In-Memory Key-Value Store Live Migration with NetMigrate

Zeying Zhu, Yibo Zhao, Alan Zaoxing Liu

UNIVERSITY OF MARYLAND

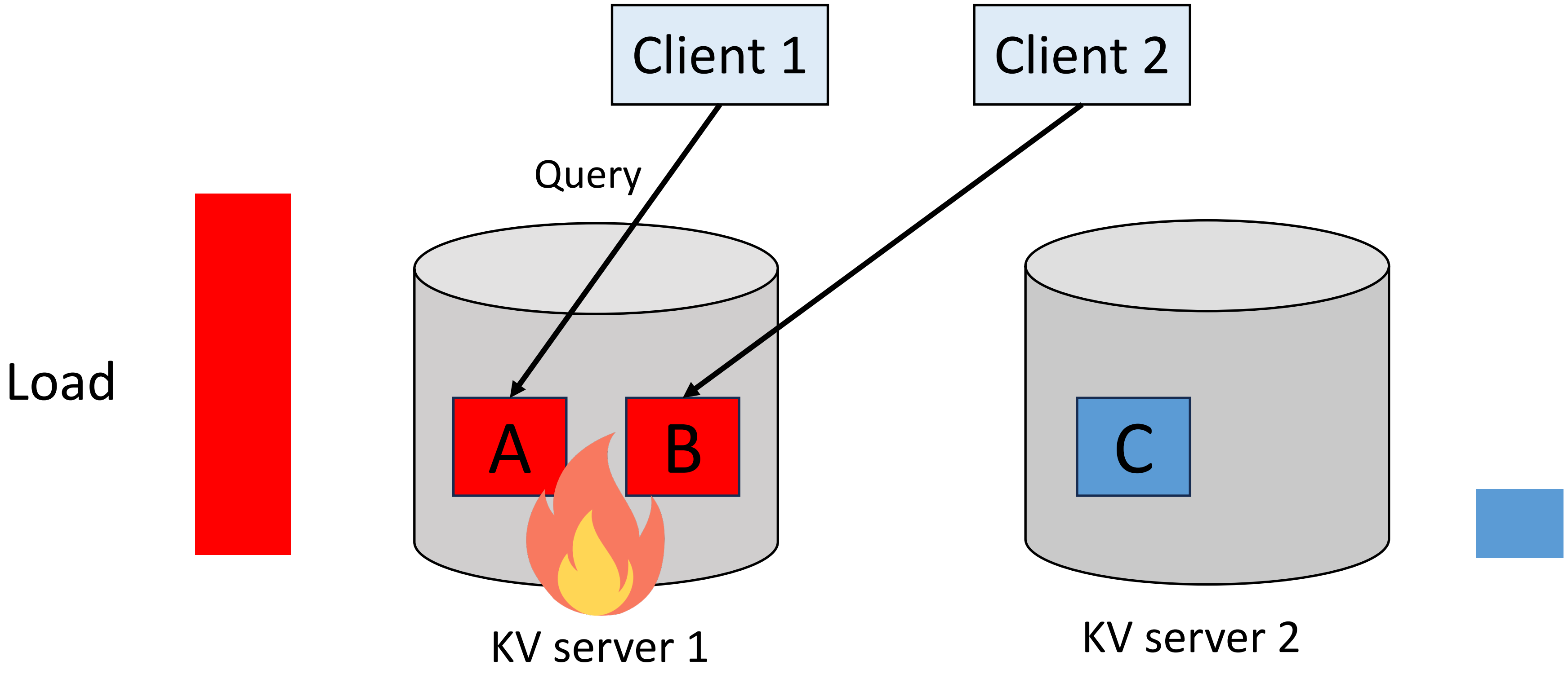
In-Memory Key-Value Stores

- Key-value stores are widely used
  - Feature store of machine learning inference
  - In-memory caching
  - Real-time analytics

- Data amount is large
  - Store billions of records
  - Retrieve millions of records under low latency constraints

Live Migration is A Key Technique

- No service downtime during key-value shard migration between nodes.
- Why migrate data?
  - Load balancing



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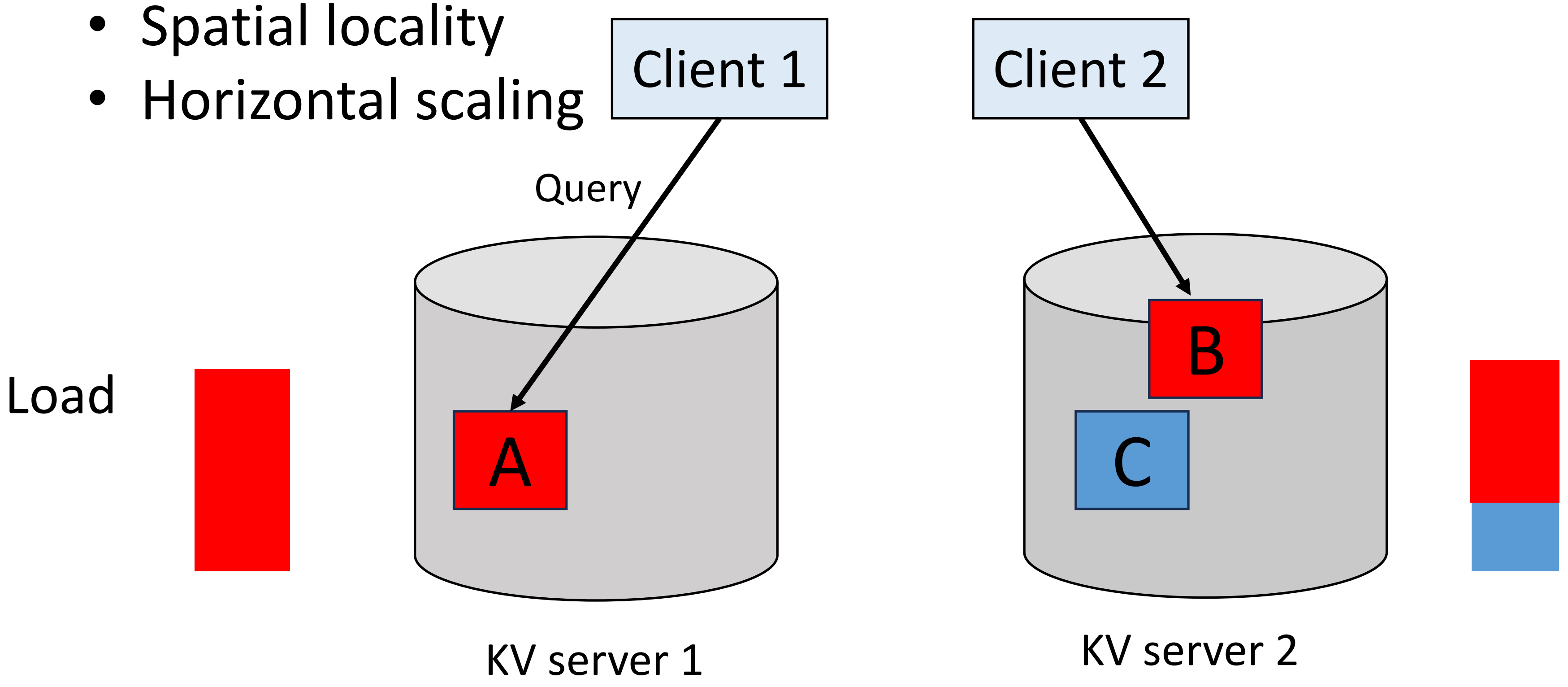
  - Horizontal scaling



