Rocksteady: Fast Migration for Low-Latency In-memory Storage

Chinmay Kulkarni, Aniraj Kesavan, Tian Zhang, Robert Ricci, Ryan Stutsman

Introduction

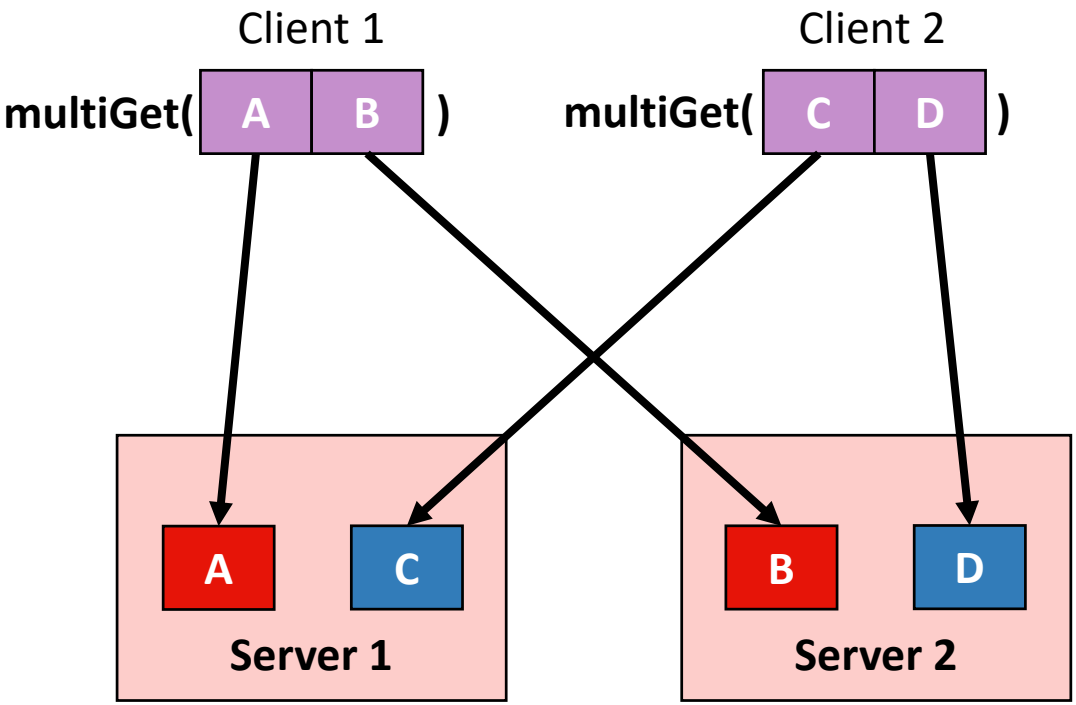
- Distributed low-latency in-memory key-value stores are emerging
  - Predictable response times ~**10 µs median, ~60 µs 99.9th-tile**

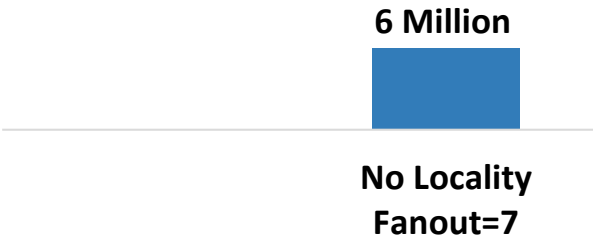
- **Problem:** Must migrate data between servers
  - Minimize performance impact of migration → **go slow?**
  - Quickly respond to hot spots, skew shifts, load spikes → **go fast?**

- **Solution:** **Fast** data migration with **low impact**
  - Early ownership transfer of data, leverage workload skew
  - Low priority, parallel and adaptive migration

- **Result:** Migration protocol for RAMCloud in-memory key-value store
  - Migrates **256 GB in 6 minutes,** 99.9th-tile latency less than **250 µs**
  - Median latency recovers from **40 µs to 20 µs in 14 s**

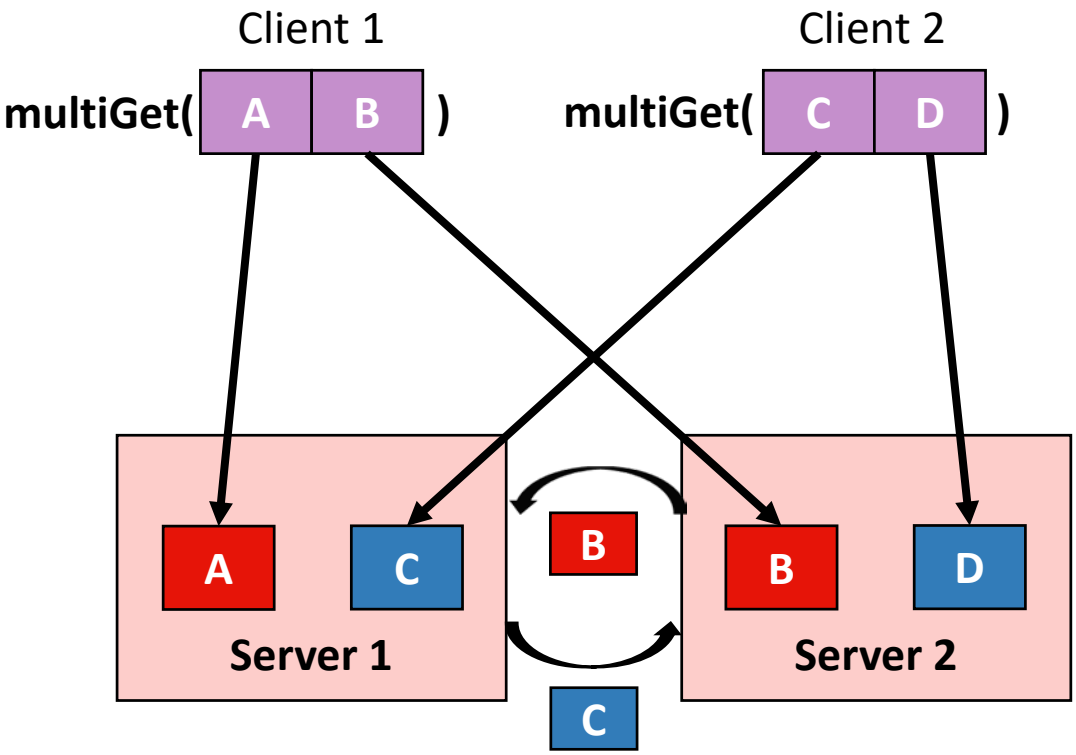
Why Migrate Data?

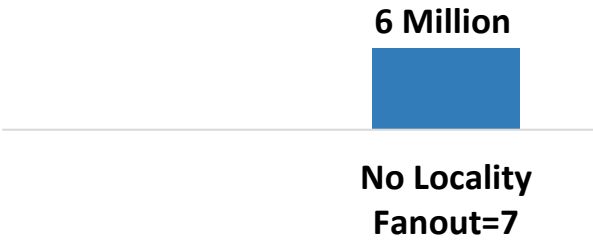




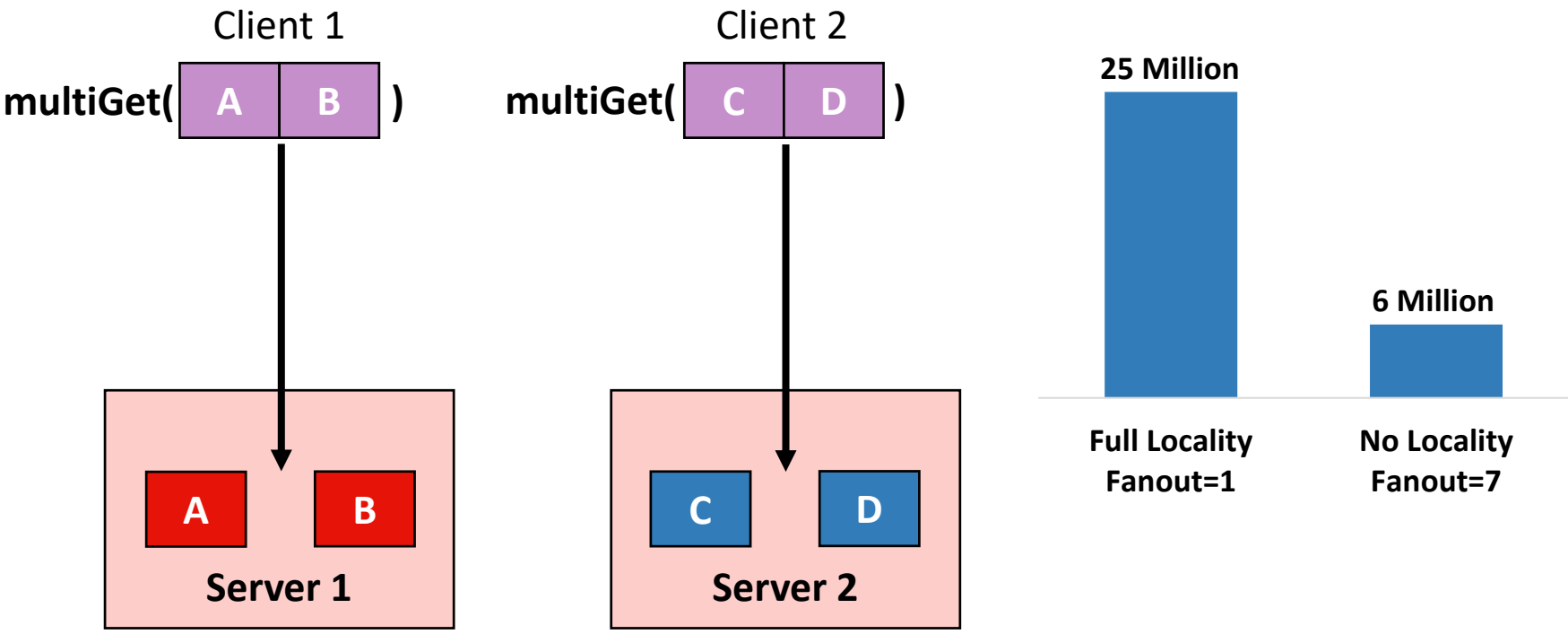
Poor spatial locality → High multiGet() fan-out → More RPCs

