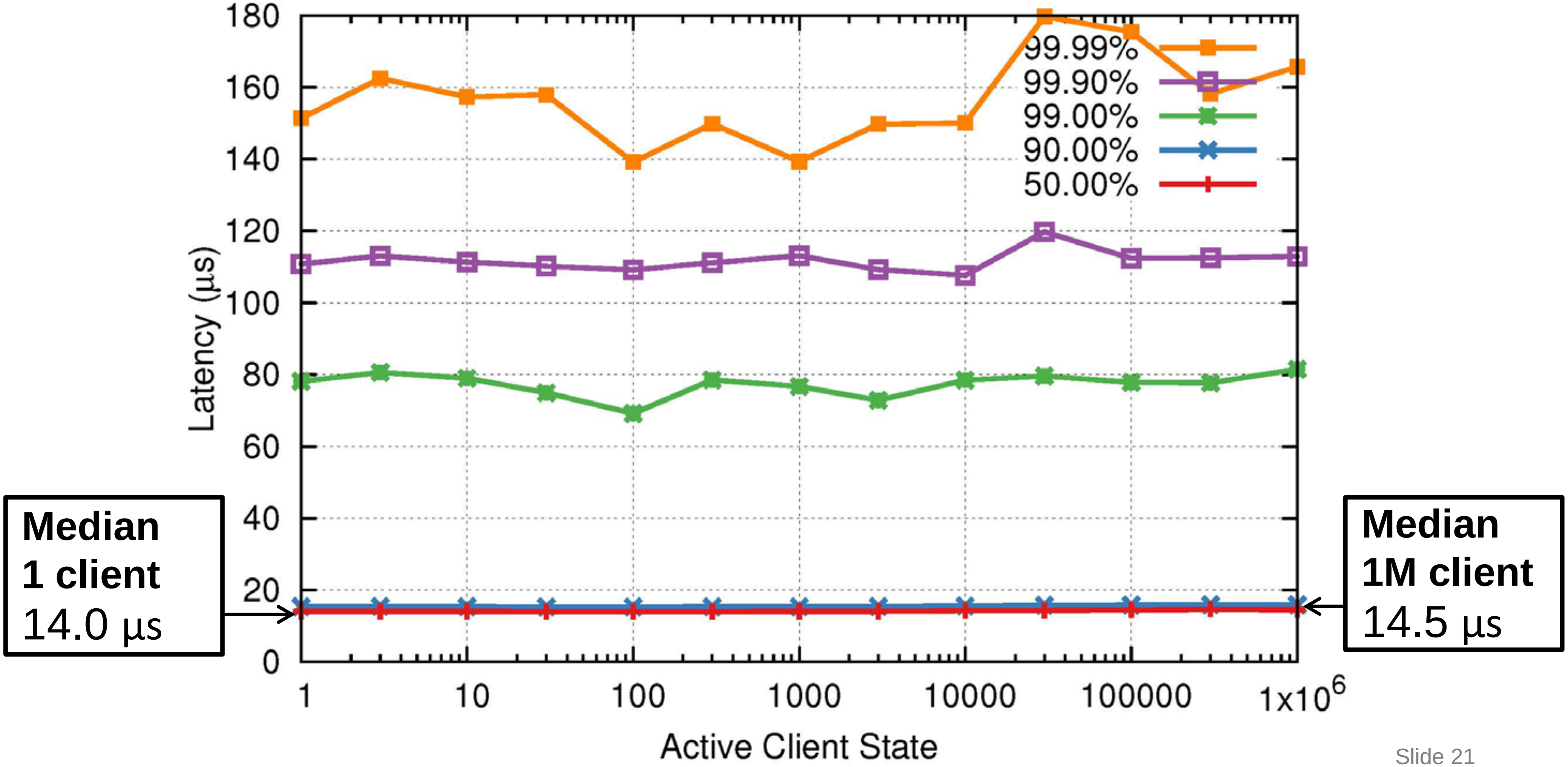


Impact on Throughput



Impact of Many Client States

- **Storage impact:** 116B per client ➔ 116MB for 1M clients
- **Latency impact** (linearizable write, unloaded):