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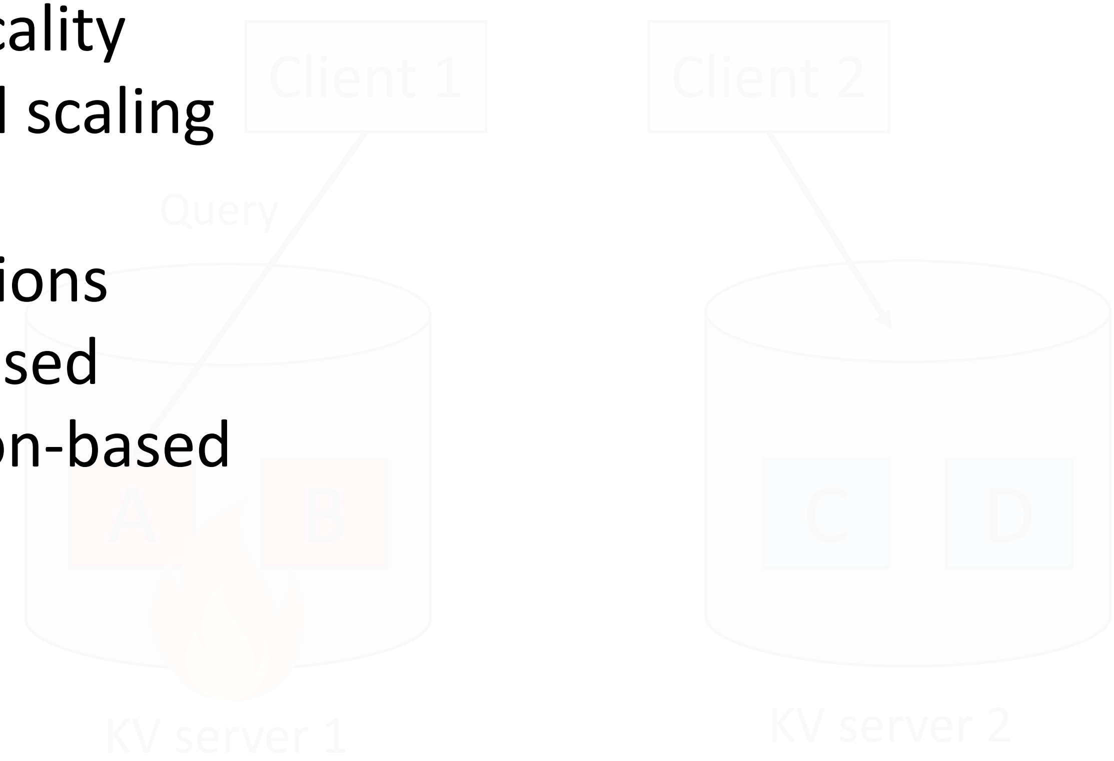
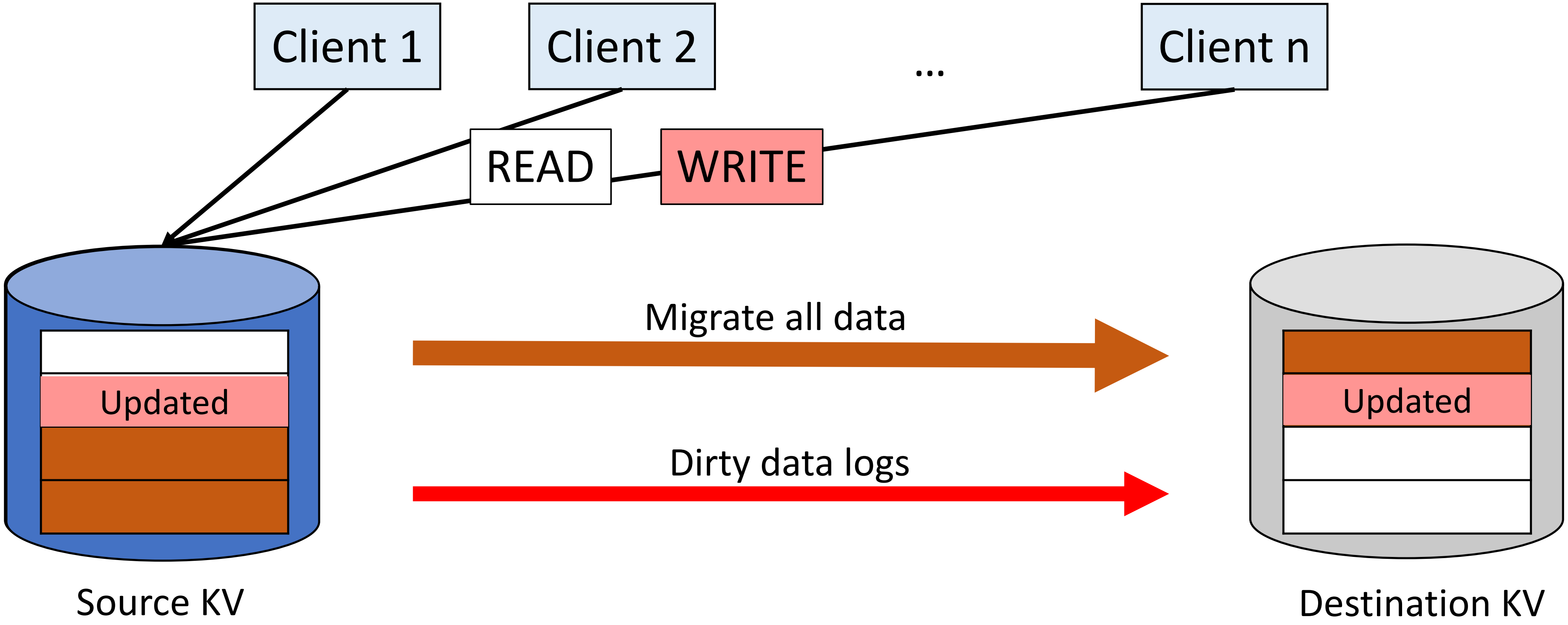
- Existing solutions
  - Source-based
  - Destination-based
  - Hybrid



Source-based Migration

READ: served by source

WRITE: served by source



RAMCloud [TOCS ‘15], Remus [SIGMOD’22]

Source-based Migration

READ: served by source

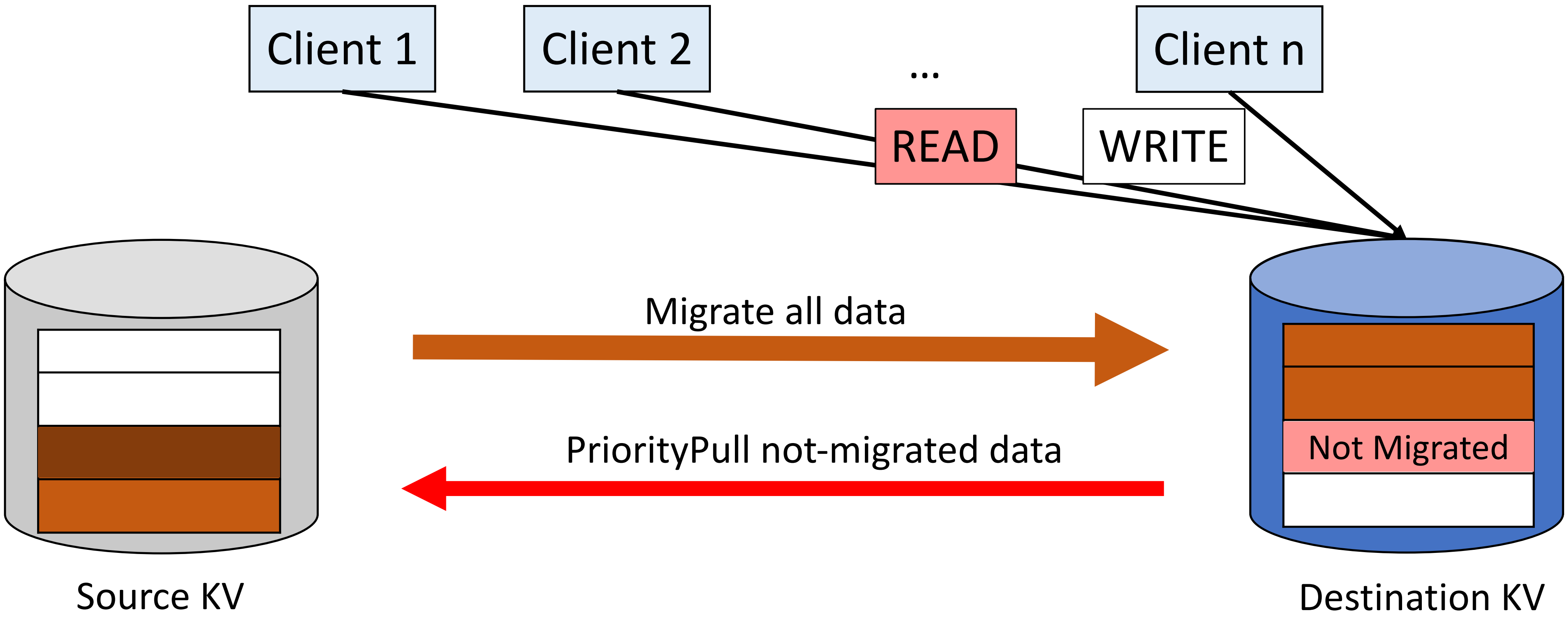
WRITE: served by source

- Low query latency during migration because source node already has the queried data
- Extra dirty data transfer from source to destination
- Downtime when terminating migration

RAMCloud [TOCS ‘15], Remus [SIGMOD’22]

Destination-based Migration

READ: served by destination
WRITE: served by destination



Rocksteady [SOSP'17]

Destination-based Migration

READ: served by destination
WRITE: served by destination

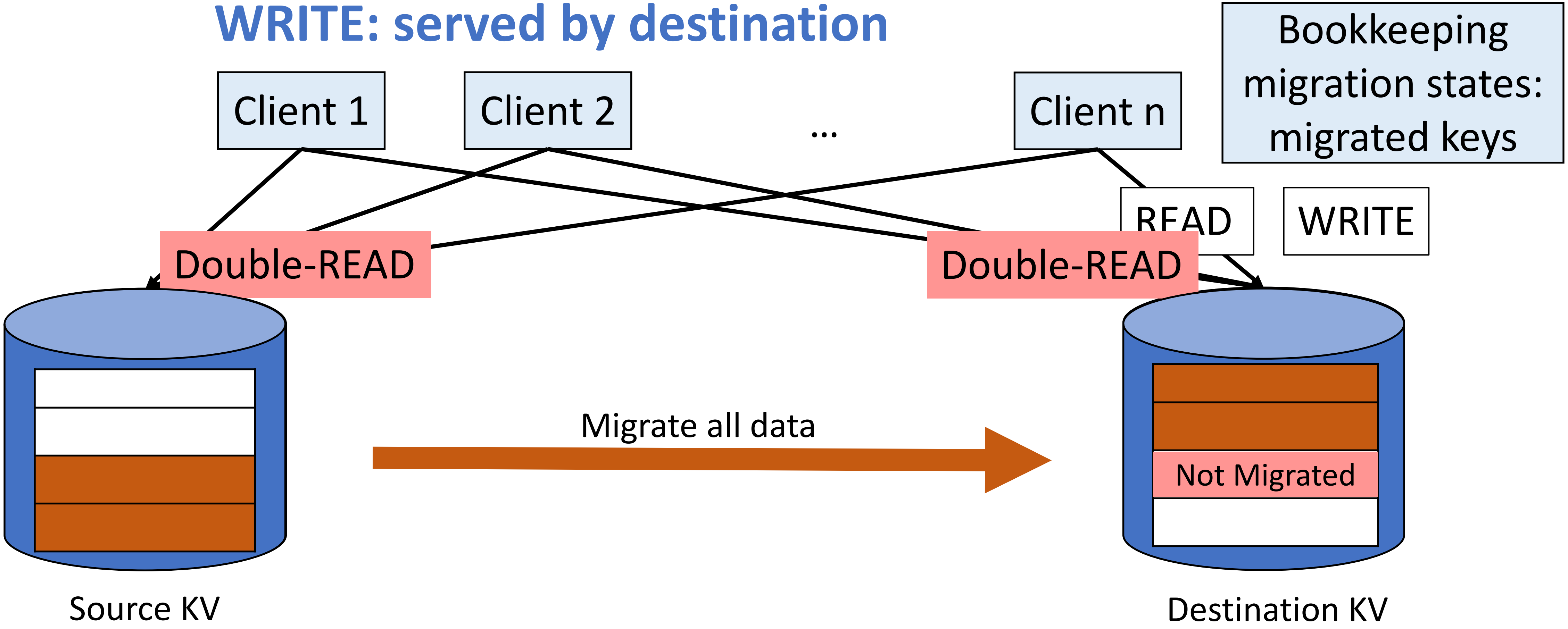
- Quickly shift source node’s pressure, short migration time
- High query latency due to missed data access in the destination (increase 100%~400%)
- Low throughput (drop 66%)