Migrate To Improve Spatial Locality





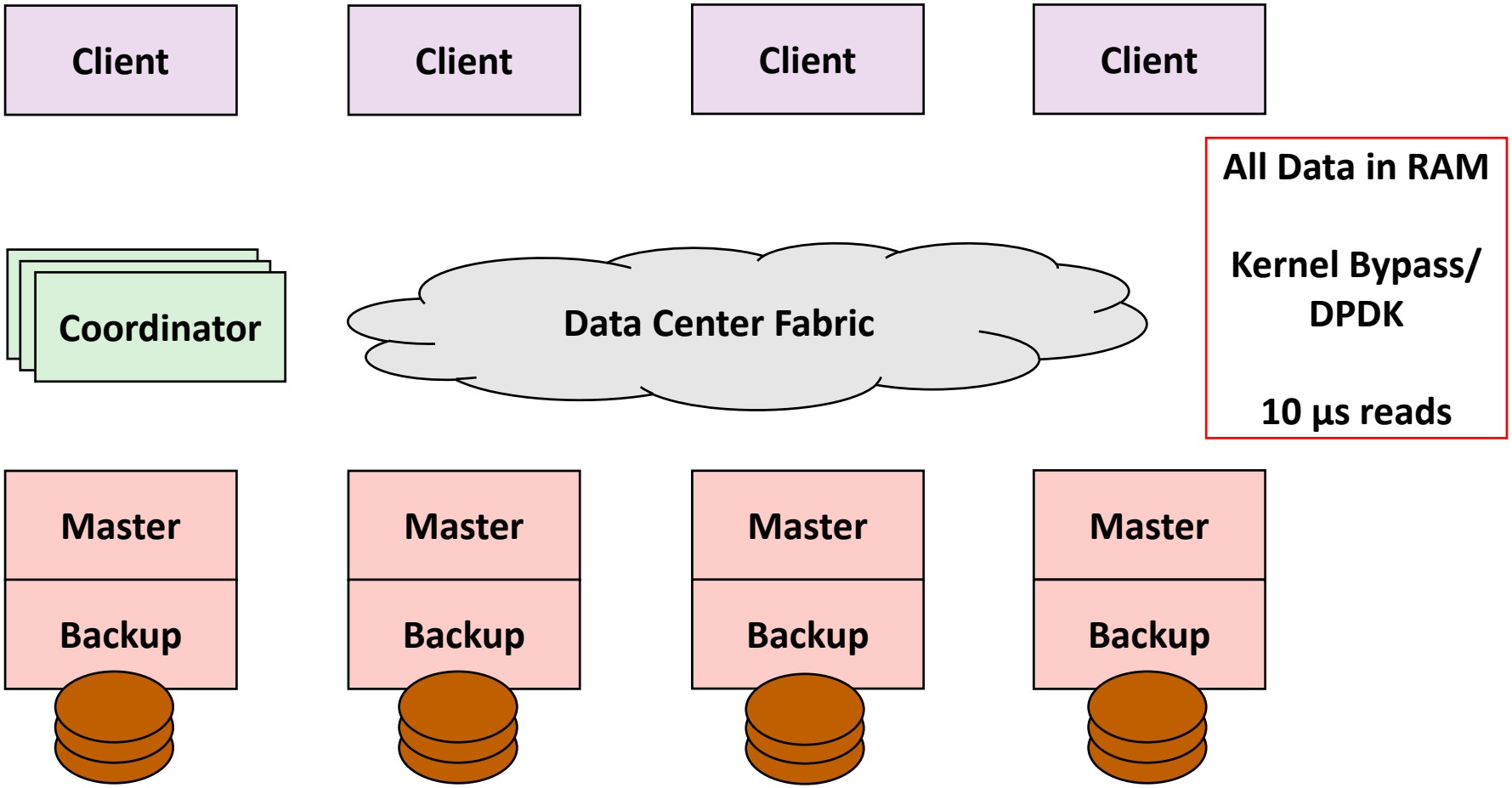
Spatial Locality Improves Throughput



Better spatial locality → Fewer RPCs → Higher throughput

Benefits multiGet(), range scans

The RAMCloud Key-Value Store



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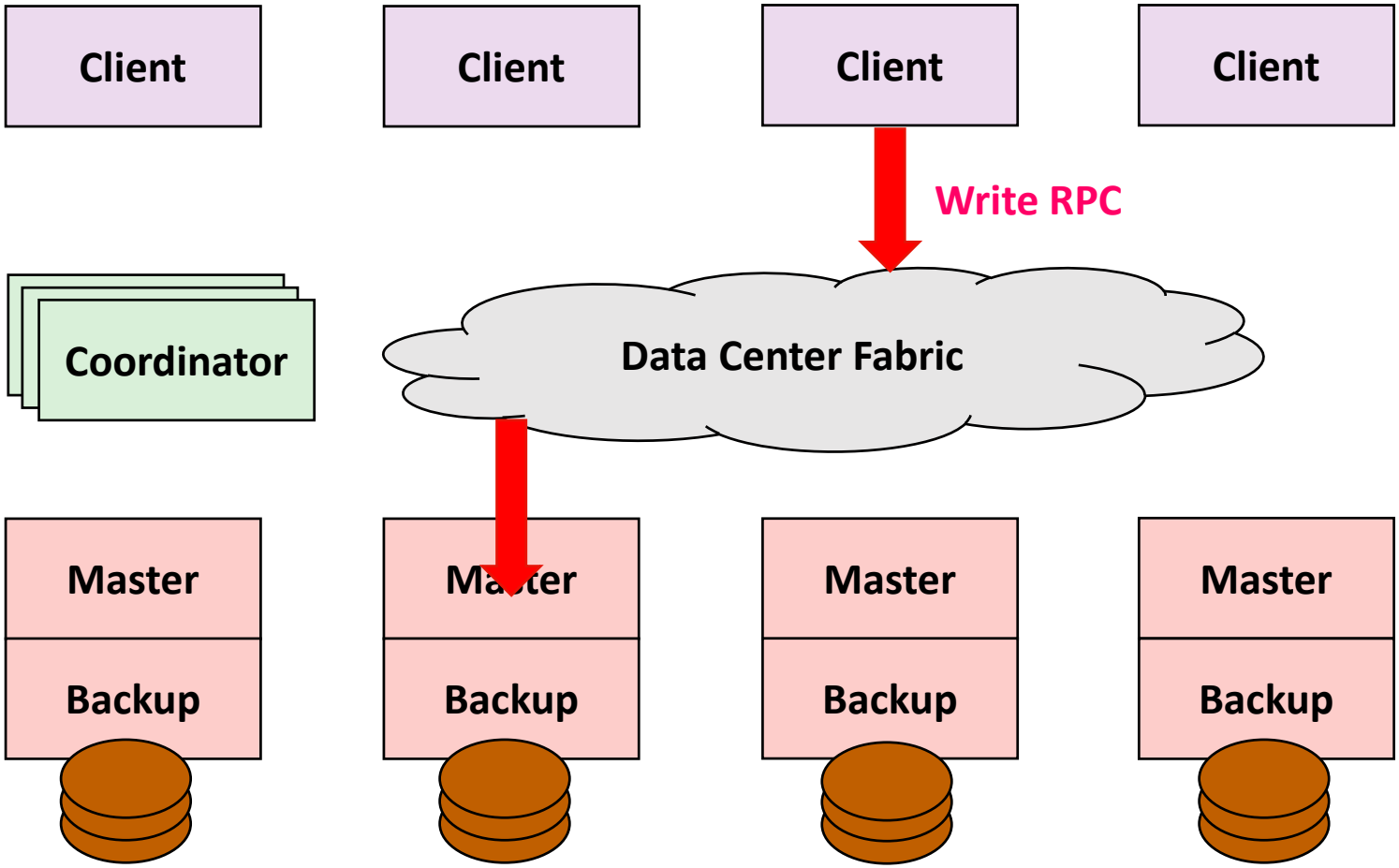

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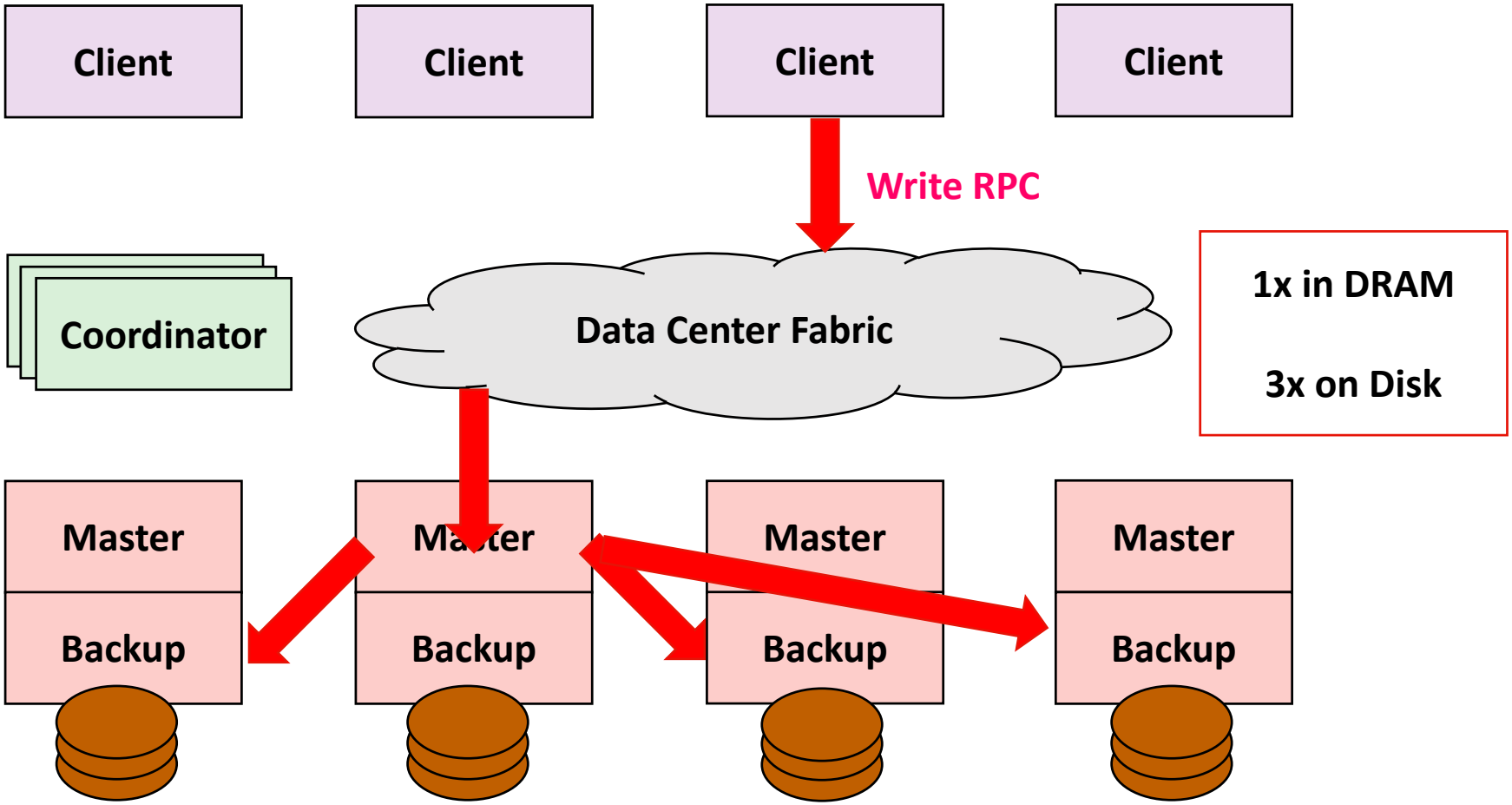
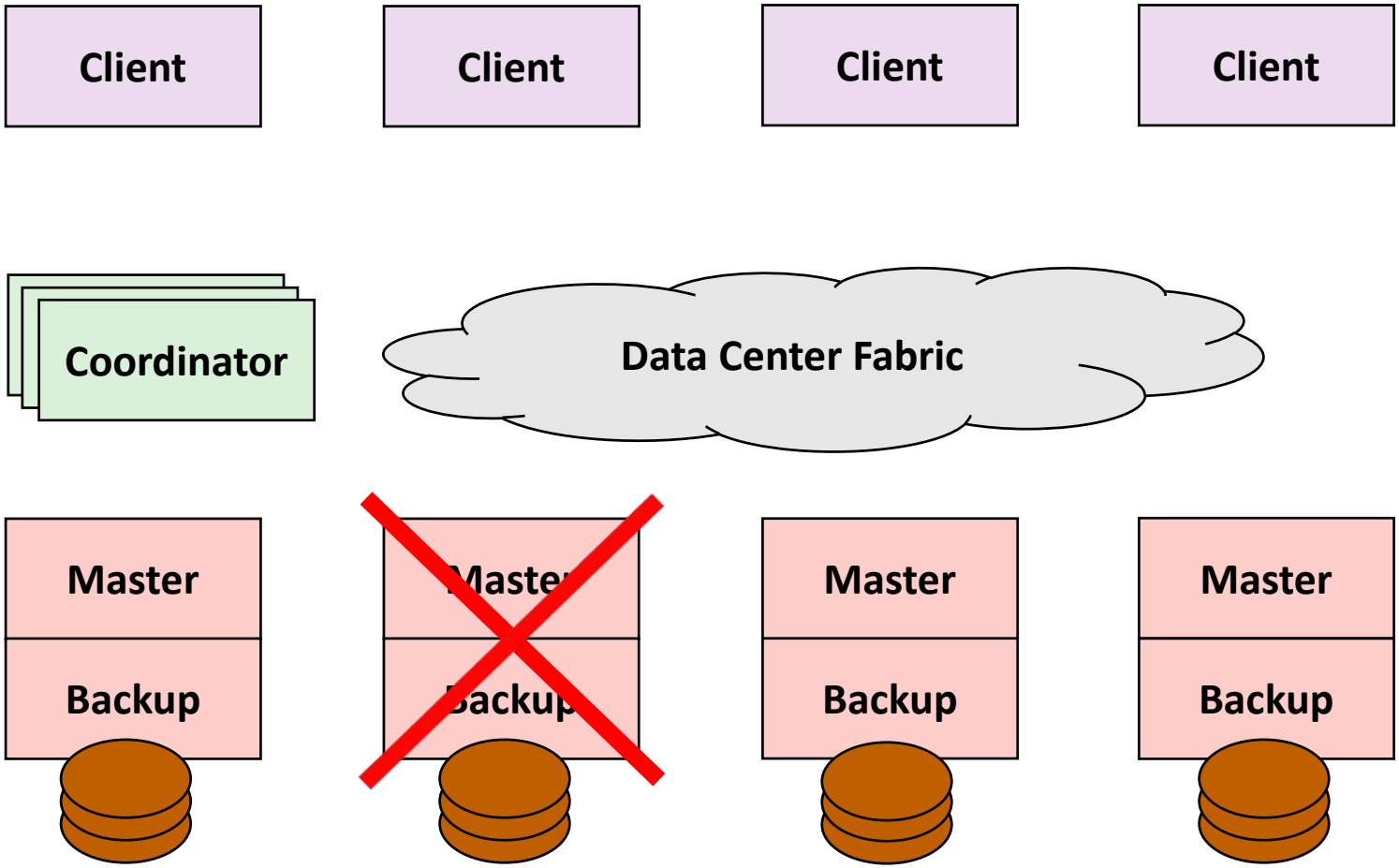


Fault-tolerance & Recovery In RAMCloud



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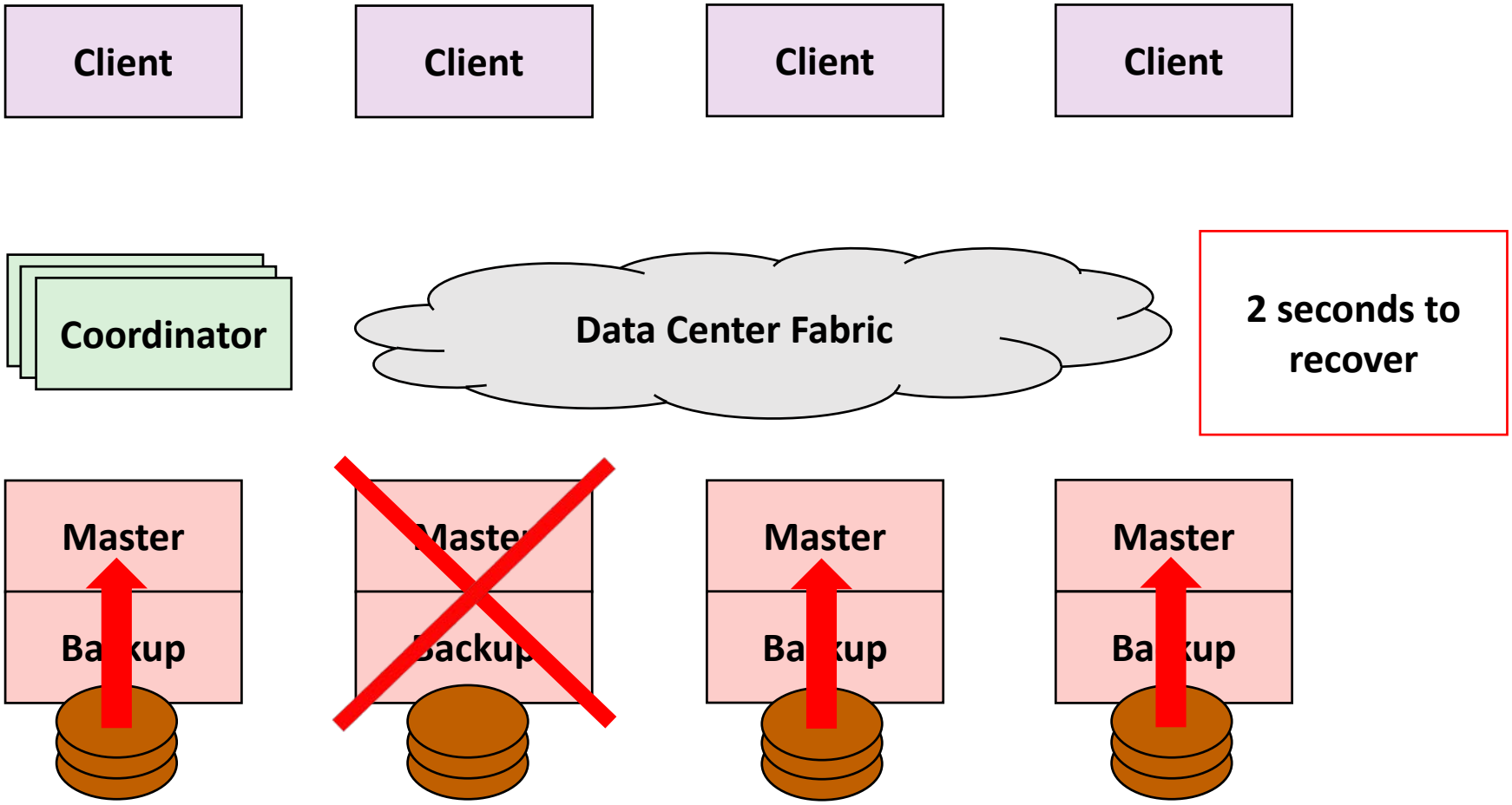