Case study: Distributed Transactions with RIFL

- **Extended use of RIFL for more complex operations**
- **Two-phase commit protocol based on Sinfonia**
- **RIFL reduced mechanisms of Sinfonia significantly**
- **Lowest possible round-trip for distributed transactions**

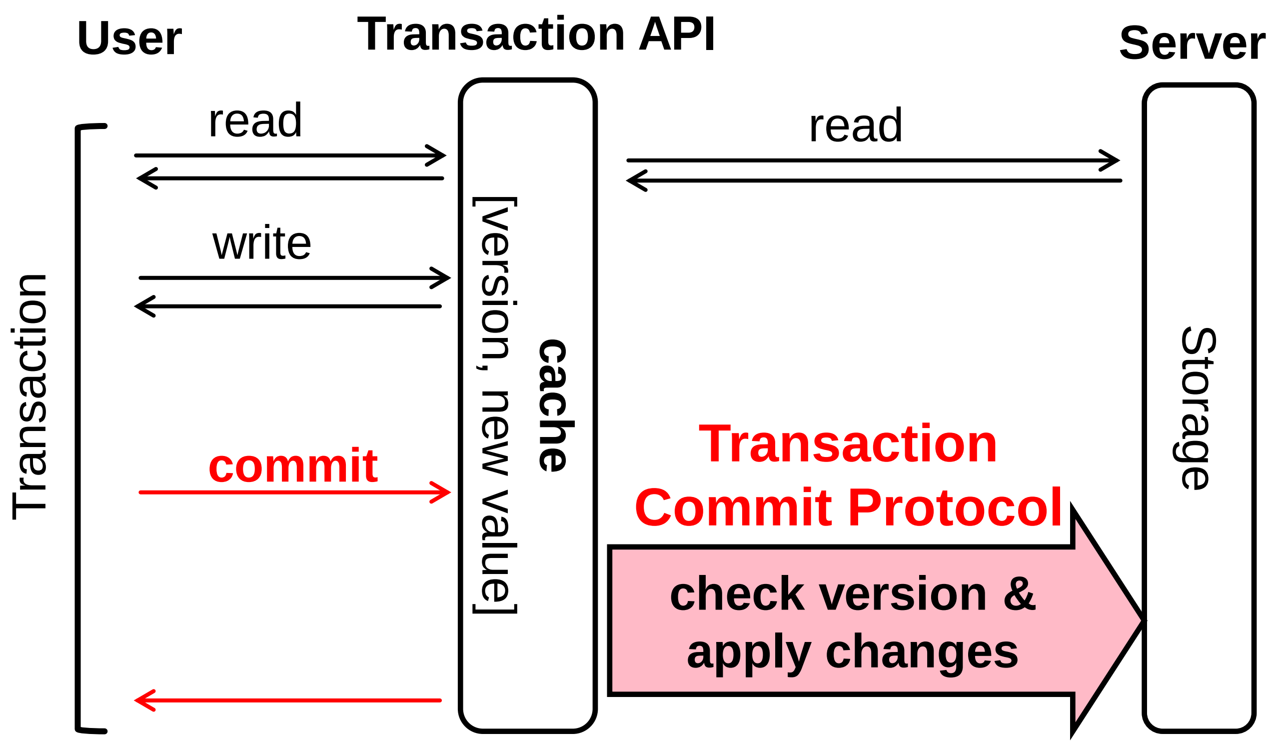
Transaction Client API

```
class Transaction {
        read(tableId, key) => blob
        write(tableId, key, blob)
        delete(tableId, key)
        commit() => COMMIT or ABORT
}
```

- **Optimistic concurrency control**
- **Mutations are “cached” in client until commit**