Rocksteady [SOSP’17]

Hybrid Migration

READ: served by both source and destination

WRITE: served by destination



Fulva [SRDS '19]

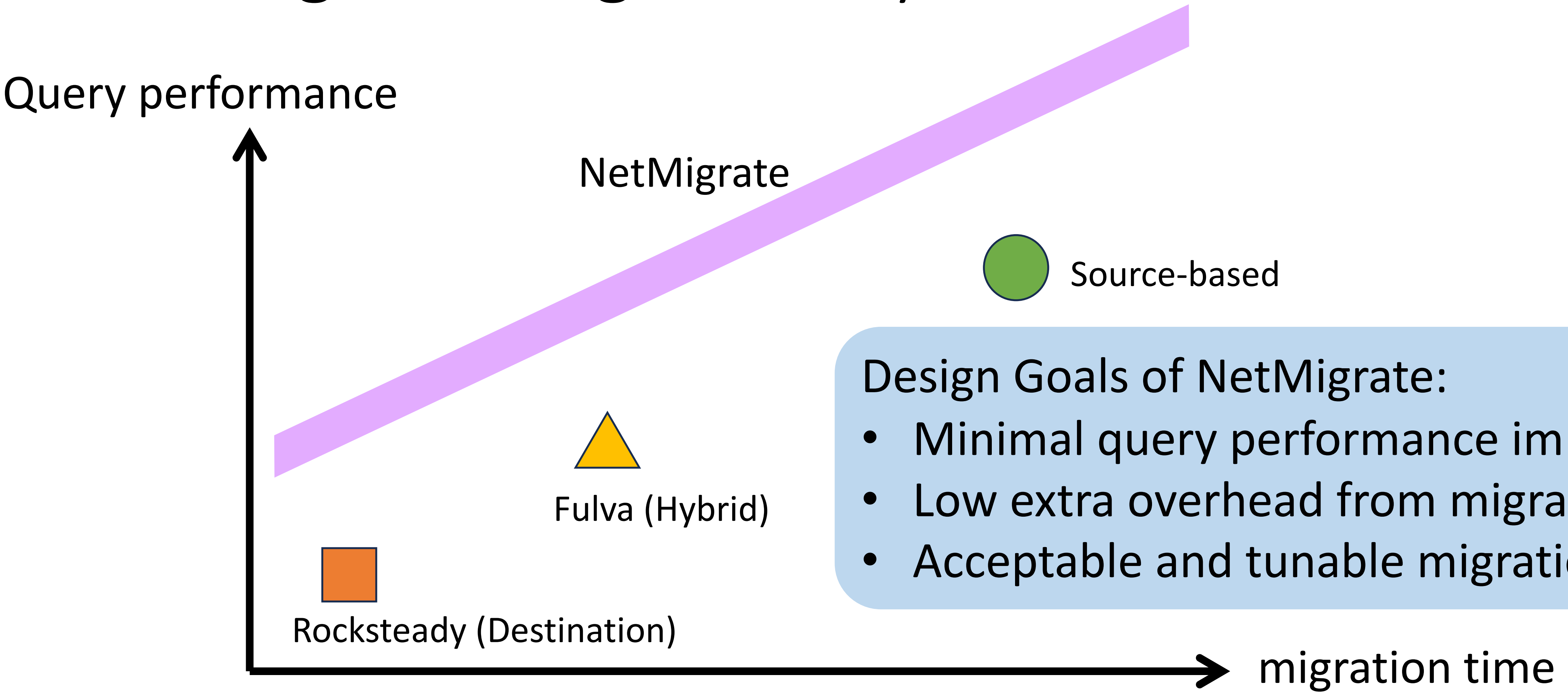
Hybrid Migration

READ: served by both source and destination
WRITE: served by destination

- Leverage both so performance is better when most of data is in the source.
- Double-read incurs large bandwidth overhead between clients and servers (~50%) because of no fine-grained state tracking.

Fulva [SRDS ‘19]

Existing Live Migration Systems



Design Goals of NetMigrate:

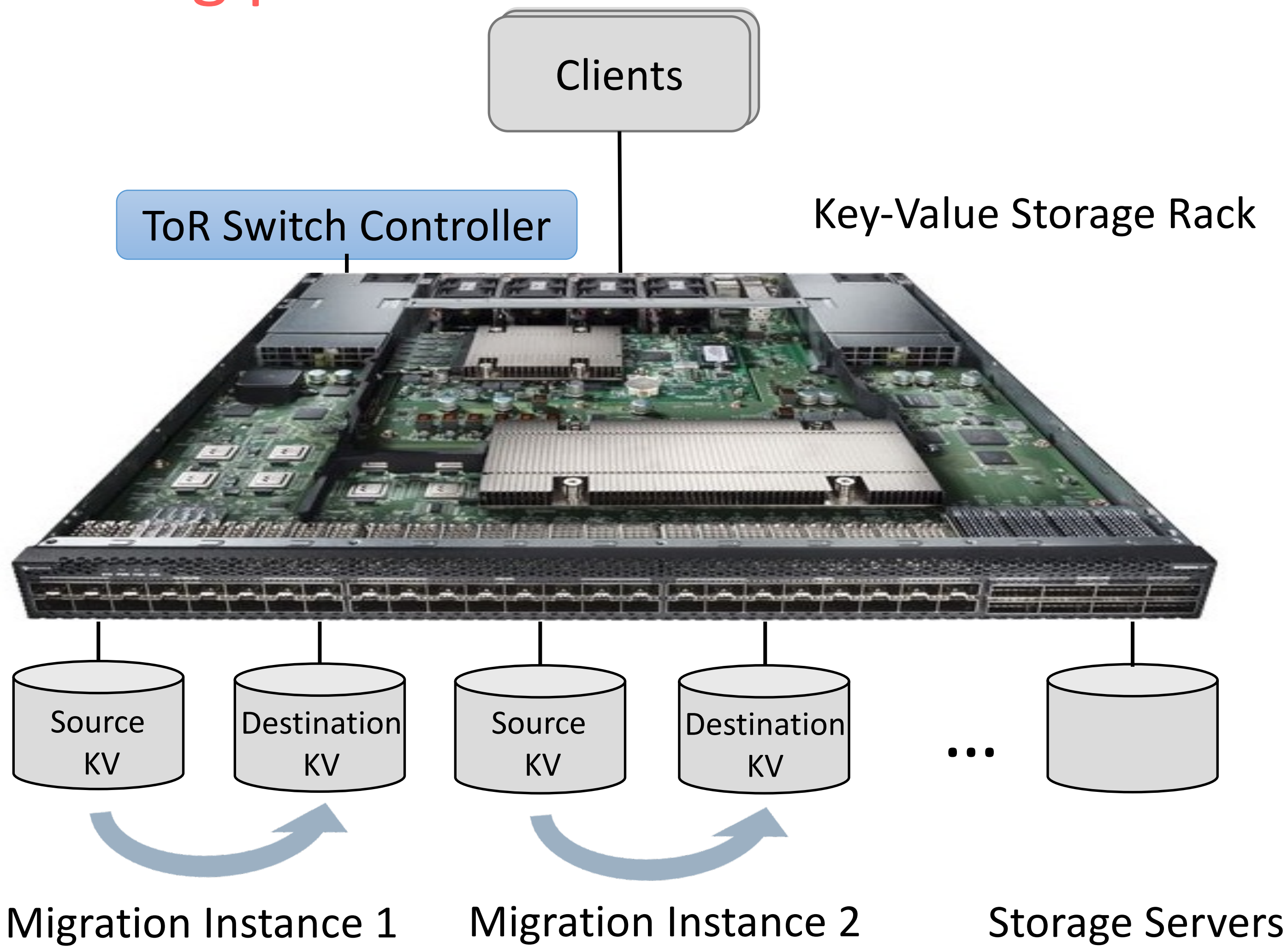
- Minimal query performance impact
- Low extra overhead from migration
- Acceptable and tunable migration time