Performance Goals For Migration

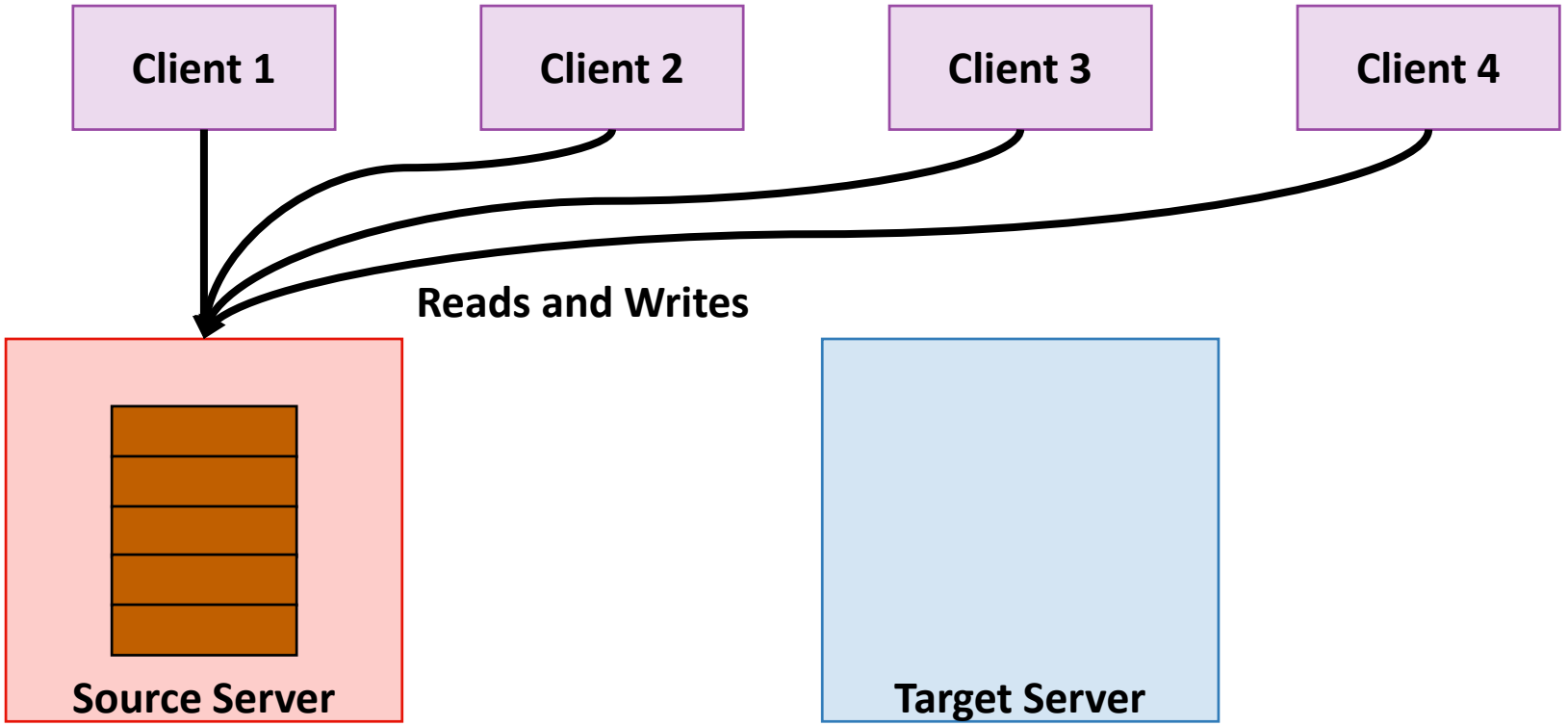
- **Maintain low access latency**
  - 10 µsec median latency → System extremely sensitive
  - Tail latency matters at scale → Even more sensitive

- **Migrate data fast**
  - Workloads dynamic → Respond quickly
  - Growing DRAM storage: 512 GB per server
    - Slow data migration → Entire day to scale cluster

Rocksteady Overview: Early Ownership Transfer

Problem: **Loaded source can bottleneck migration**

Solution: **Instantly shift ownership and all load to target**



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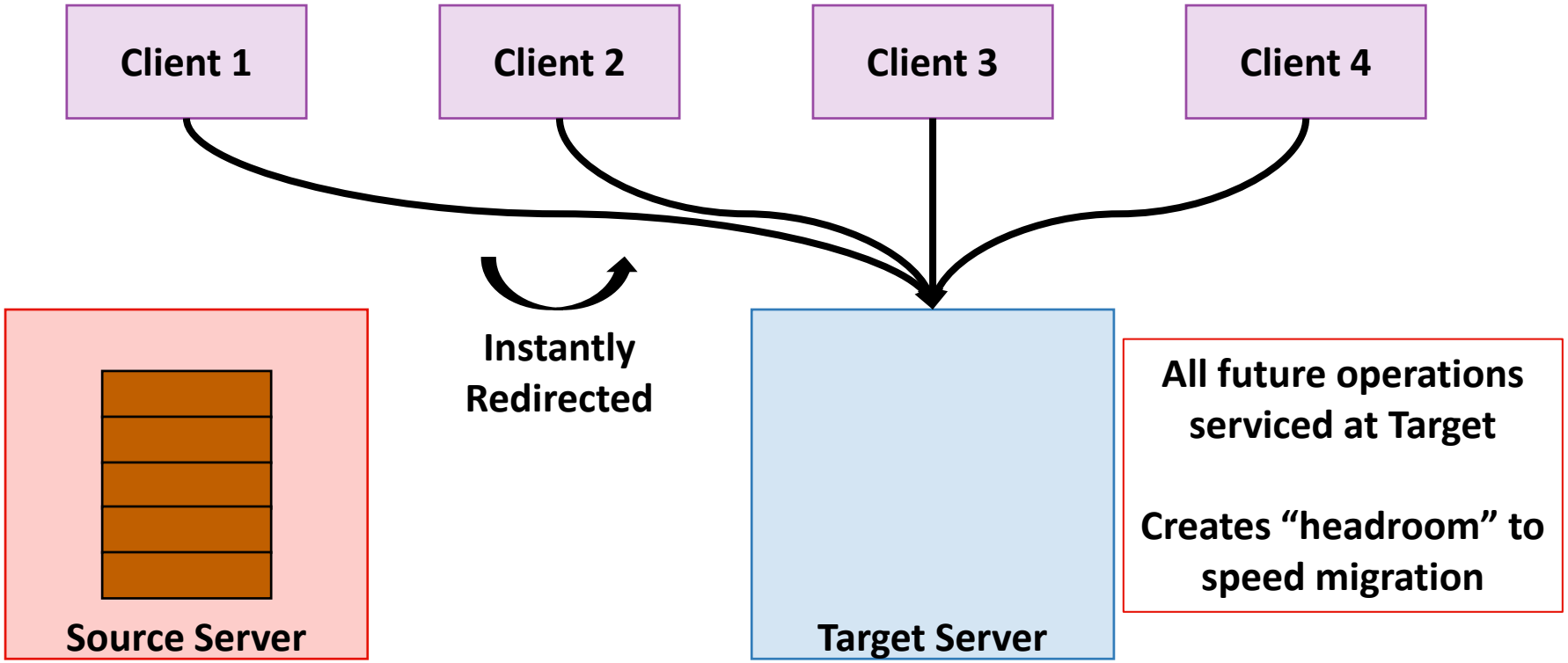
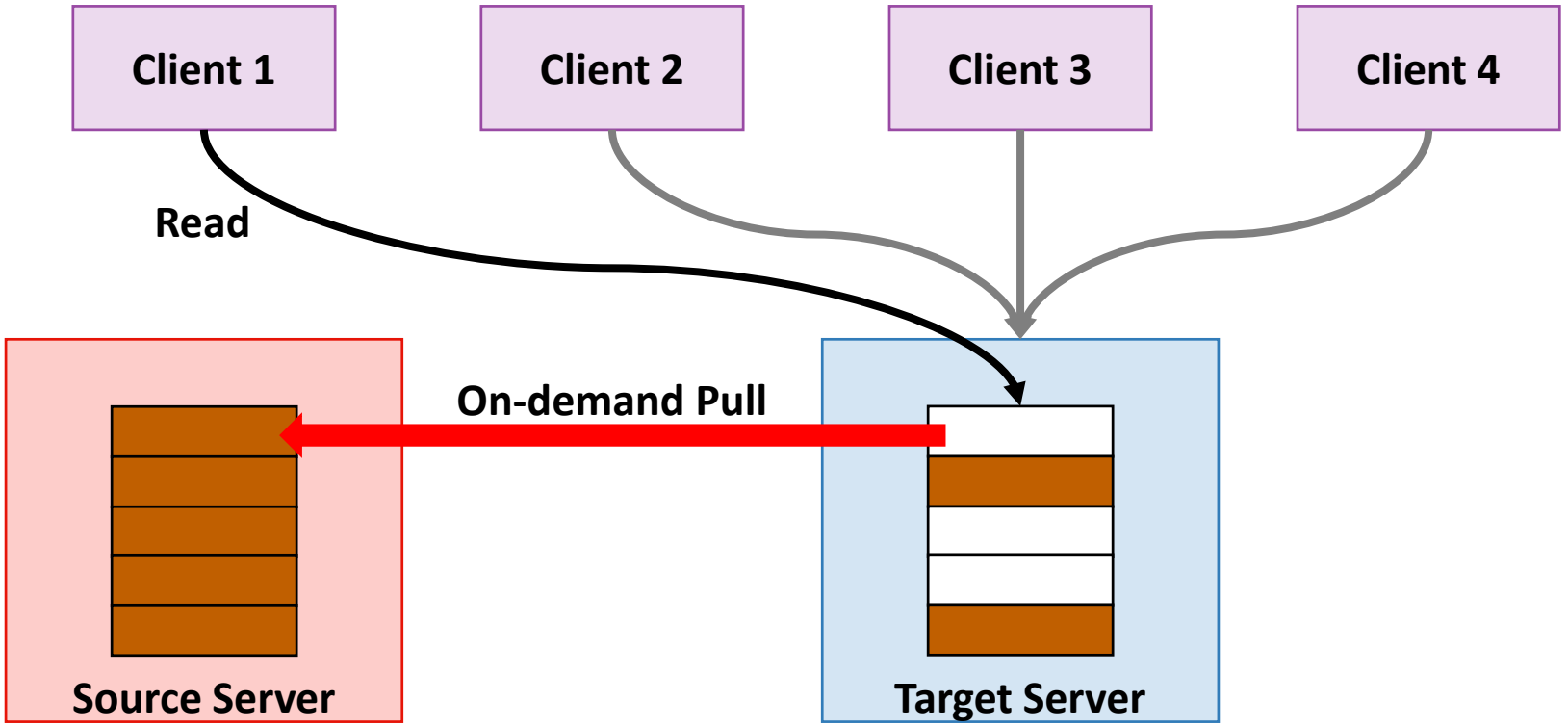


Rocksteady Overview: Leverage Skew

Problem: **Data has not arrived at source yet**

Solution: **On demand migration of unavailable data**



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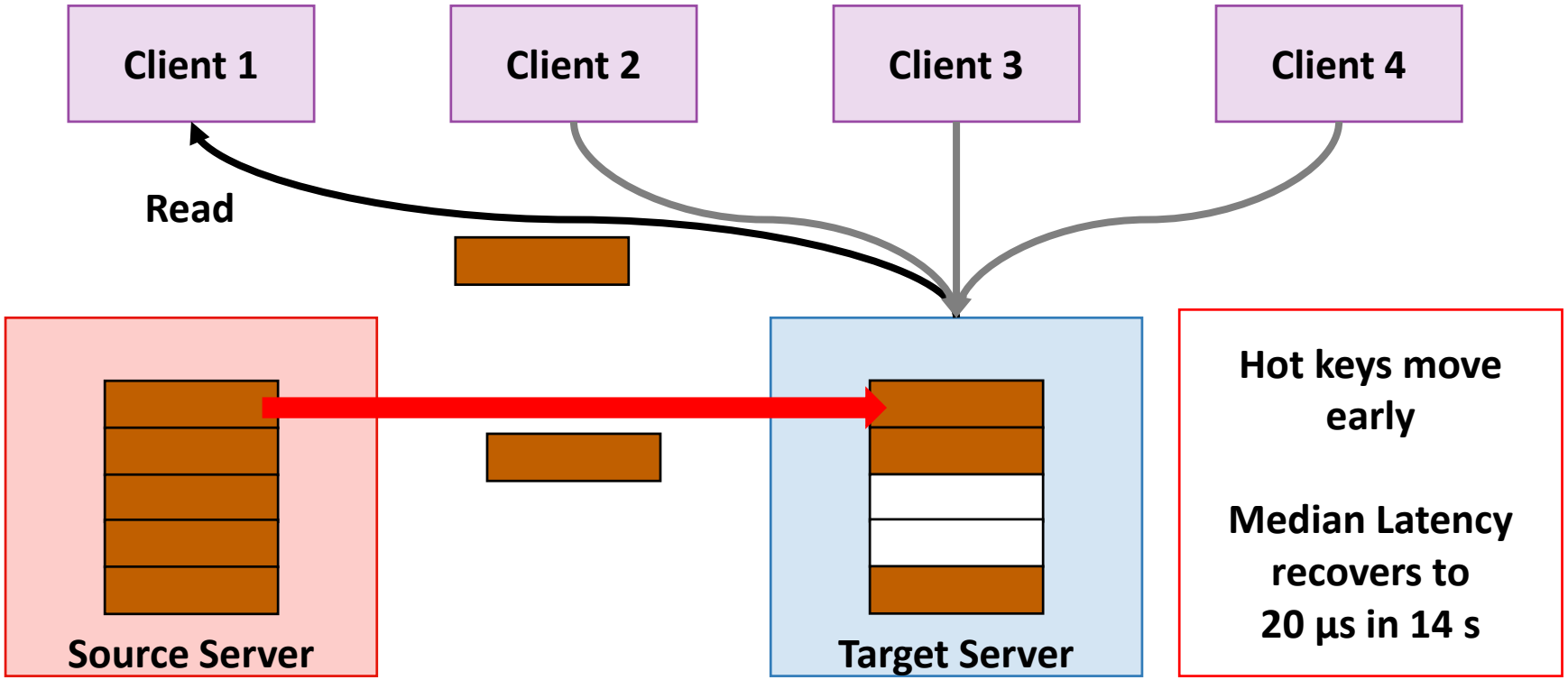