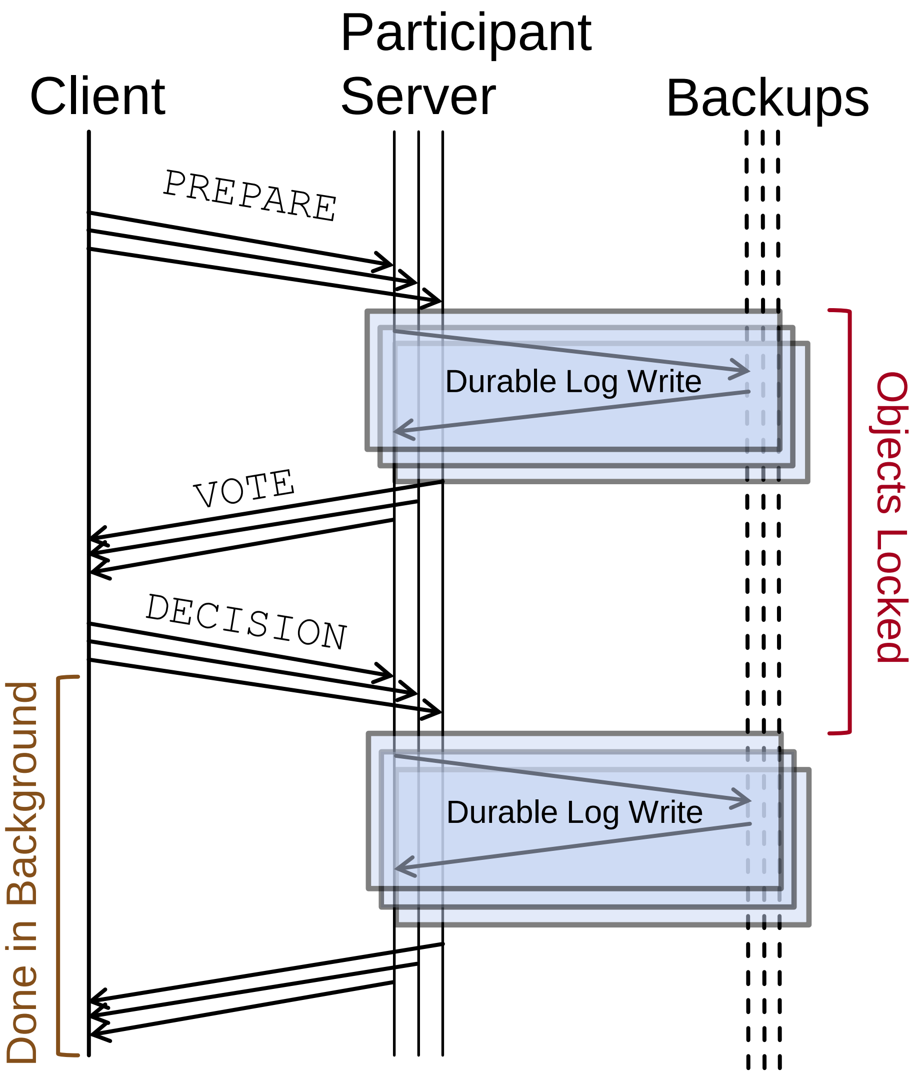
Transaction Commit Semantics

- **commit(): atomic multi-object operation**
  - Operations in client's cache are transmitted to servers
  - Conditioned on a version (same version ≡ object didn't change)