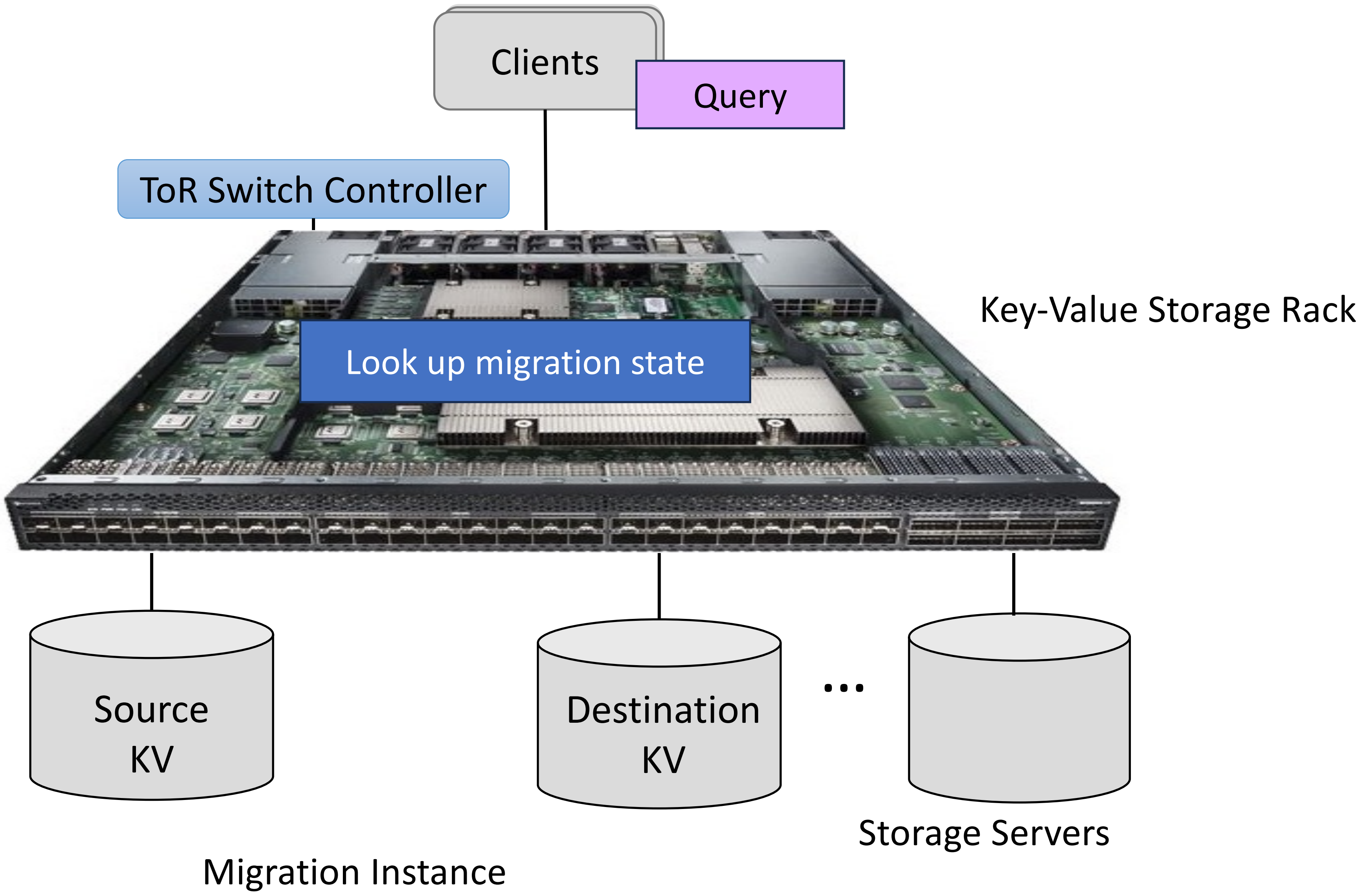
Tradeoff between query performance and migration time

Existing solutions don't know where the data is and pay cost of going to wrong places.

Key Idea: Programmable Top-of-Rack switches to track the migration states.

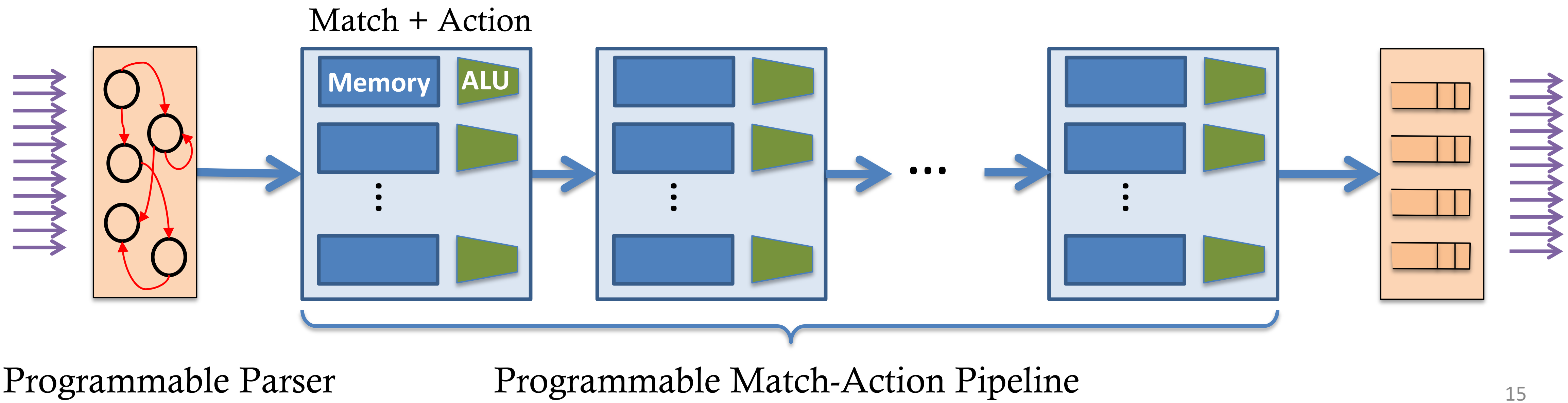
- Centralized view of all data movement
- Real-time information of who owns the data




Clients
Query
ToR Switch Controller
Key-Value Storage Rack
Look up migration state
Source KV
Destination KV
...
Storage Servers
Migration Instance

A Typical Programmable Switch Architecture

- Flexible programmability
  - ➢ Parse, read and update custom fields **at line rate**
- Registers
  - ➢ Store data
- High line-rate packet processing 12.4 Tbps



Design Challenges of NetMigrate

- Challenge #1: How to track fine-grained migration states?
  - On-switch resources are limited (e.g., 64MB SRAM vs. Millions of KV pairs)
- Challenge #2: How to query during migration?
  - Maintain data consistency during migration.
    - Read-After-Write, Write-After-Read, Write-After-Write.
- Challenge #3: How to support dynamic migration policies?

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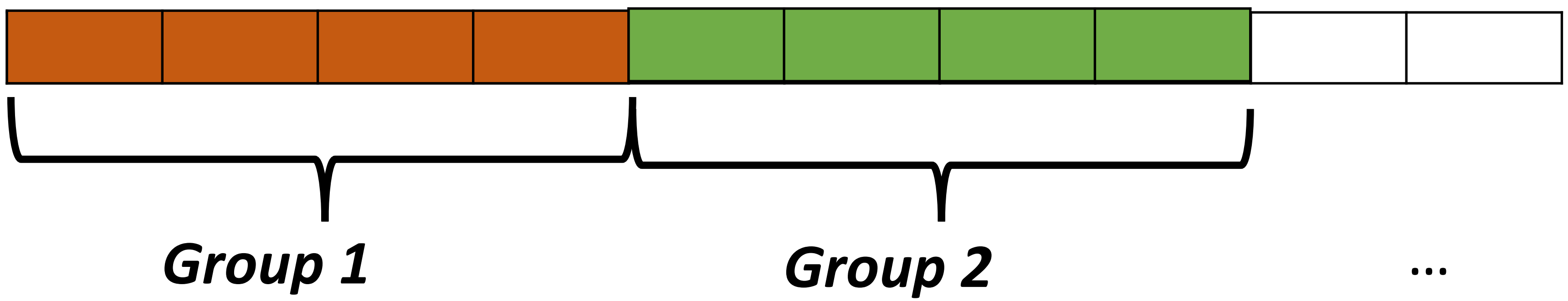
Shrink Record Granularity for Limited Switch Resources

On-switch resources are limited (e.g., 64MB SRAM vs. Millions of KV pairs)