Rocksteady Overview: Adaptive and Parallel

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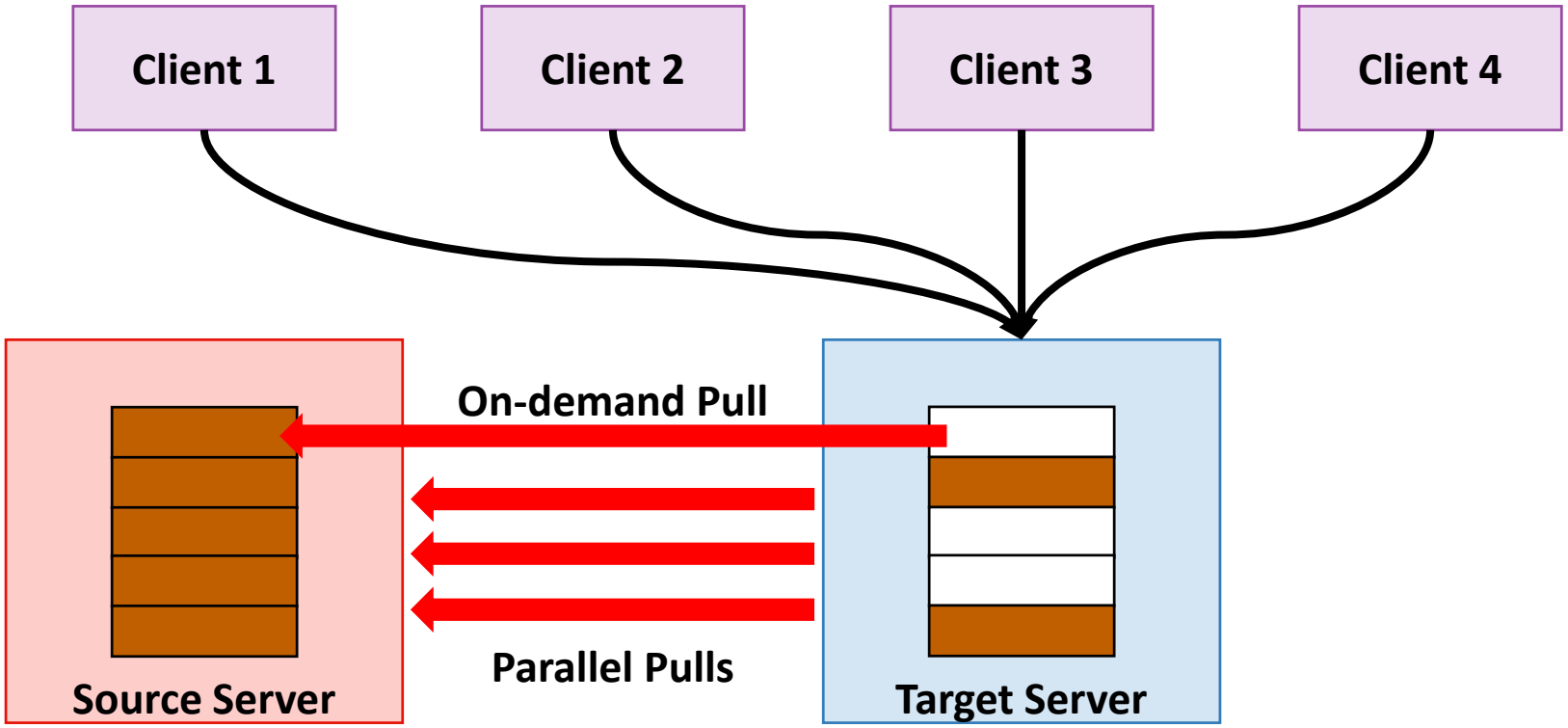

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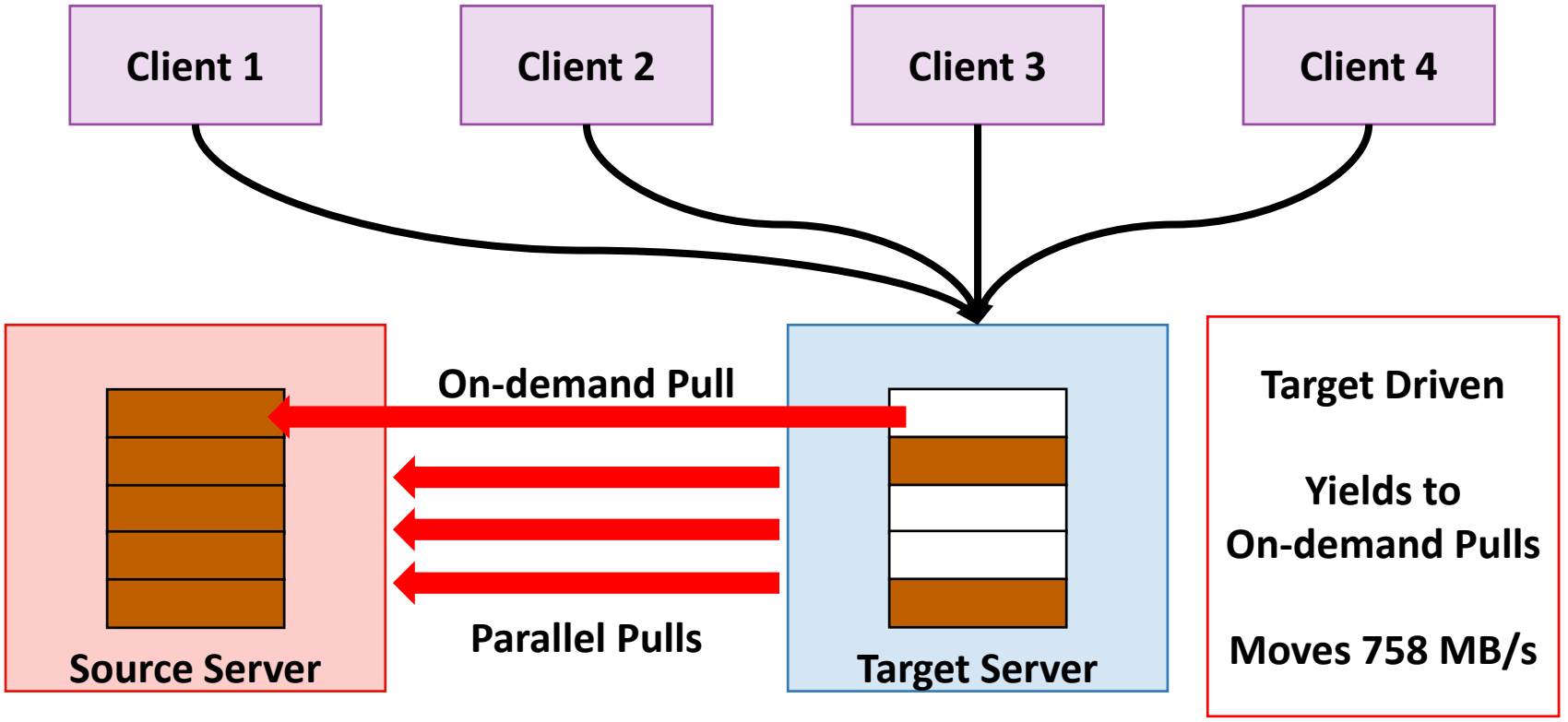
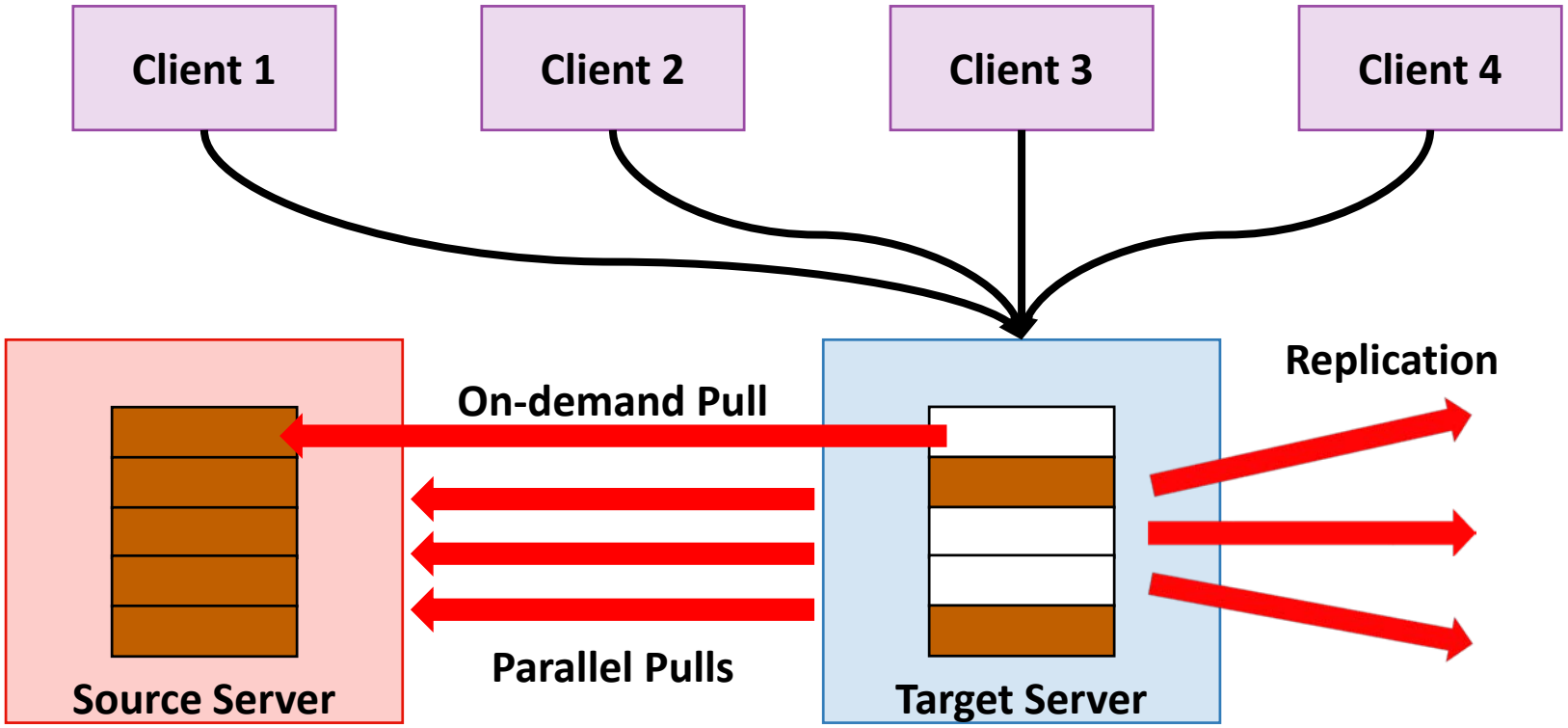


Rocksteady Overview: Eliminate Sync Replication

Problem: **Synchronous replication bottleneck at target**

Solution: **Safely defer replication until after migration**



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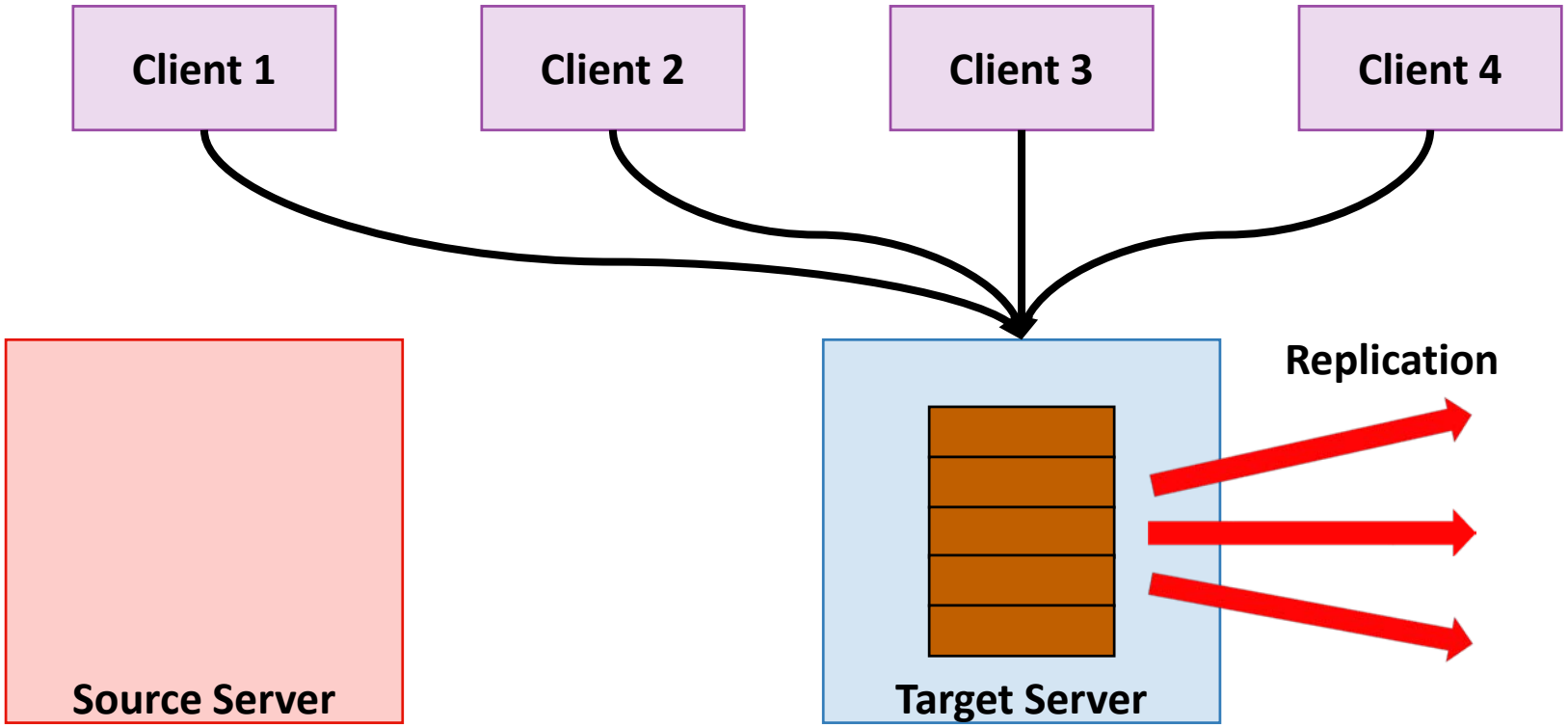


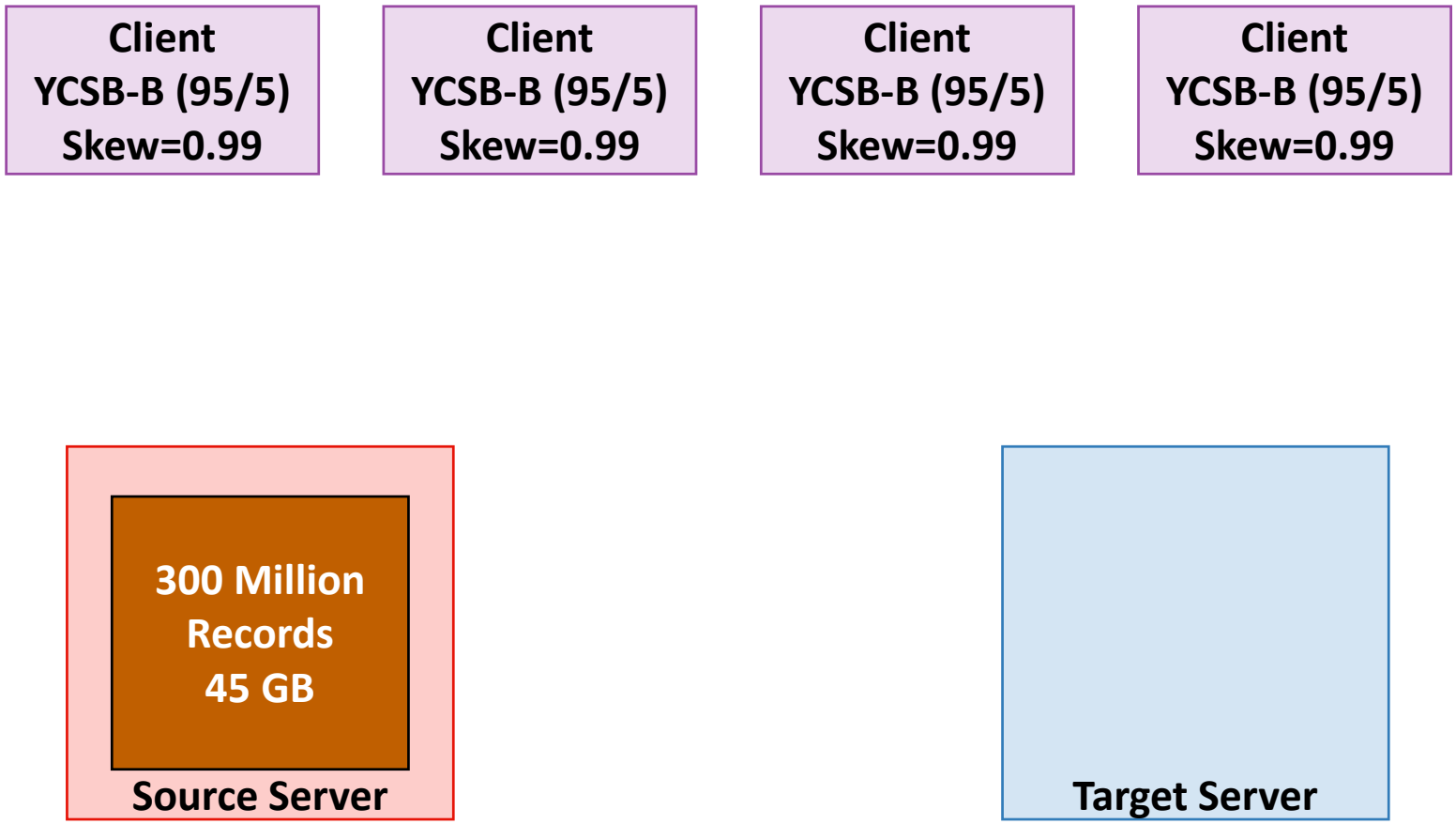
Rocksteady: Putting it all together

- **Instantaneous ownership transfer**
  - Immediate load reduction at overloaded source
  - Creates “headroom” for migration work
- **Leverage skew to rapidly migrate hot data**
  - Target comes up to speed with little data movement
- **Adaptive parallel, pipelined at source and target**
  - All cores avoid stalls, but yield to client-facing operations
- **Safely defer replication at target**
  - Eliminates replication bottleneck and contention