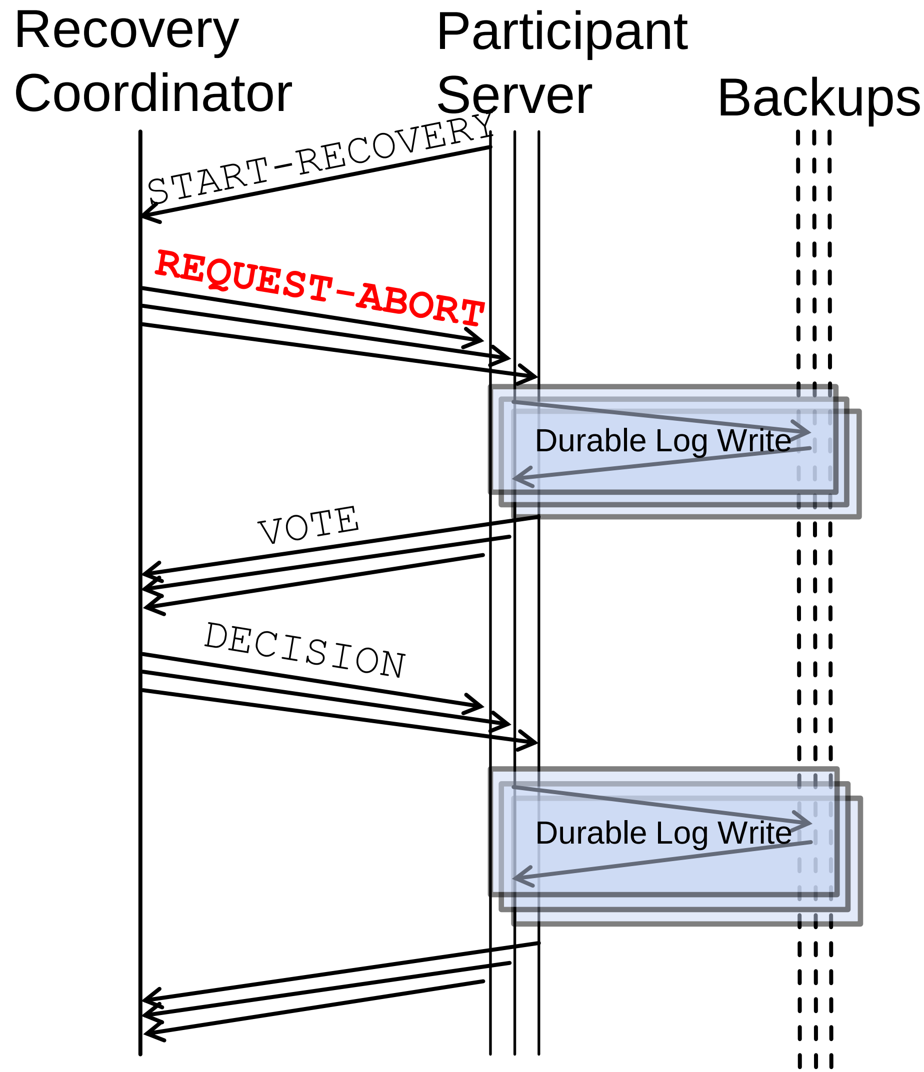
Transaction Commit Protocol

- **Client-driven 2PC**
- **RPCs:**
  - `PREPARE() => VOTE`
  - `DECISION()`
- **Fate of TX is determined after 1st phase**
- **Client blocked for 1 RTT + 1 log write**
- **Decisions processed in background**



Transaction Recovery on Client-crash

- **Server-driven 2PC**
- **Initiated by "worried" server**
- **RPCs:**
  - `START-RECOVERY()`
  - **`REQUEST-ABORT() => VOTE`**
  - `DECISION()`