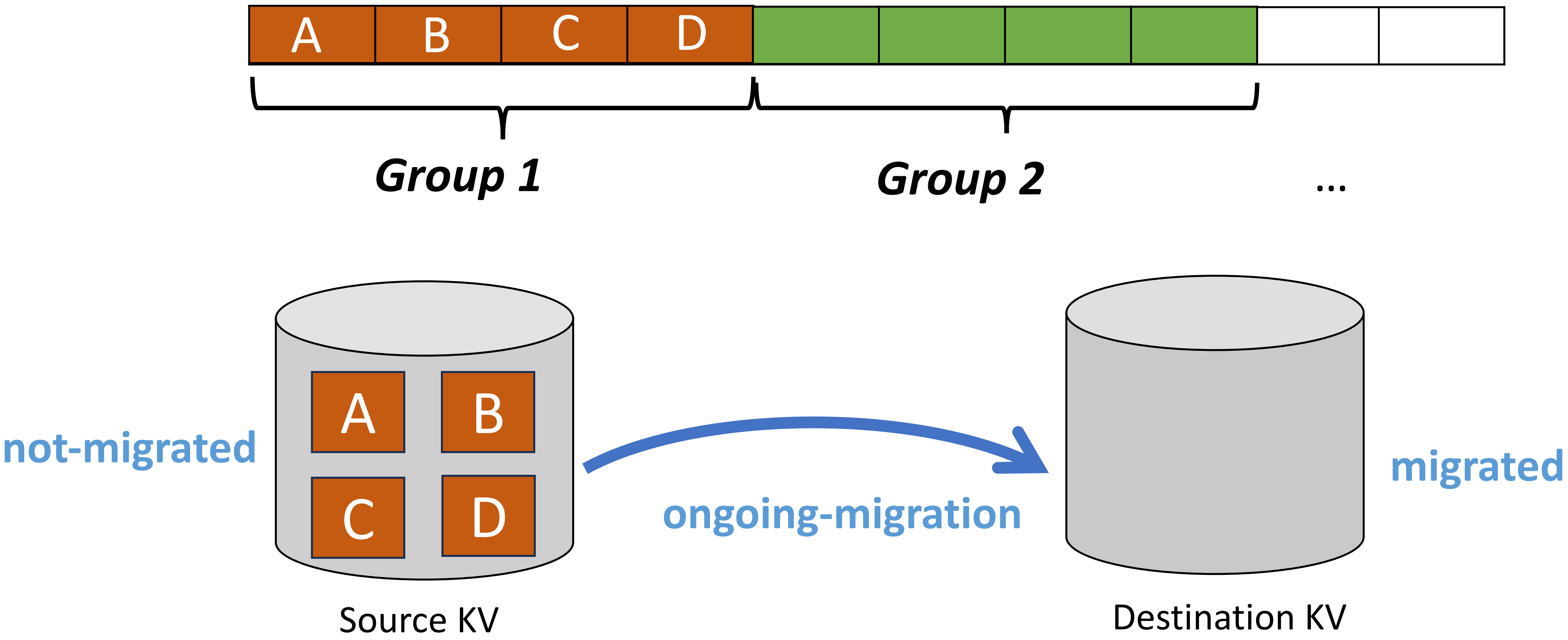
KVS data structure: hash table



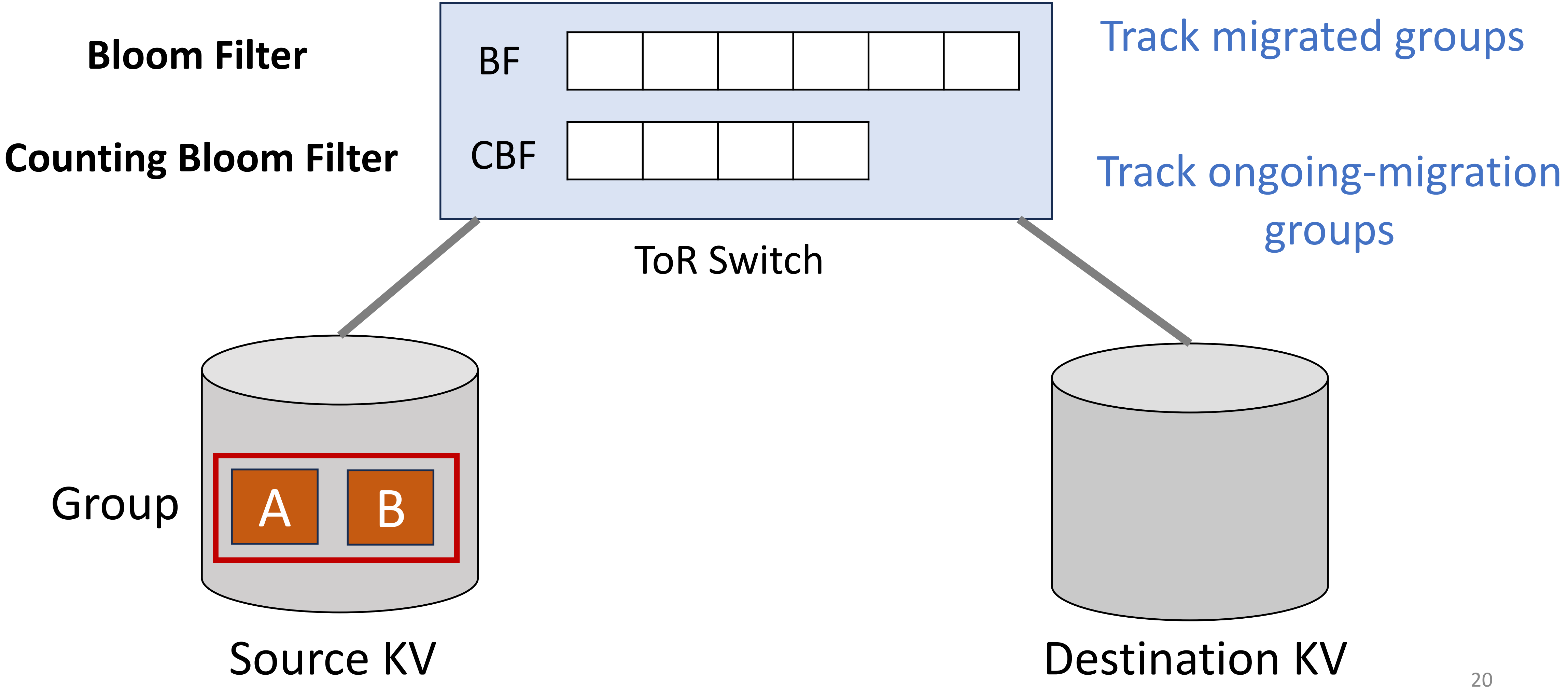
Track migration in a coarser record granularity

Three States to Understand Data Location

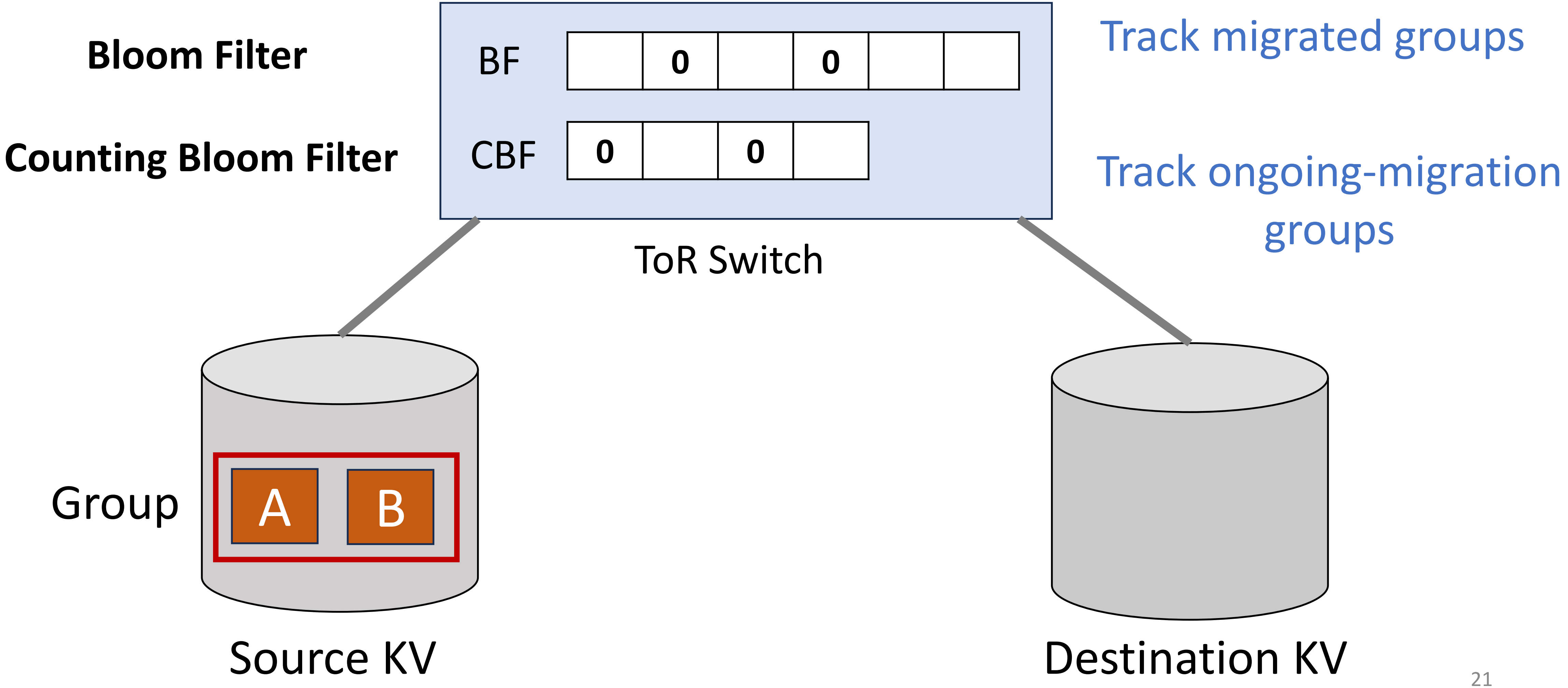
Group migration states: migrated, ongoing-migration, not-migrated