Rocksteady

- **Instantaneous ownership transfer**
- Leverage skew to rapidly migrate hot data
- Adaptive parallel, pipelined at source and target
- Safely defer synchronous replication at target

Evaluation Setup



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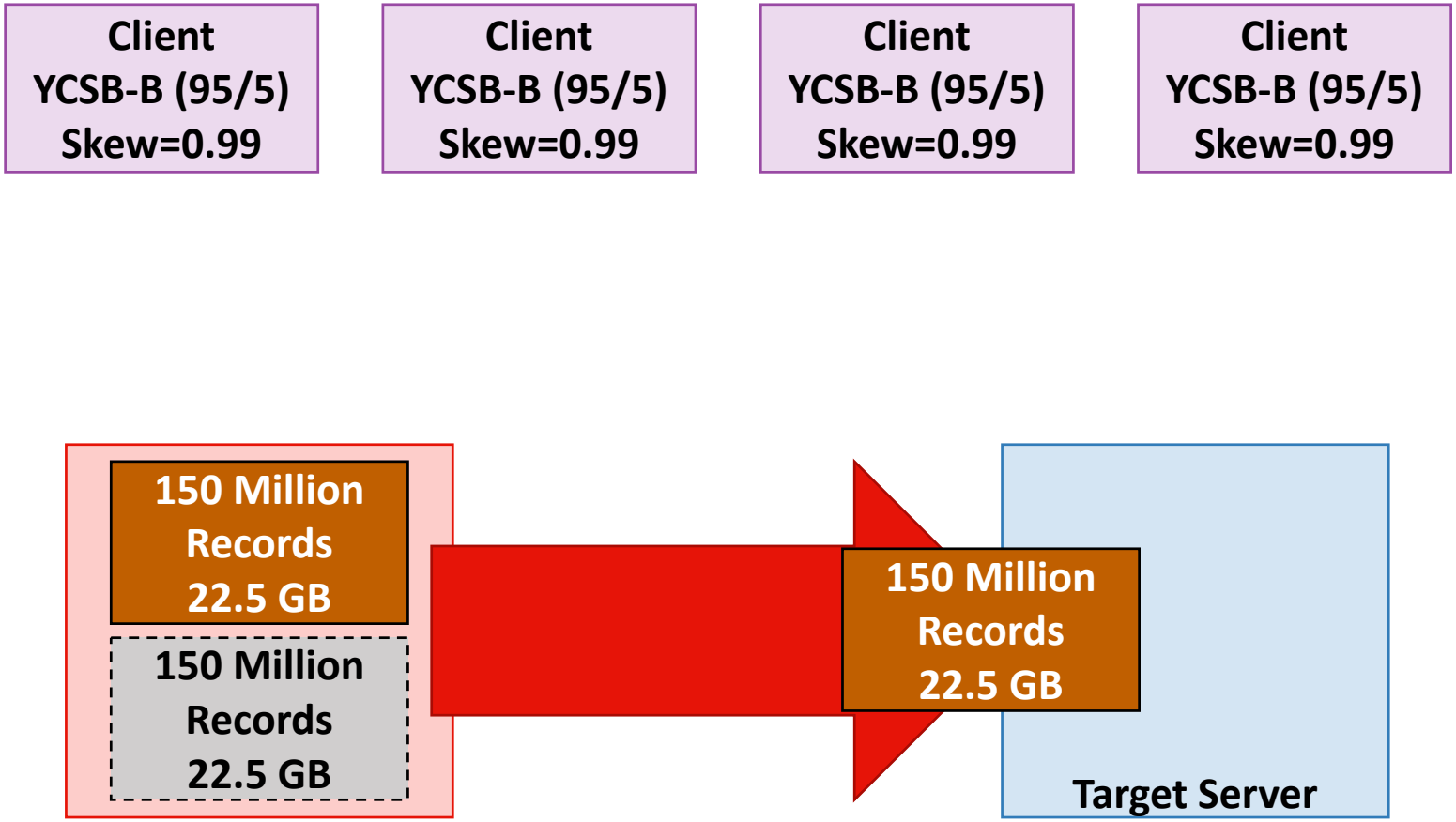
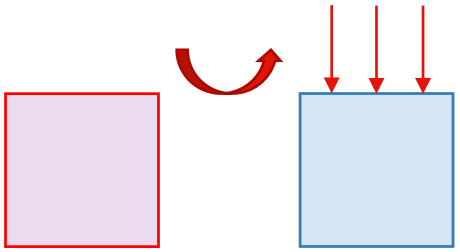
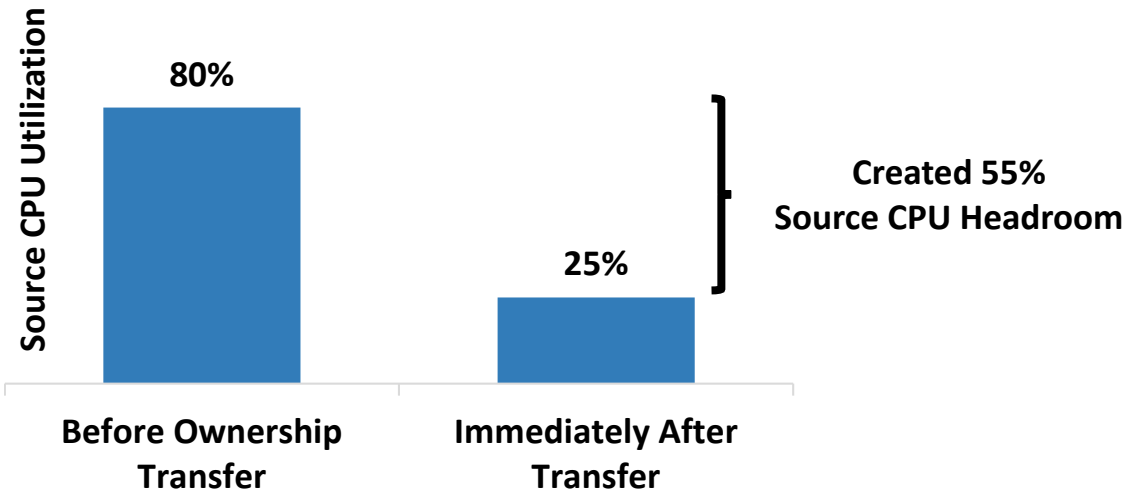


Instantaneous Ownership Transfer





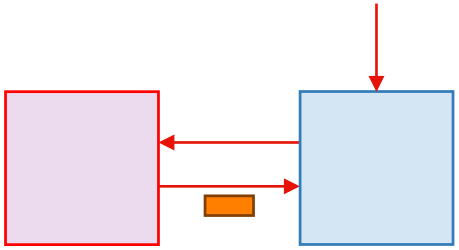
Before migration: Source over-loaded, Target under-loaded

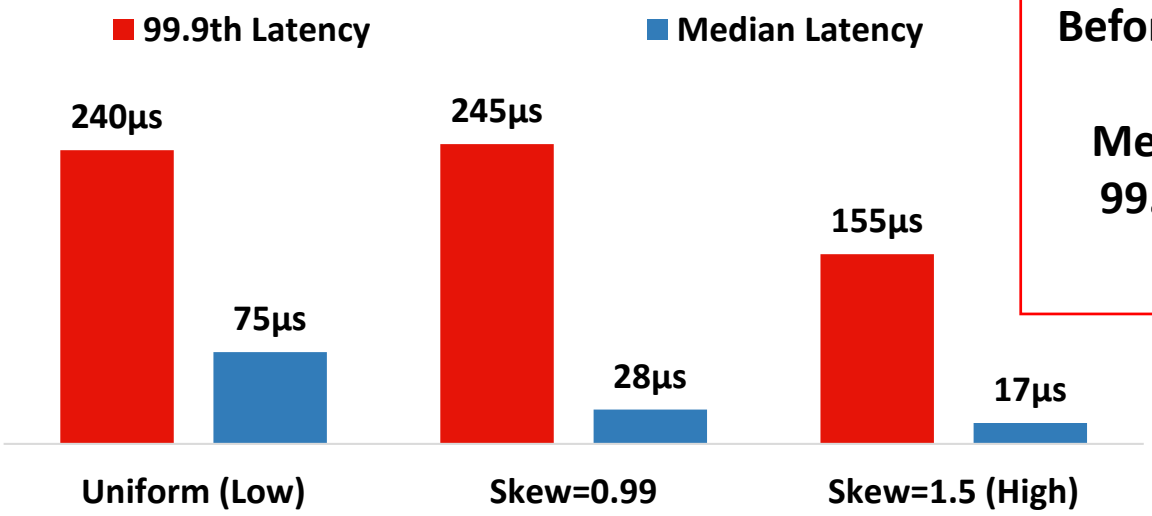
Ownership transfer creates Source headroom for migration

Rocksteady

- Instantaneous ownership transfer
- **Leverage skew to rapidly migrate hot data**
- Adaptive parallel, pipelined at source and target
- Safely defer synchronous replication at target

Leverage Skew To Move Hot Data





Before Migration:

Median=10 µs
99.9th = 60 µs

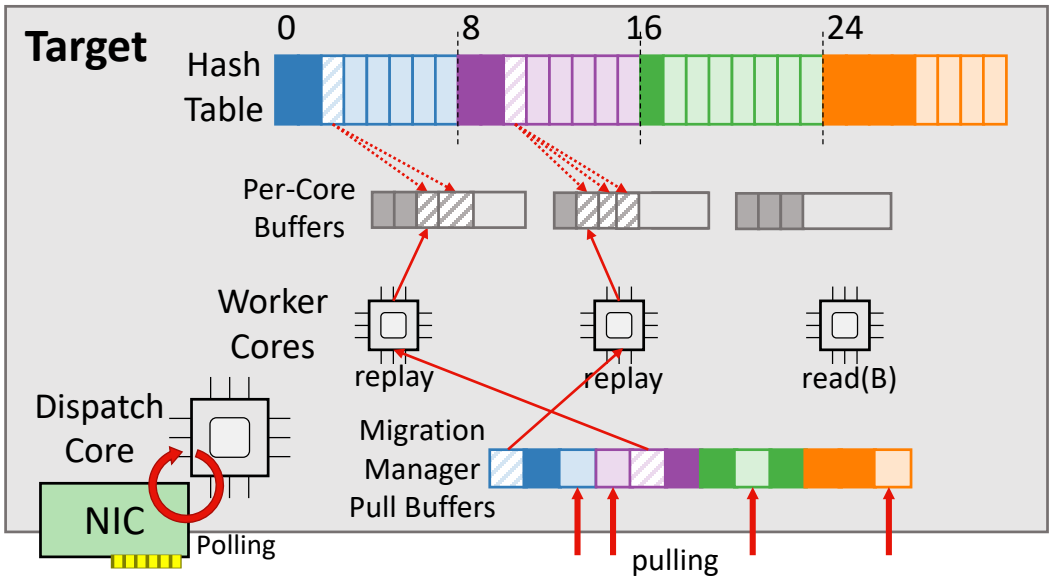
After ownership transfer, hot keys pulled on-demand

More skew → Median restored faster (migrate fewer hot keys)

Rocksteady

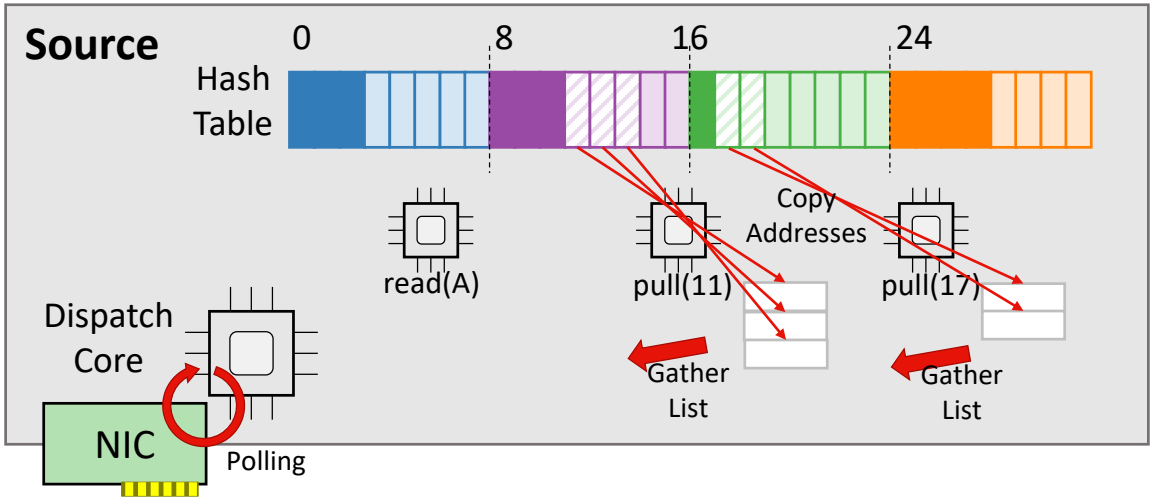
- Instantaneous ownership transfer
- Leverage skew to rapidly migrate hot data
- **Adaptive parallel, pipelined at source and target**
- Safely defer synchronous replication at target

Parallel, Pipelined, & Adaptive Pulls



- **Target driven, migration manager**
- **Co-partitioned hash tables, pull from partitions in parallel**
- **Replay pulled data into per-core buffers**