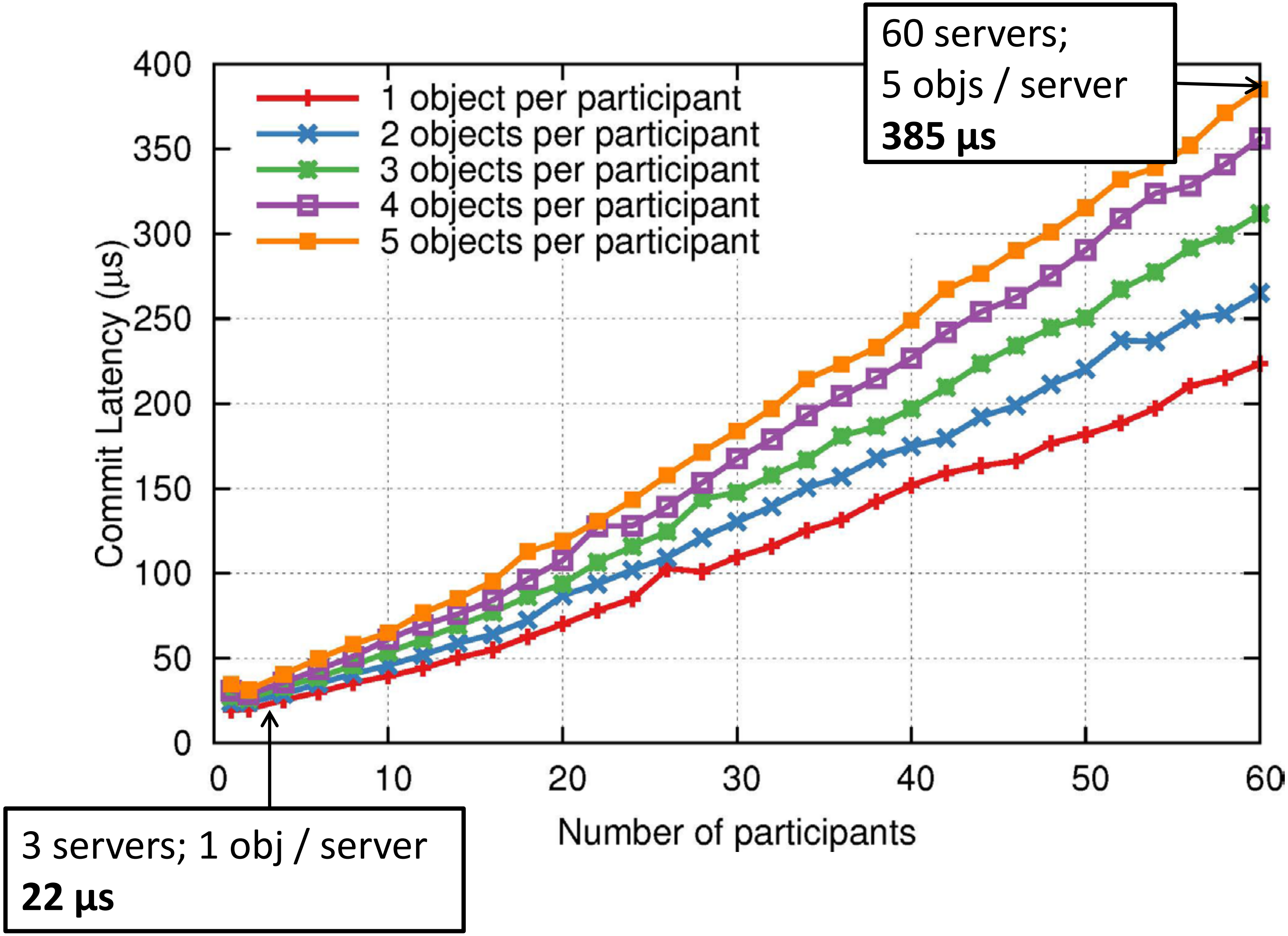
RIFL Simplifies TX Recovery

- **`PREPARE()` => `VOTE` is linearizable RPC**
- **Server crash: client retries PREPARE**
- **Client crash: recovery coordinator sends fake PREPARE (REQUEST-ABORT)**
  - Query ResultTracker with **same RPC ID** from client
  - Writes completion record of PREPARE / REQUEST-ABORT
- **Race between client's 2PC and recovery coordinator's 2PC is safe**

Performance of Transactions in RAMCloud

- Simple distributed transactions commits in 22 µs
- TPC-C benchmark shows RIFL-based transactions outperform H-Store