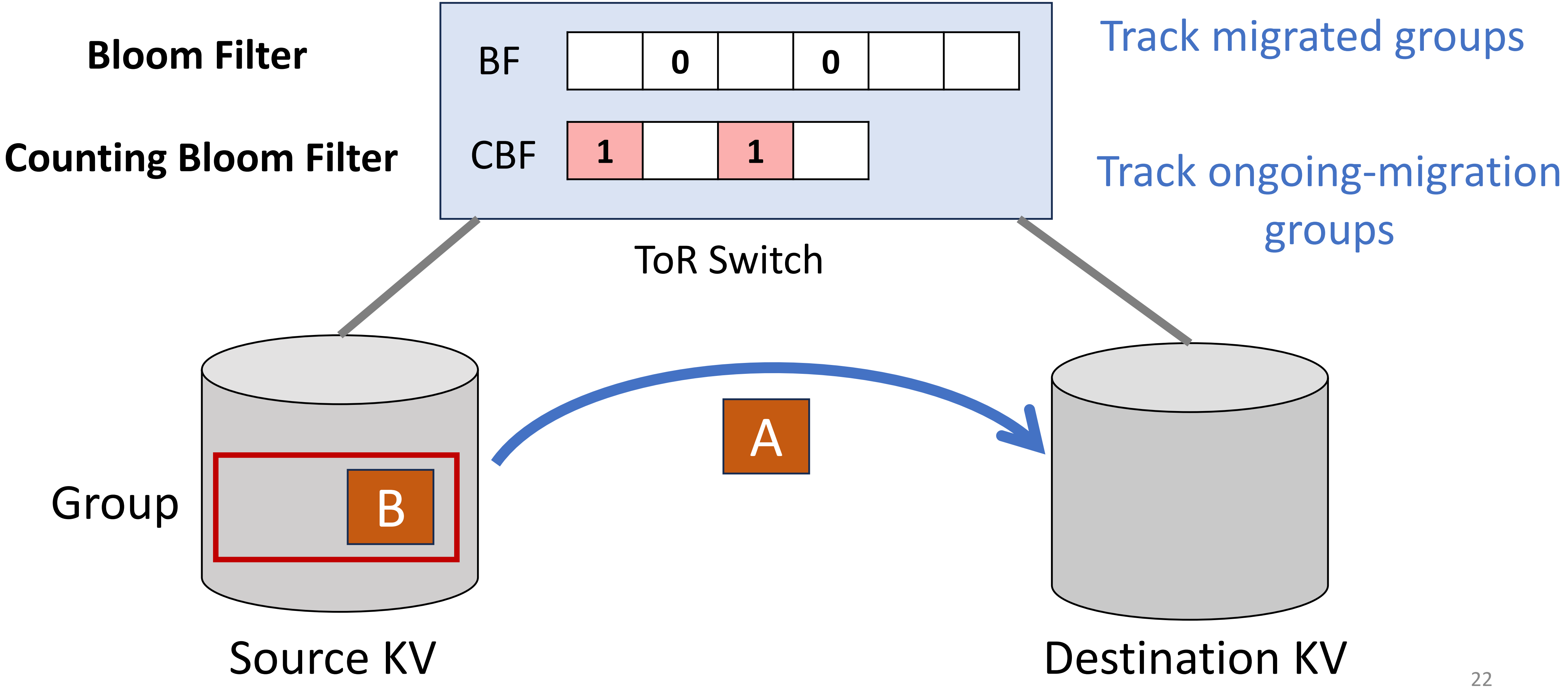
Probabilistic Ownership Tracking



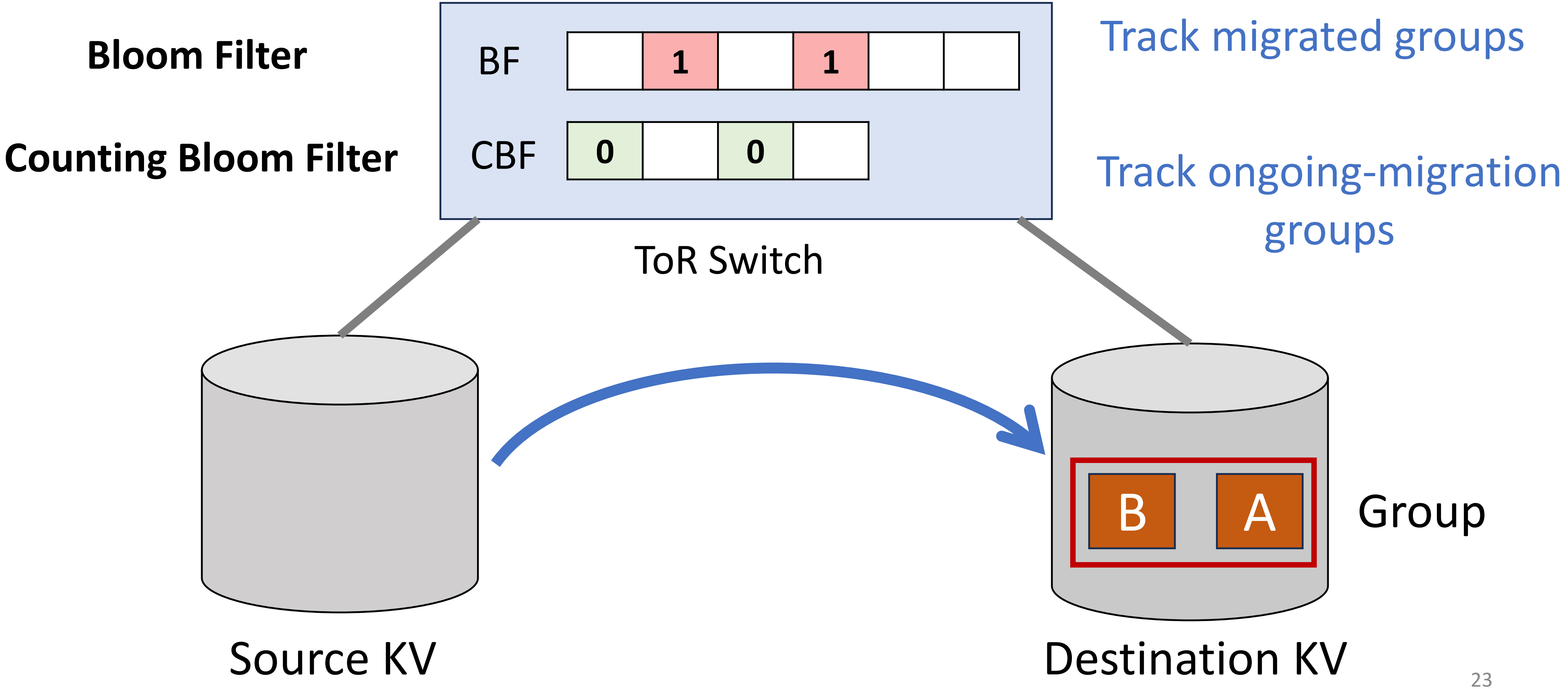
Not Started Migration



Ongoing Migration



Finished Migration



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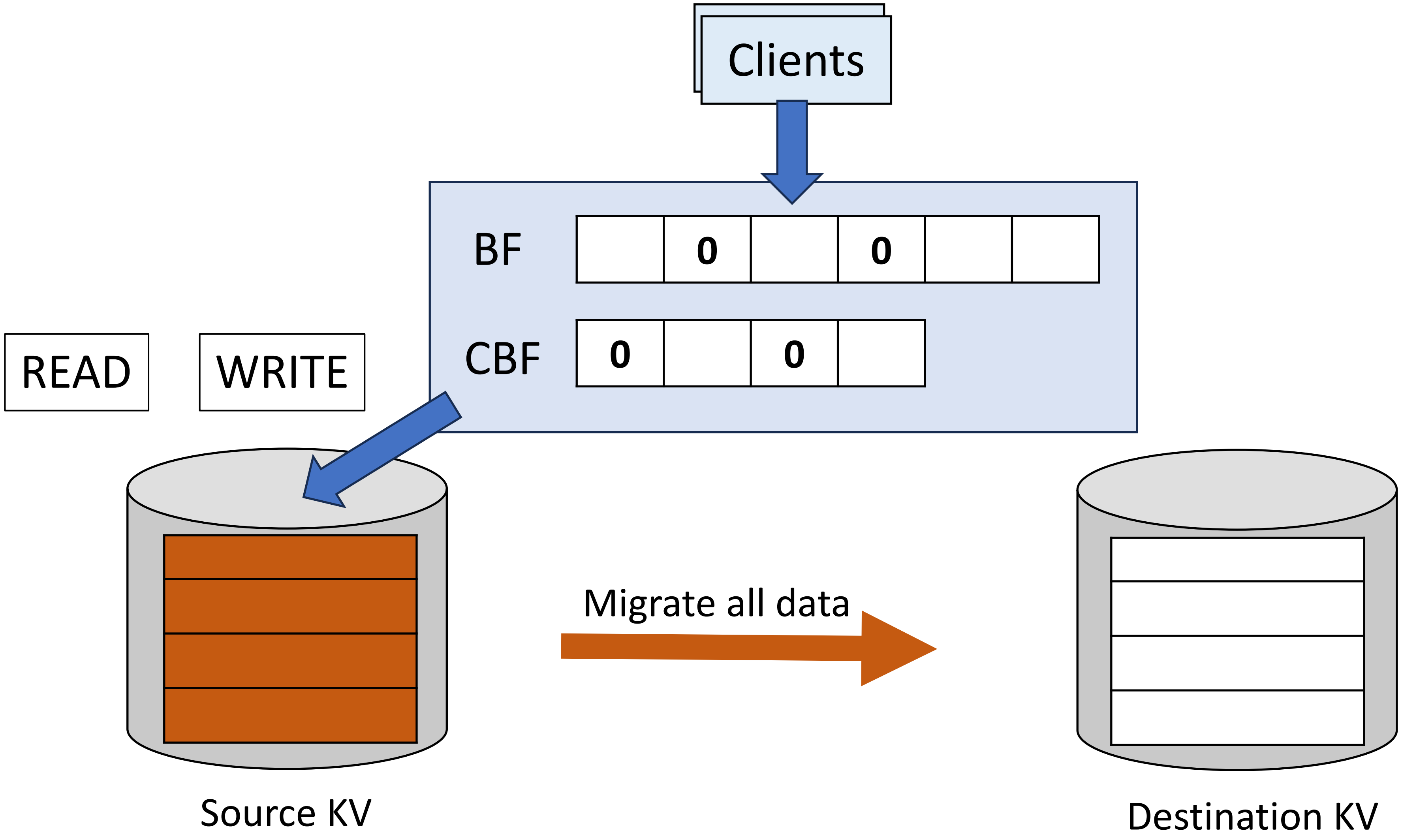
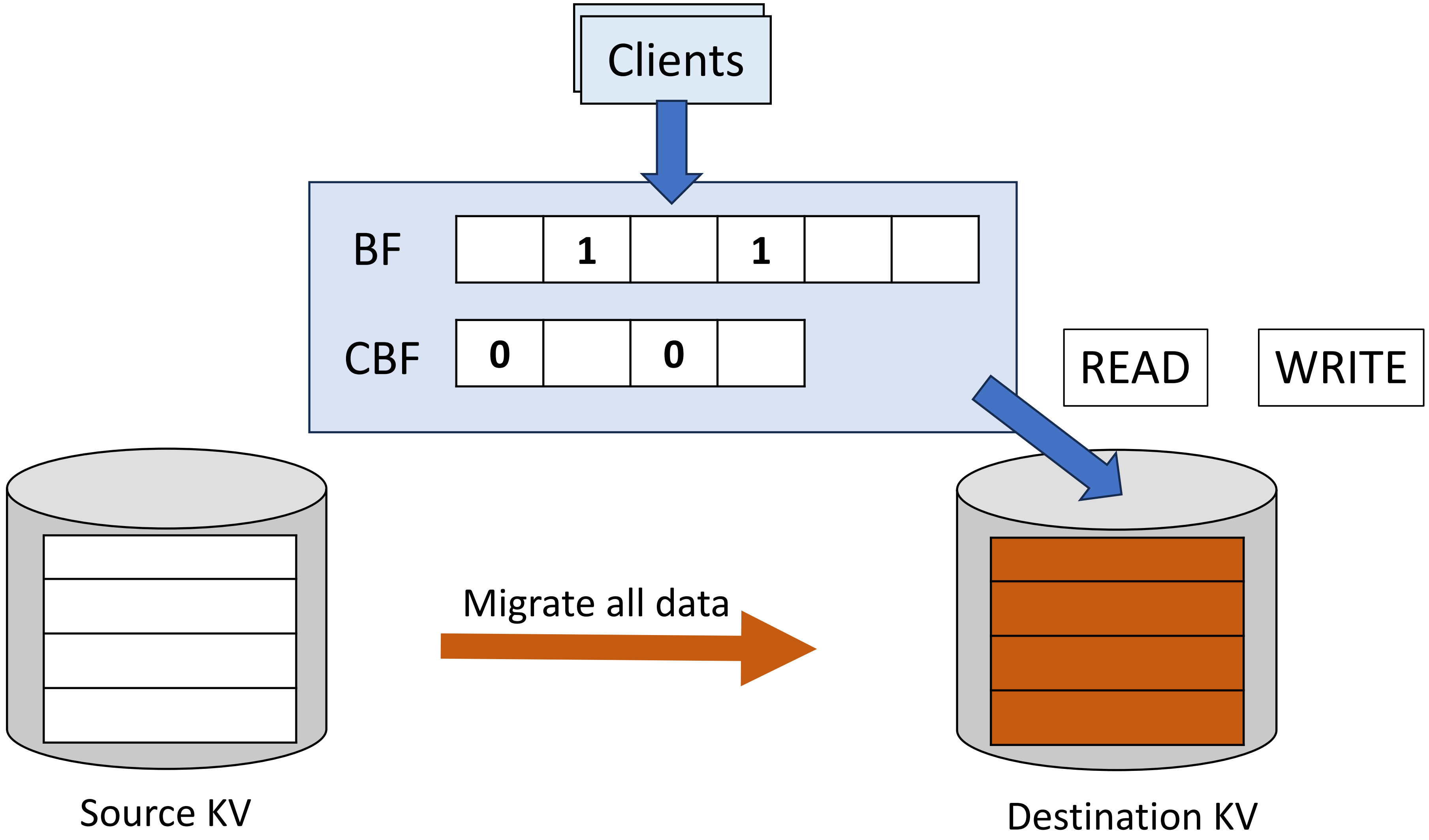
Data is Consistent When Not Started Migration