Parallel, Pipelined, & Adaptive Pulls



- **Stateless passive Source**
- **Granular 20 KB pulls**

Parallel, Pipelined, & Adaptive Pulls

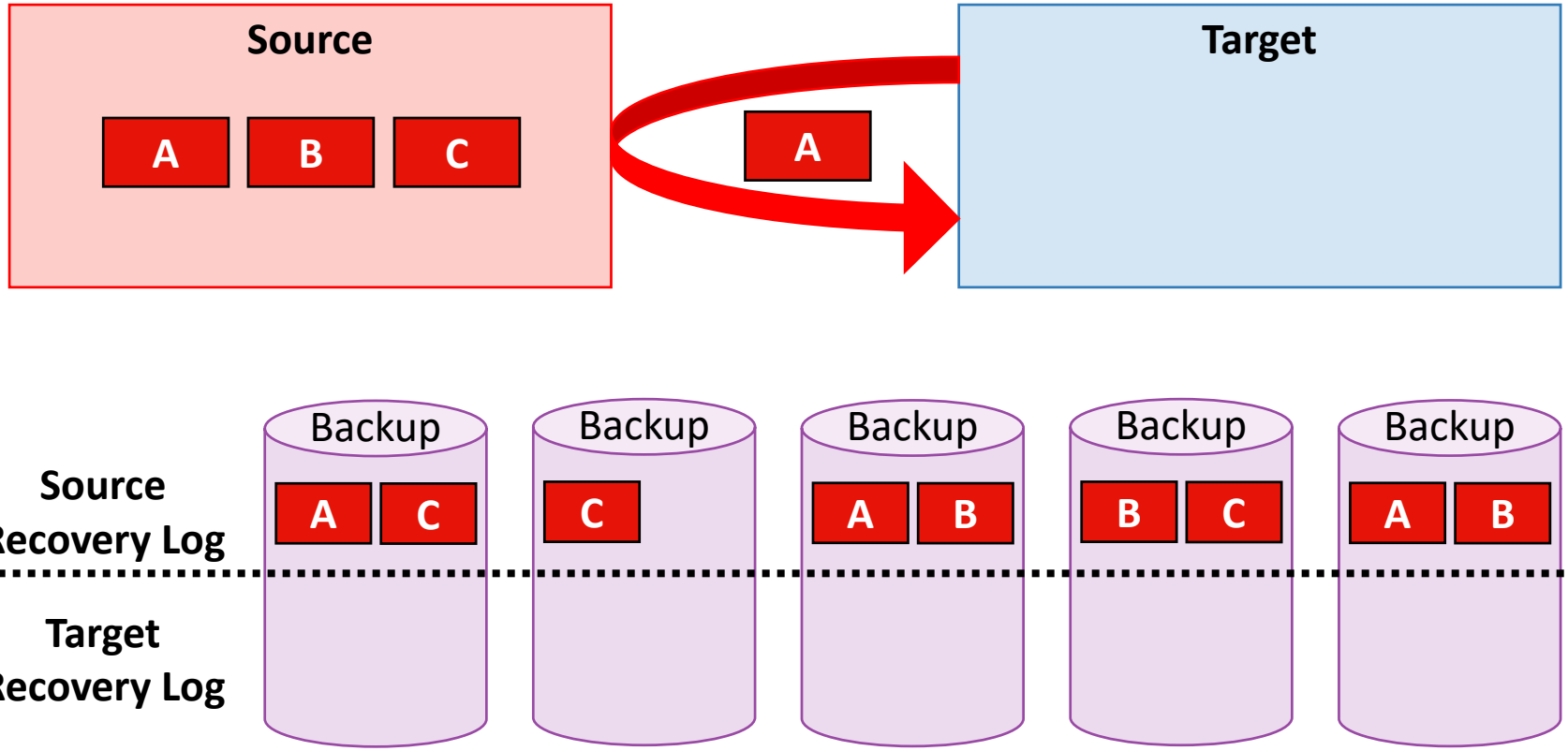
- **Redirect any idle CPU for migration**
- **Migration yields to regular requests, on-demand pulls**

Rocksteady

- Instantaneous ownership transfer
- Leverage skew to rapidly migrate hot data
- Adaptive parallel, pipelined at source and target
- **Safely defer synchronous replication at target**

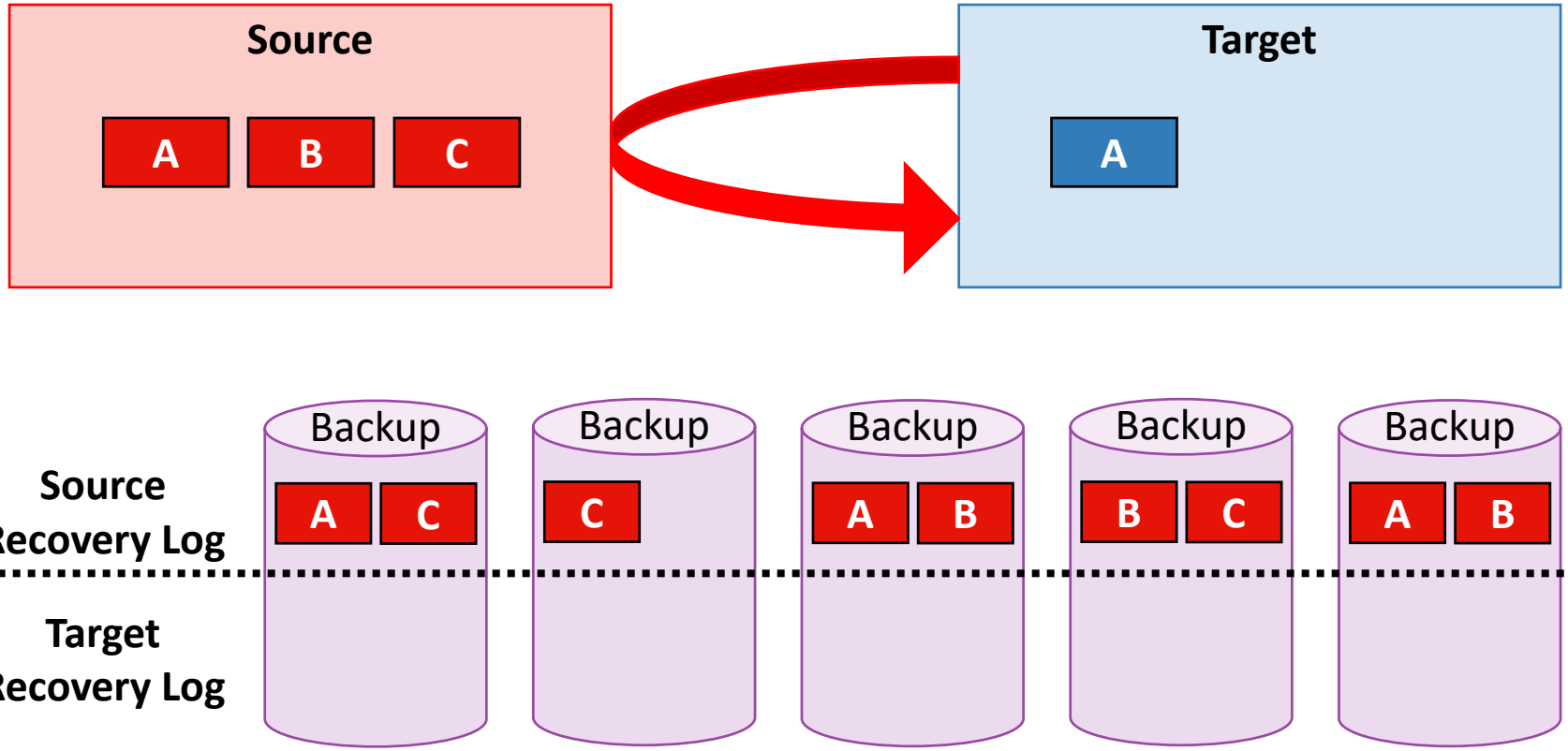
Naïve Fault Tolerance During Migration

Each server has a recovery log distributed across the cluster



Naïve Fault Tolerance During Migration

Migrated data needs to be triplicated to target's recovery log



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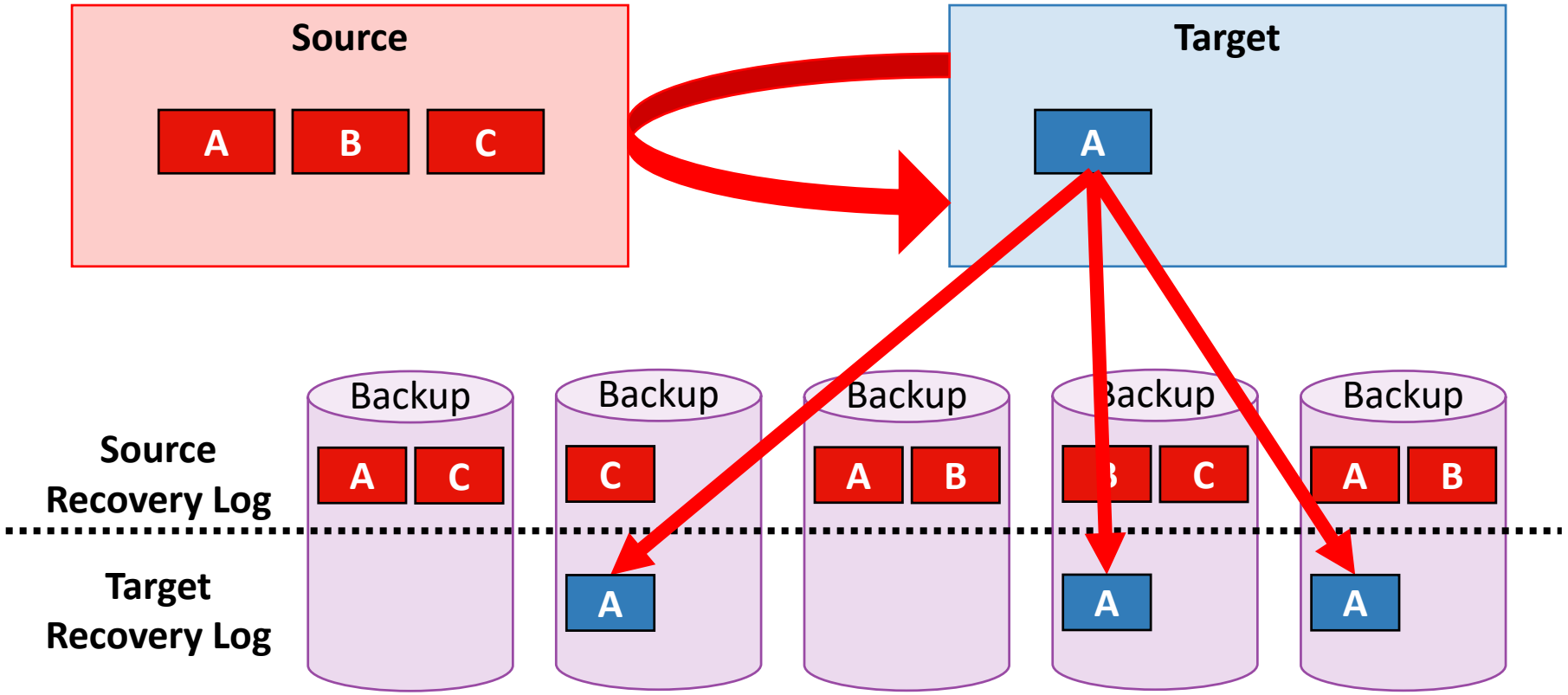
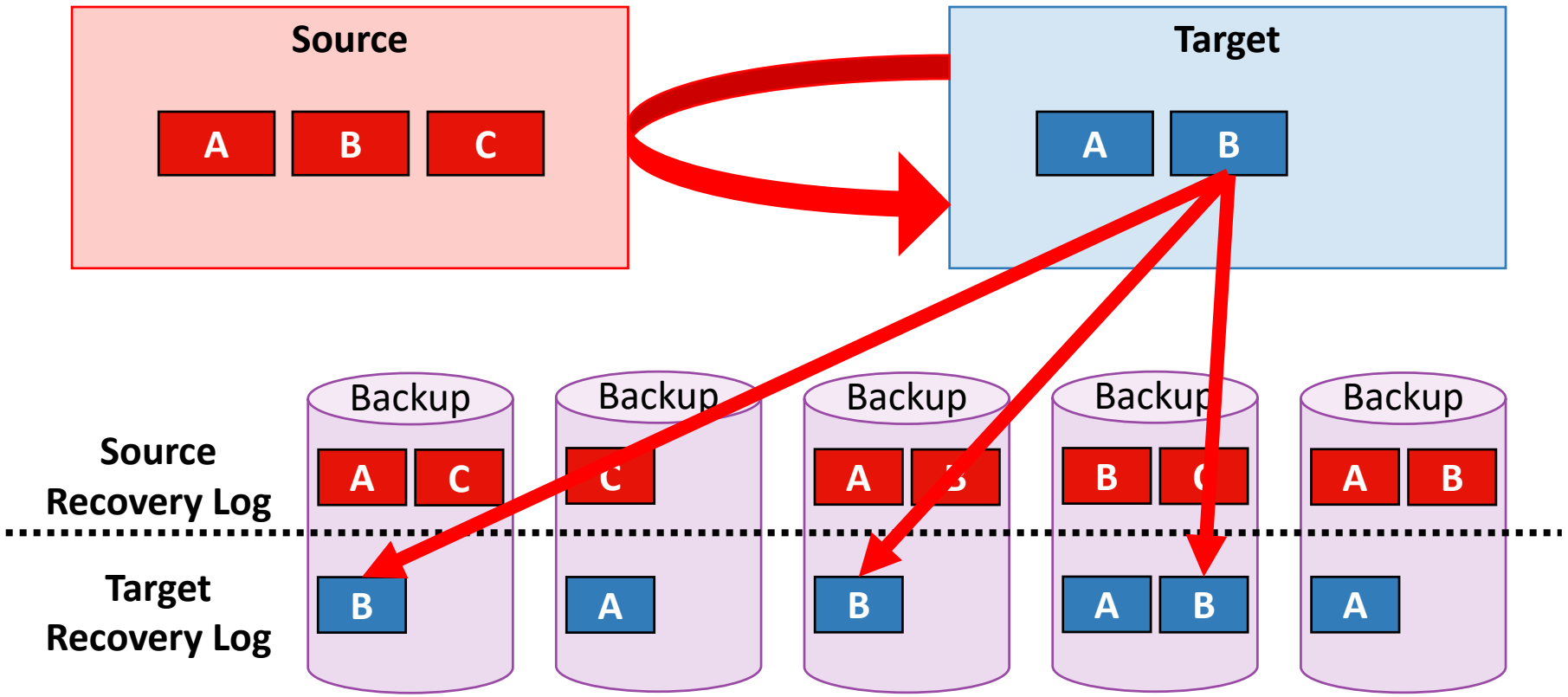