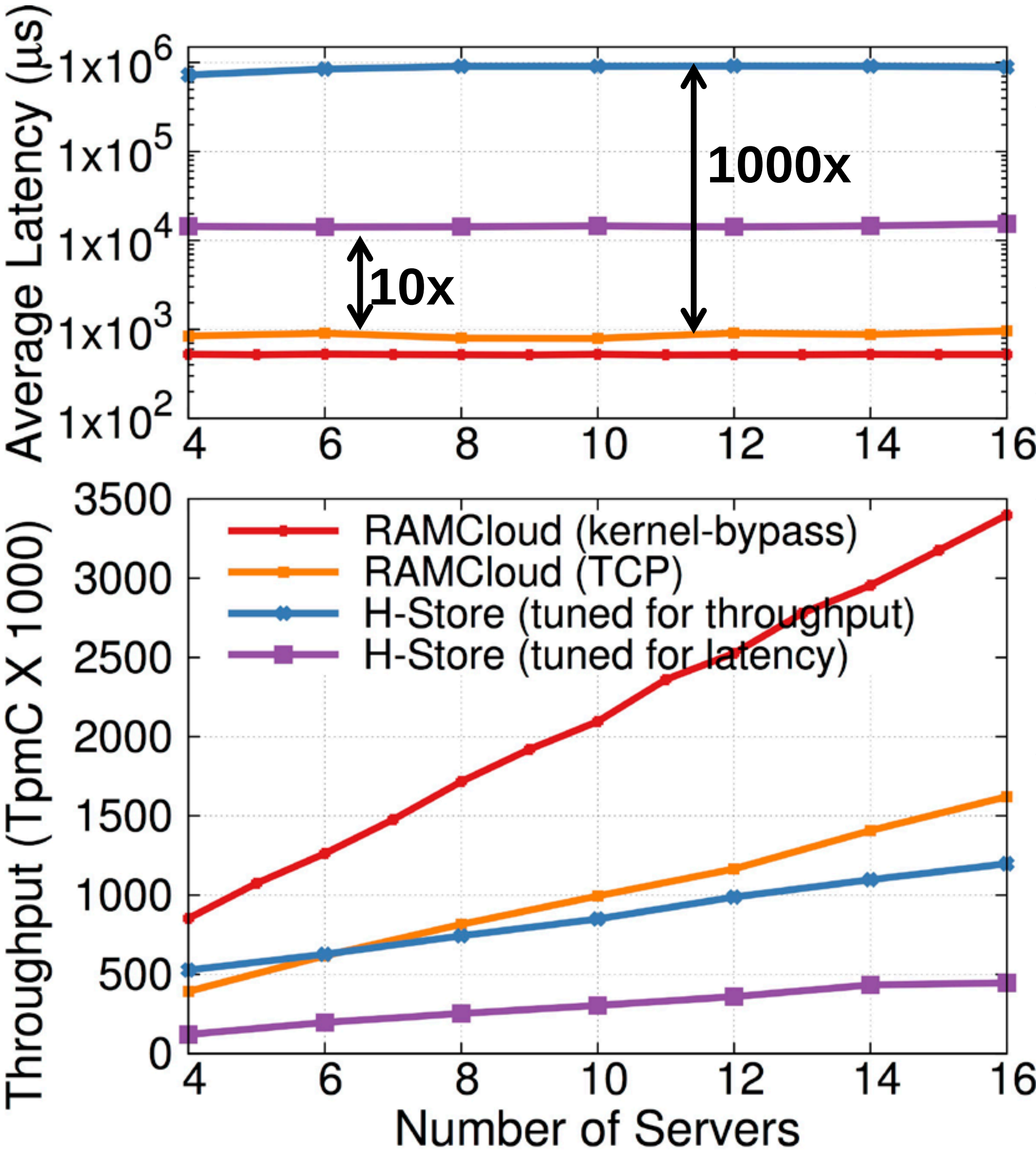
Latency of Transactions



TPC-C Benchmark

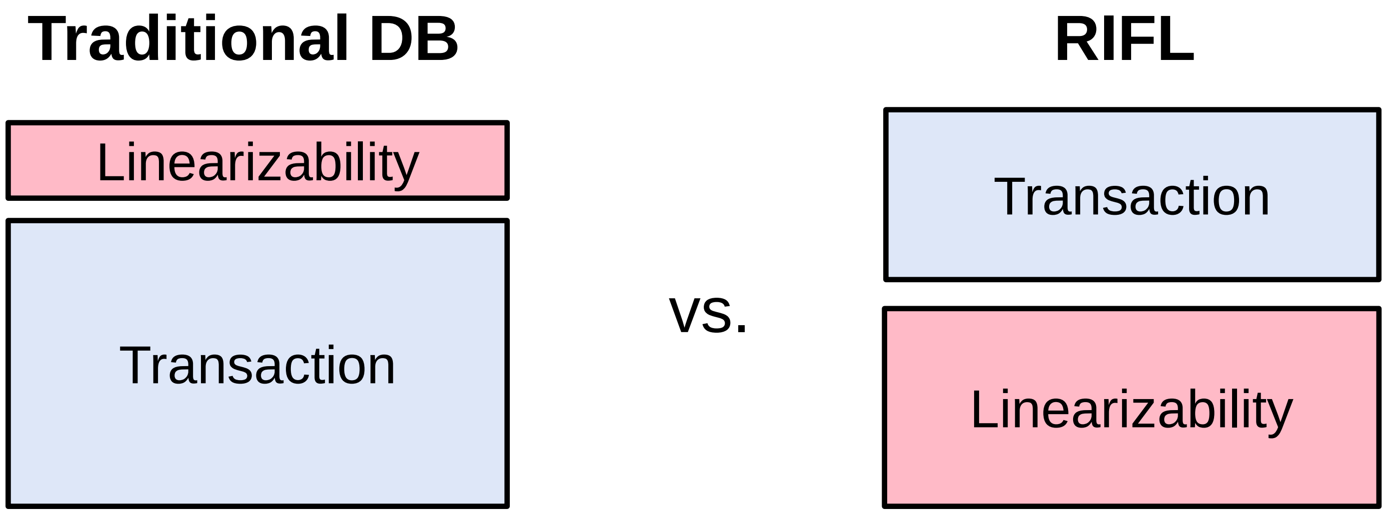
- **TPC-C simulates order fulfillment systems**
  - New-Order transaction: 23 reads, 23 writes
  - Used full-mix of TPC-C (~10% distributed)
  - Latency is measured from end to end
  - Modified TPC-C for benchmark to increase server load
- **Compared with H-Store**
  - Main-memory DBMS for OLTP
- **Two RAMCloud configurations**
  - Kernel-bypass for maximum performance
  - Kernel TCP for fair comparison

TPC-C Performance



- **TpmC:** NewOrder committed per minute
- **210,000 TpmC / server**
- **Latency: ~500µs**
- **RAMCloud faster than H-Store** (even over TCP)
- **Limited by serial log-replication** (need batching)

Should linearizability be a foundation?



- **Faster simple operations (eg. atomic increment)**
  - lower latency
  - higher throughput
- **Can be added on top of existing systems**
- **Better modular decomposition**
  - easier to implement transaction

Conclusion

- **Distinct layer for linearizability →** take back consistency in large-scale systems
- **RIFL saves results** of RPCs; If client **retries,** returns saved result **without re-executing**
  - 0.5us (< 5%) latency overhead, almost no throughput overhead.
- **RIFL** makes **transactions** easier
  - RIFL-based RAMCloud transaction: ~**20 μs** for commit
  - Outperform H-Store for TPC-C benchmark

Questions