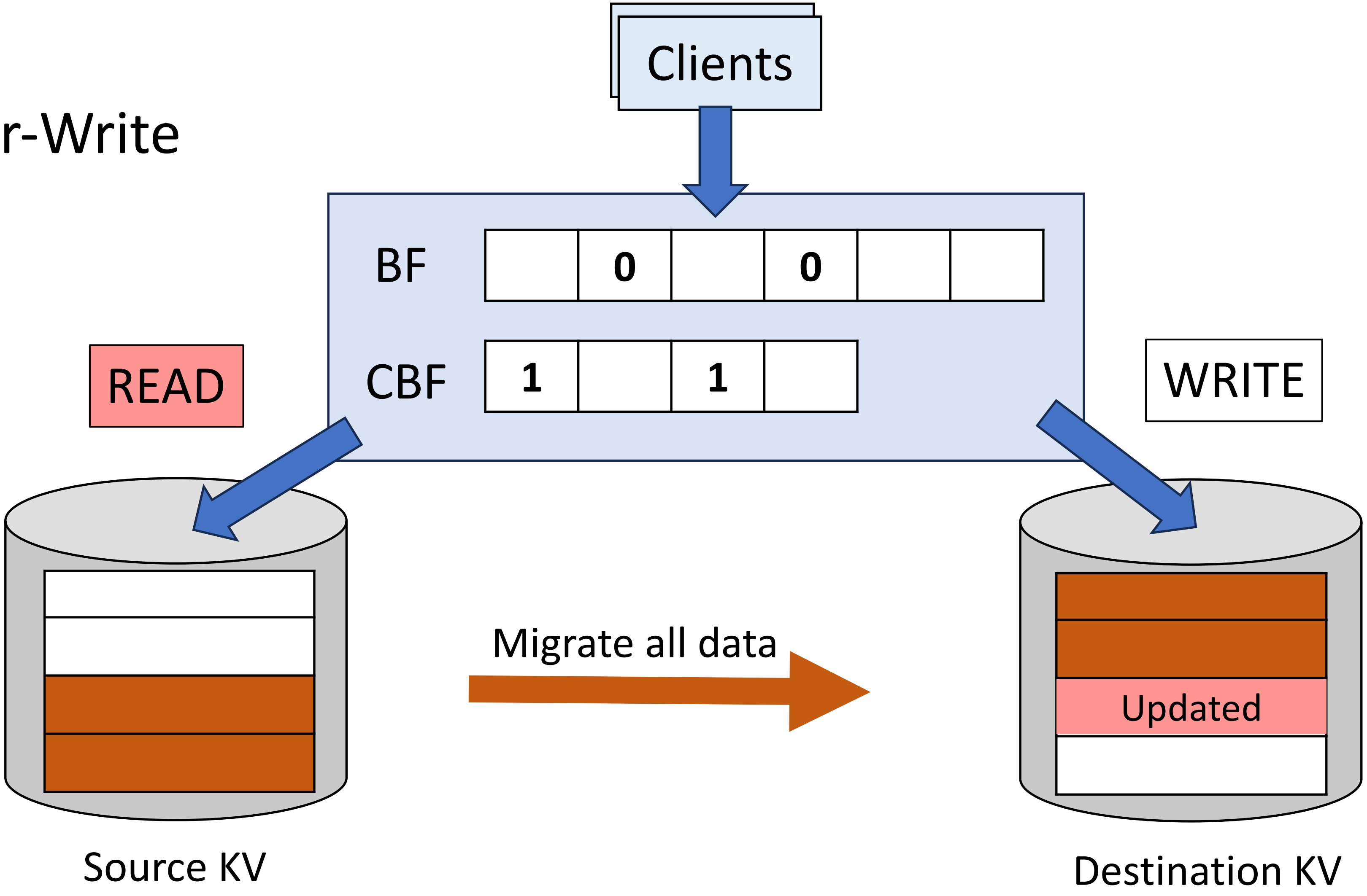


Data is Consistent When Finished Migration



An Inconsistent Example When Ongoing Migration

Read-After-Write



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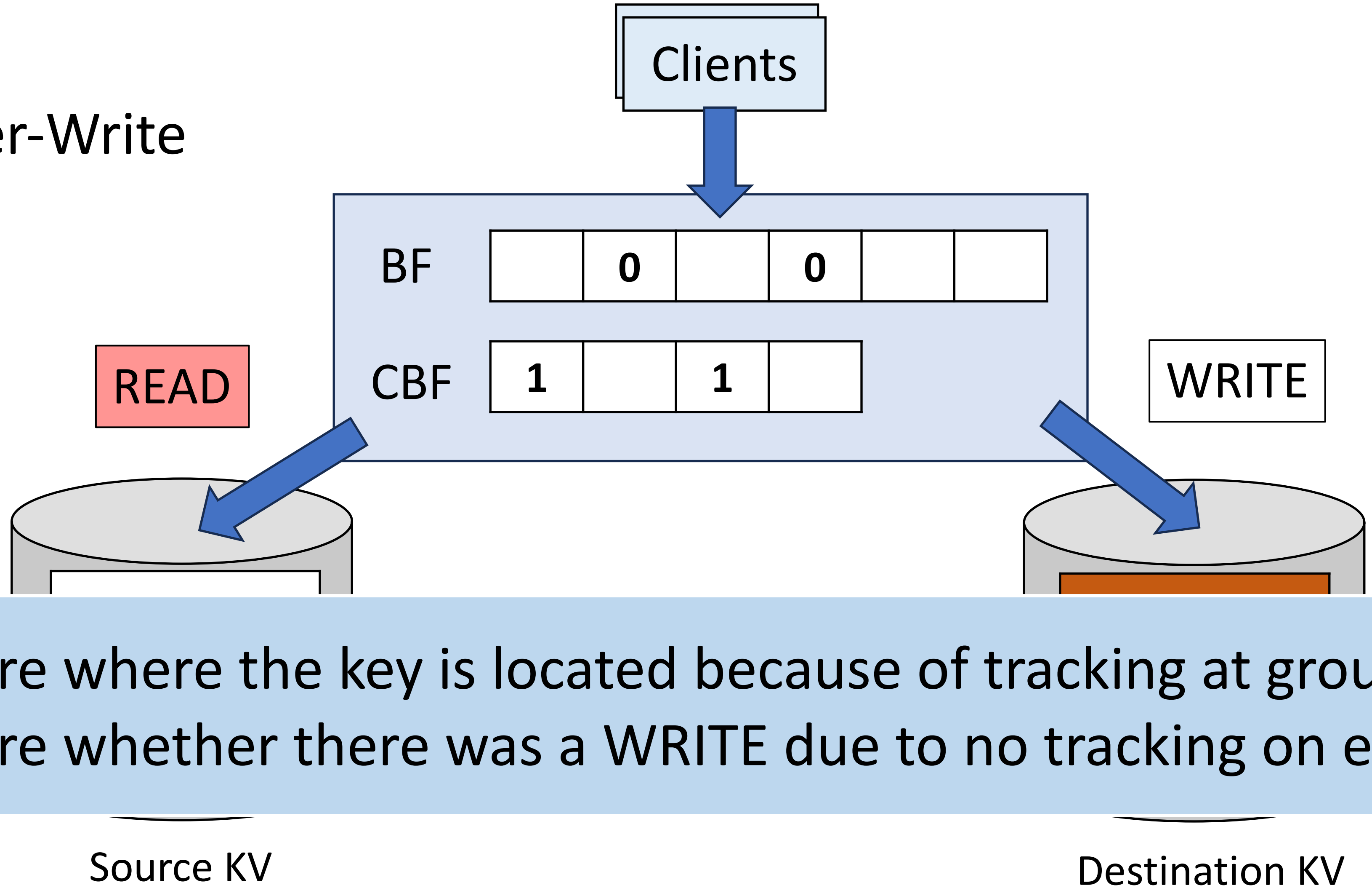
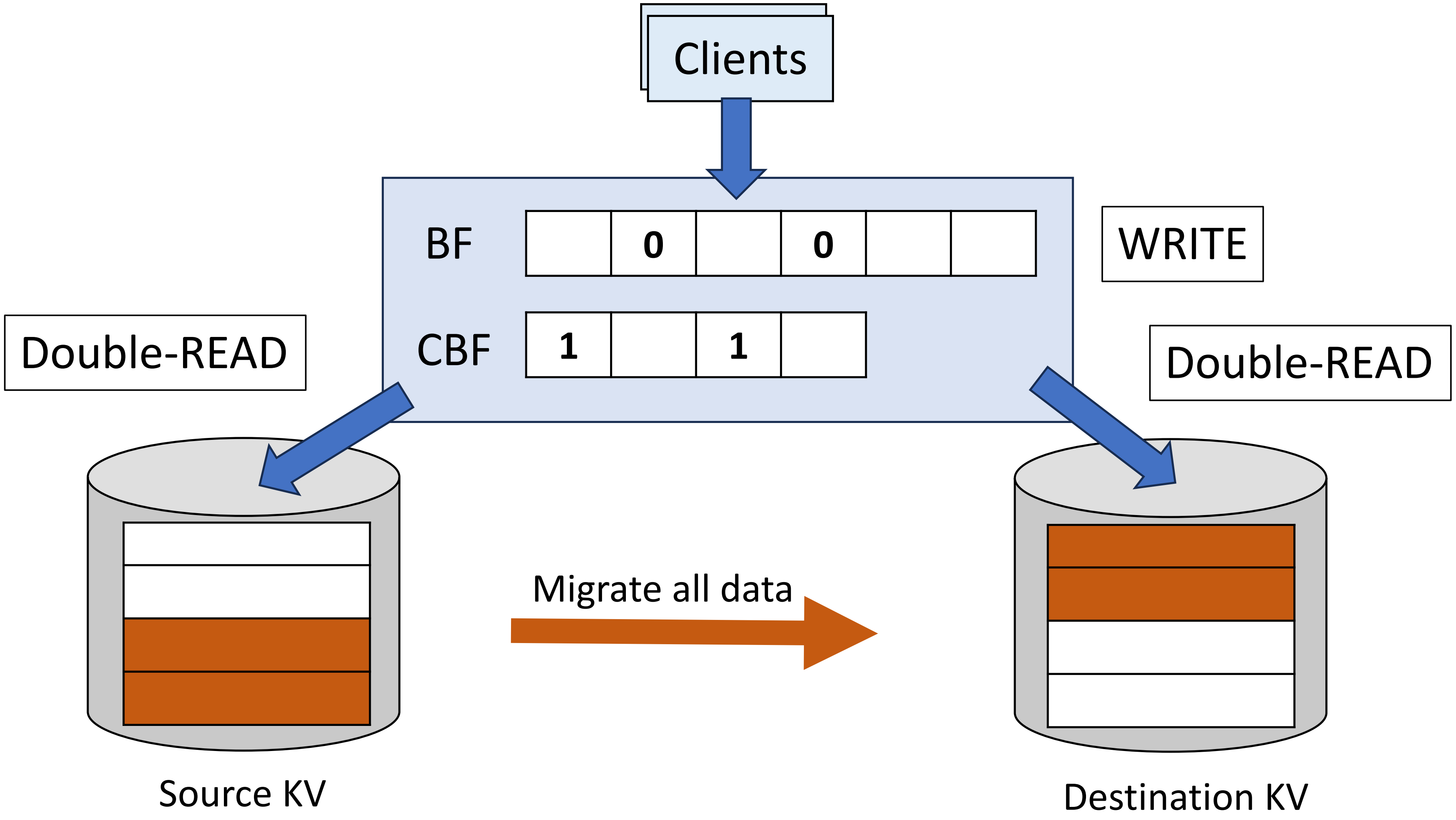