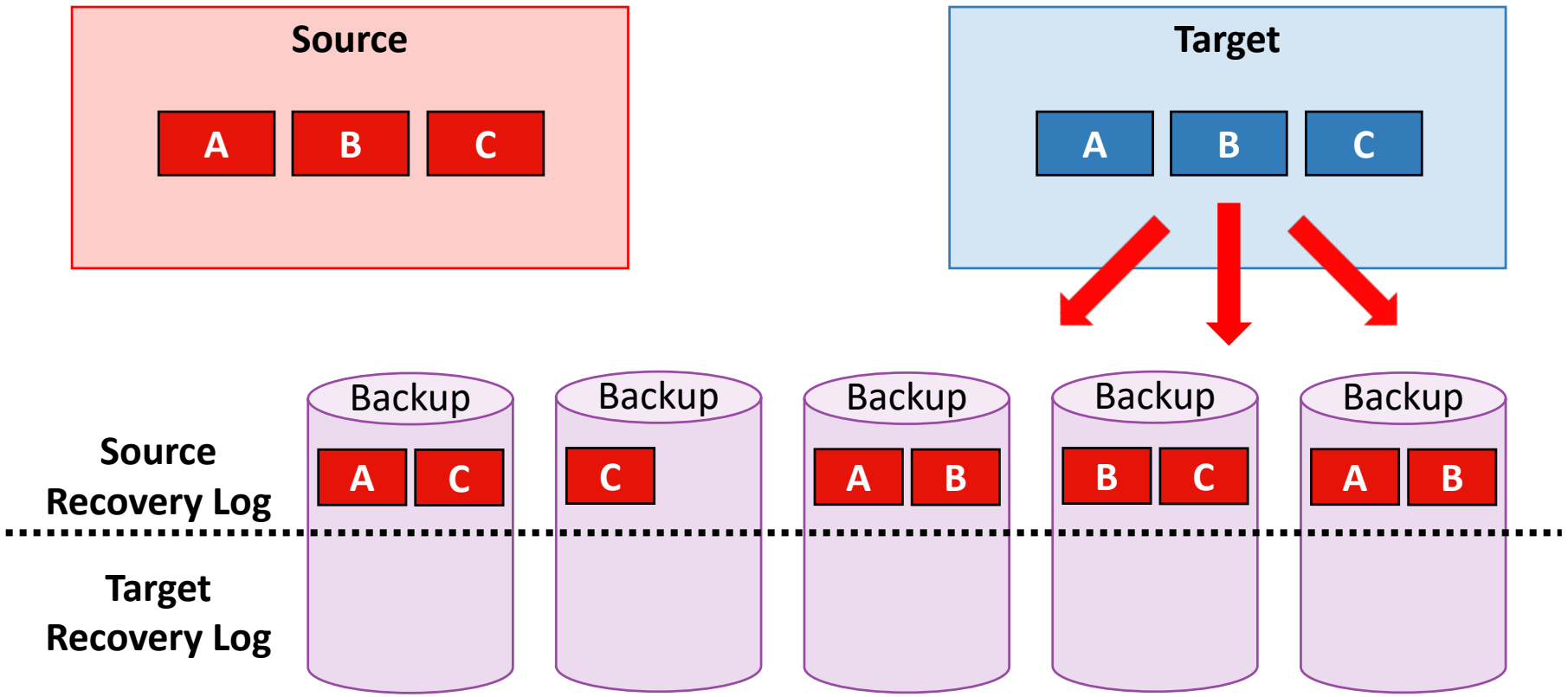
Synchronous Replication Bottlenecks Migration

Synchronous replication hits migration speed by 34%

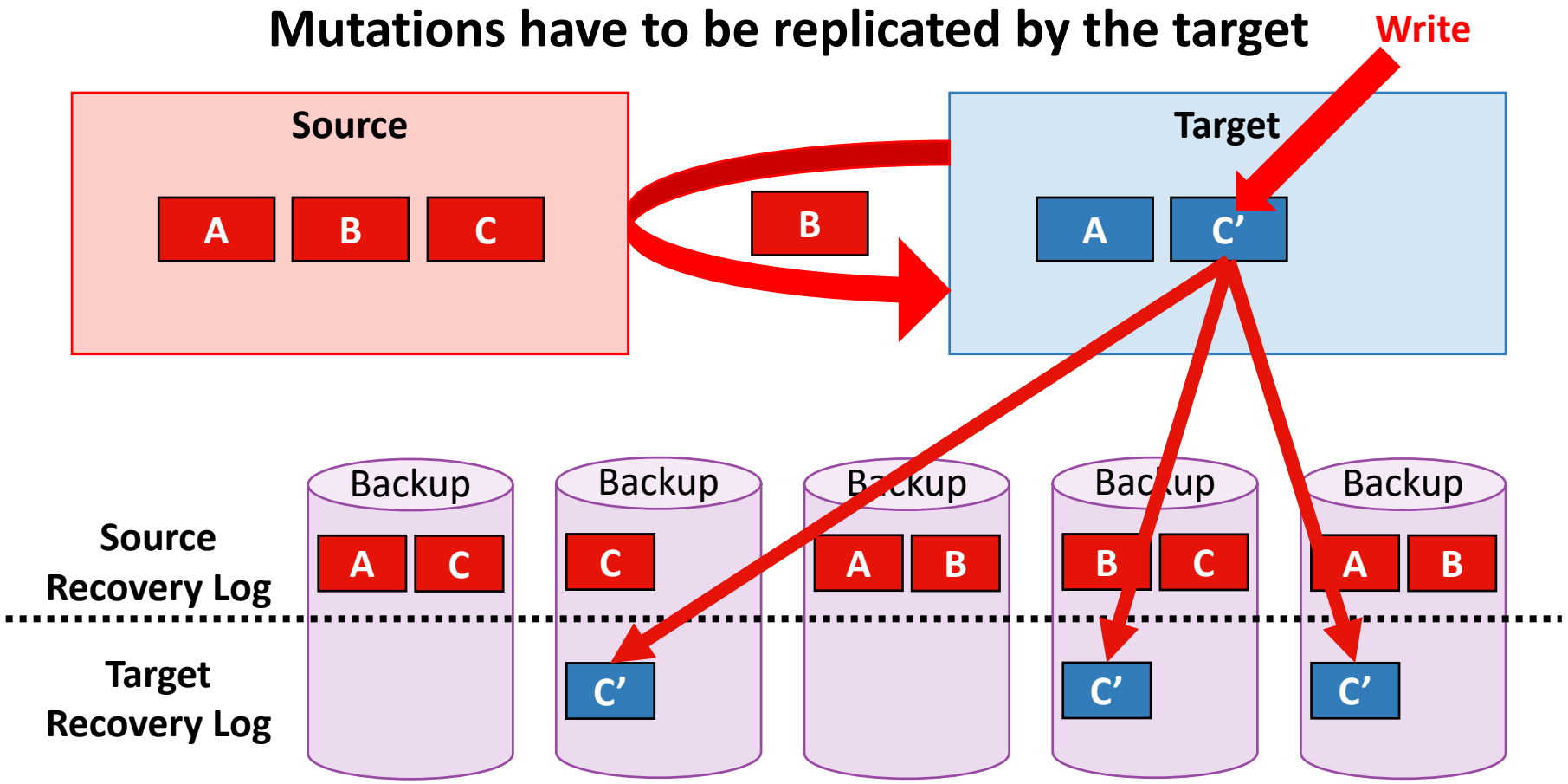


Rocksteady: Safely Defer Replication At The Target

Replicate at Target only after all data has been moved over



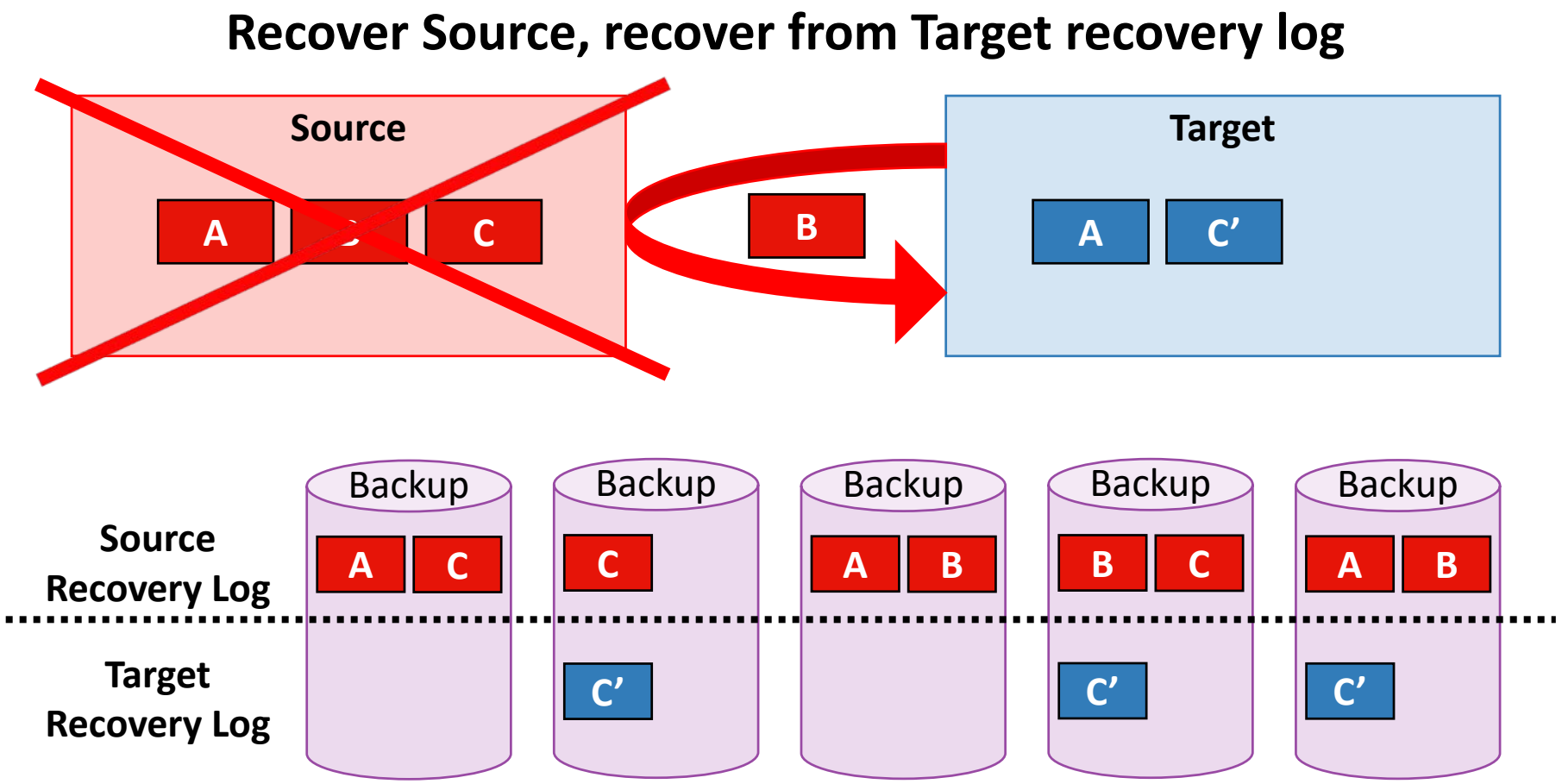
Writes/Mutations Served By Target



Crash Safety During Migration

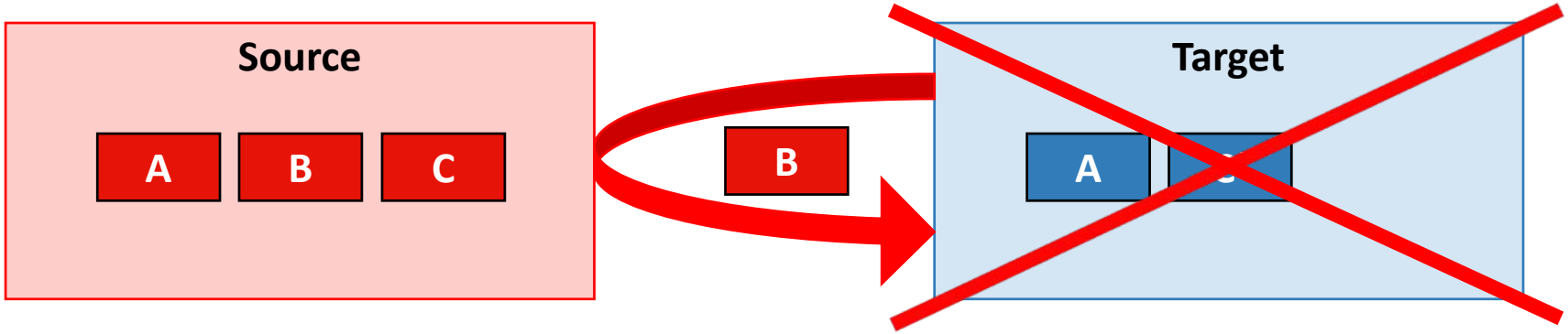
- **Need both Source and Target recovery log for data recovery**
  - Initial table state on Source recovery log
  - Writes/Mutations on Target recovery log
- **Transfer ownership back to Source in case of crash**
  - Migration cancelled
  - Recovery involves both recovery logs
- **Source takes a dependency on Target recovery log at migration start**
  - Stored reliably at the cluster coordinator
  - Identifies position after which mutations present

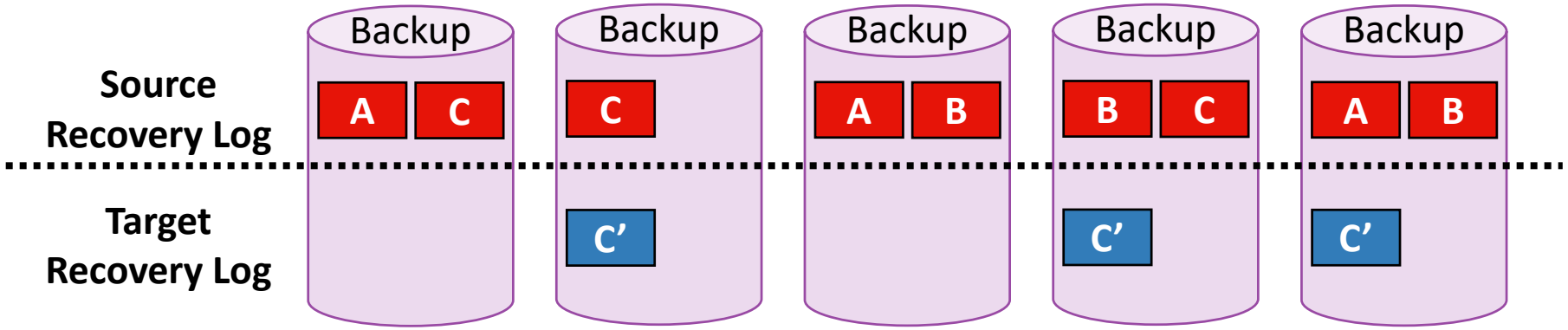
If The Source Crashes During Migration



If The Target Crashes During Migration

Recover from Source and Target recovery log, recover Target





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Safely Transfer Ownership At Migration Start

Safely Delay Replication Till All Data Has Been Moved

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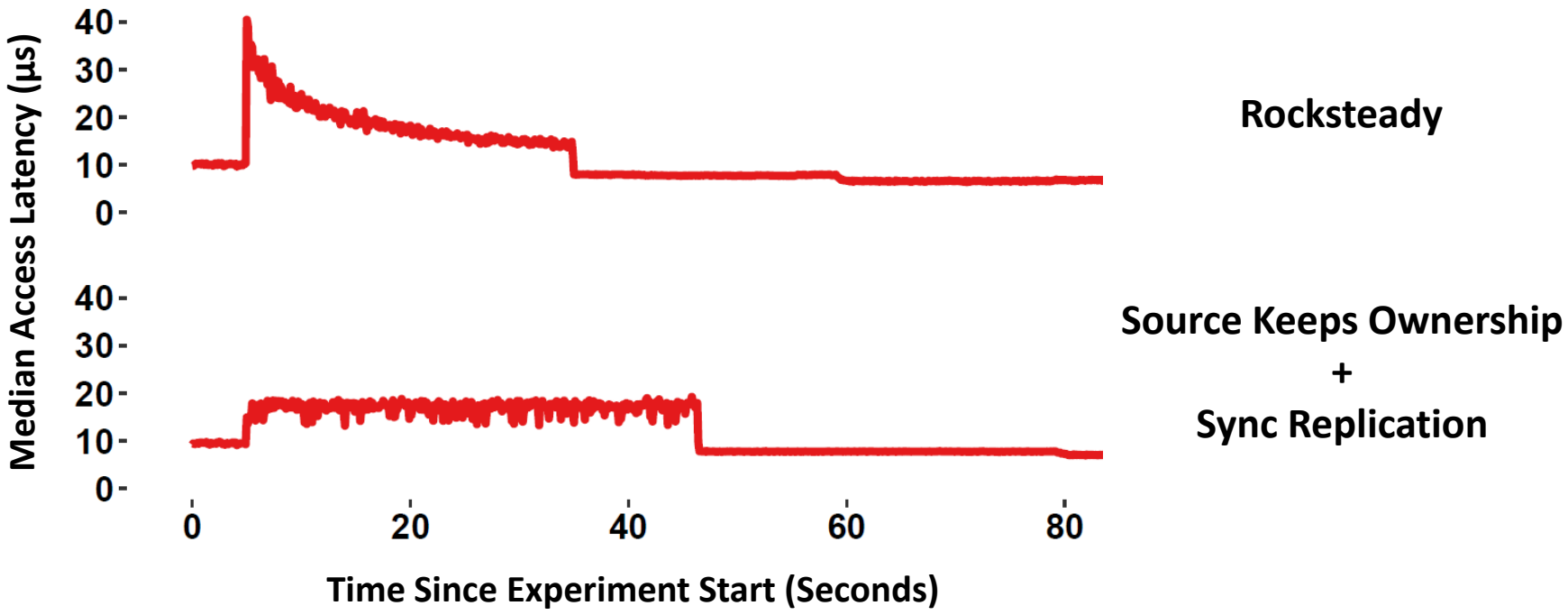
  - Stored reliably at the cluster coordinator
  - Identifies position after which mutations present

Performance of Rocksteady

YCSB-B, 300 Million objects (30 B key, 100 B value), migrate half



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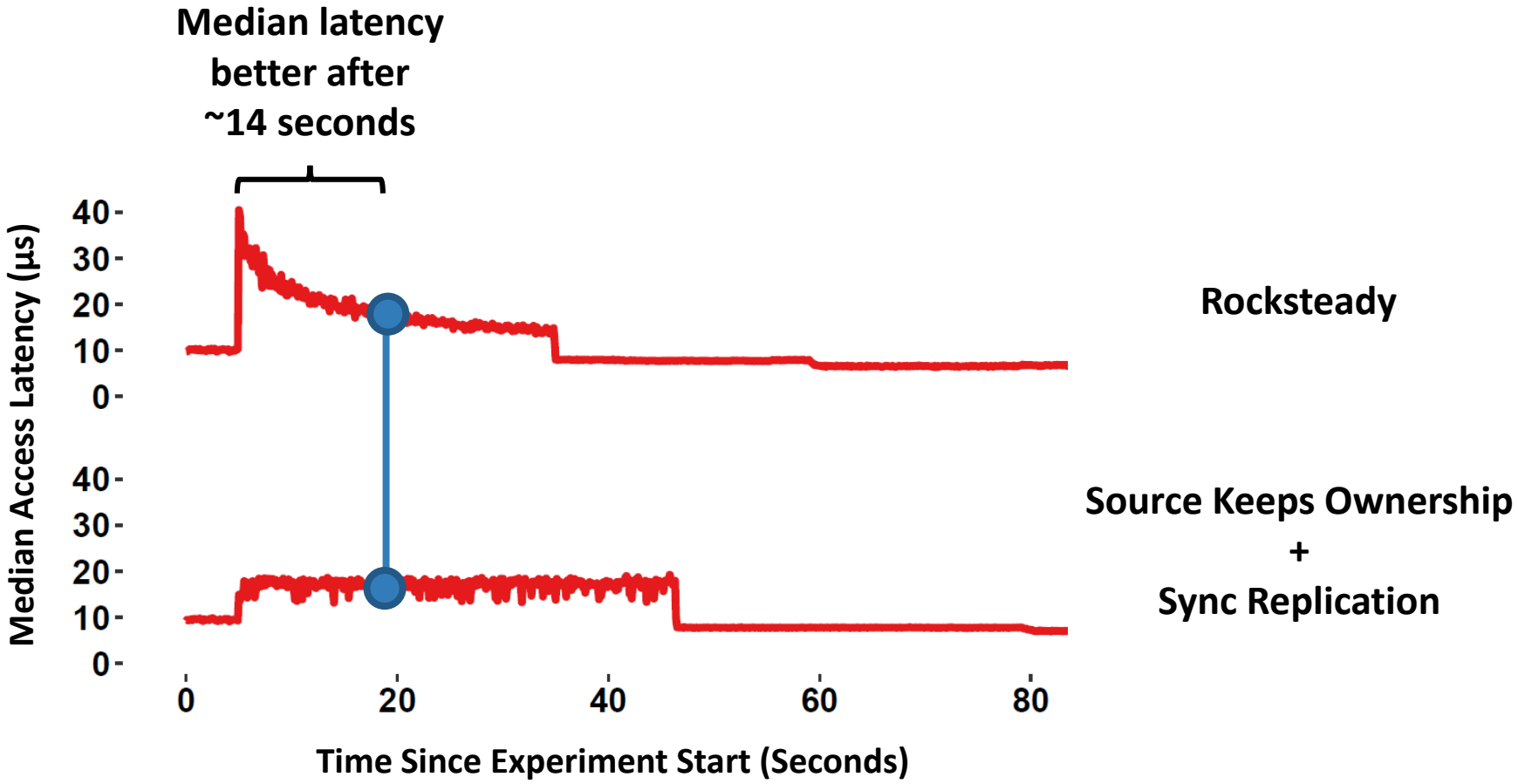

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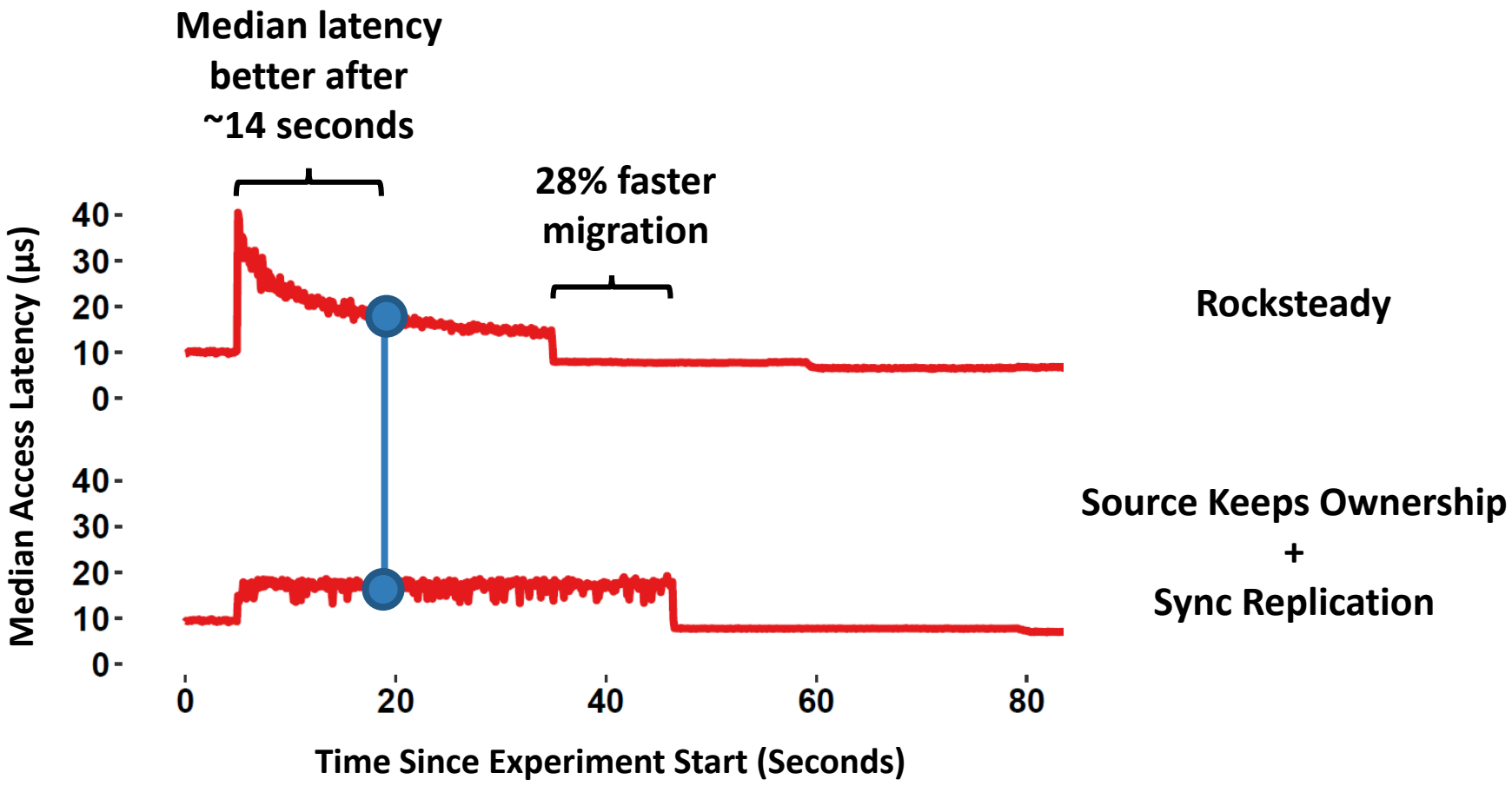


Related Work

- **Dynamo:** Pre-partition hash keys
- **Spanner:** Applications given control over locality (Directories)
- **FaRM and DrTM:** Re-use in-memory redundancy for migration
- **Squall:** Reconfiguration protocol for H-Store
  - Early ownership transfer
  - Paced background migration
  - Fully partitioned, serial execution, no synchronization
    - Each migration pull stalls execution
  - Synchronous replication at the target

Conclusion

- Distributed low-latency in-memory key-value stores are emerging
  - Predictable response times ~**10 µs median, ~60 µs 99.9th-tile**

- **Problem:** Must migrate data between servers
  - Minimize performance impact of migration → **go slow?**
  - Quickly respond to hot spots, skew shifts, load spikes → **go fast?**

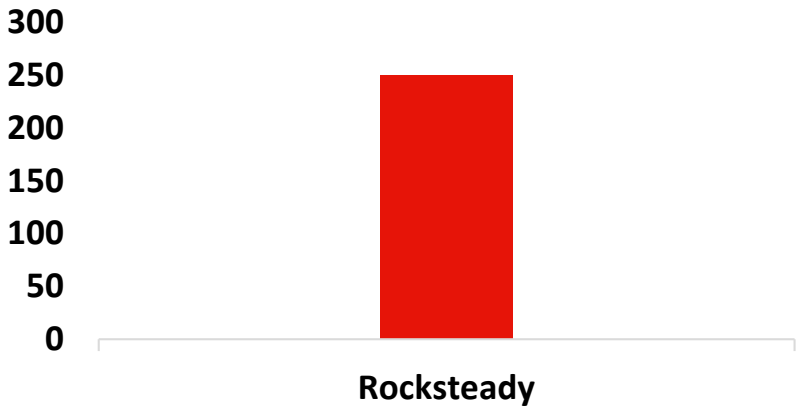
- **Solution:** **Fast** data migration with **low impact**
  - **Leverage skew**: Transfer ownership before data, move hot data first
  - Low priority, parallel and adaptive migration

- **Result:** Migration protocol for RAMCloud in-memory key-value store
  - Migrates at **758 MBps** with 99.9th-tile latency **< 250 µs**

Source Code: https://github.com/utah-scs/RAMCloud/tree/rocksteady-sosp2017

Backup Slides

Rocksteady Tail Latency Breakdown



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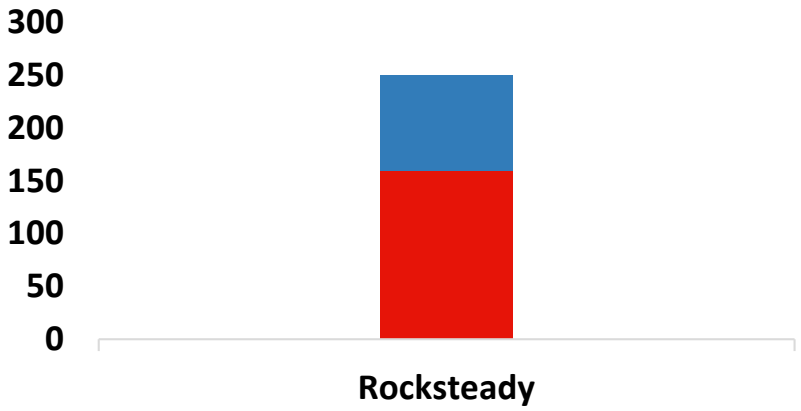

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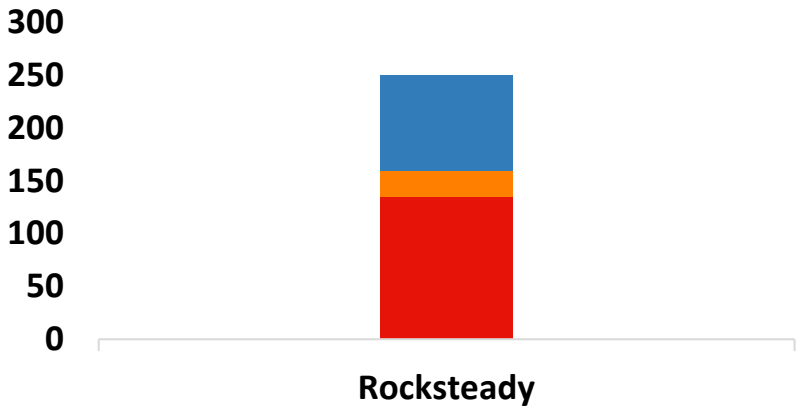
Rocksteady Tail Latency Breakdown



- Disabling parallel pulls brings tail latency down to 160 µsec
- Synchronous on-demand pulls further brings tail latency down to 135 µsec