- Not sure where the key is located because of tracking at group level.
- Not sure whether there was a WRITE due to no tracking on every WRITE.

Data is Consistent When Ongoing Migration



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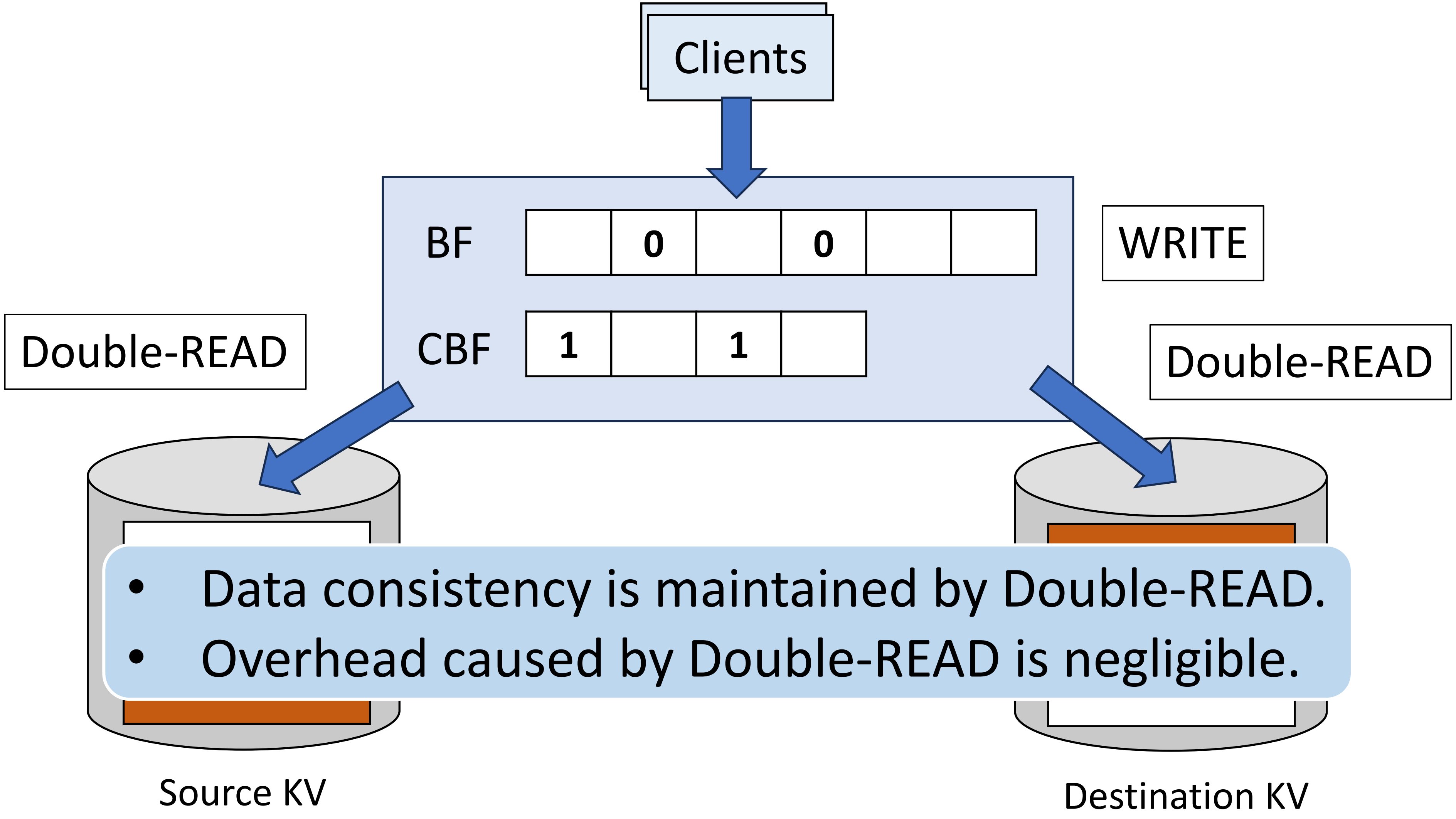
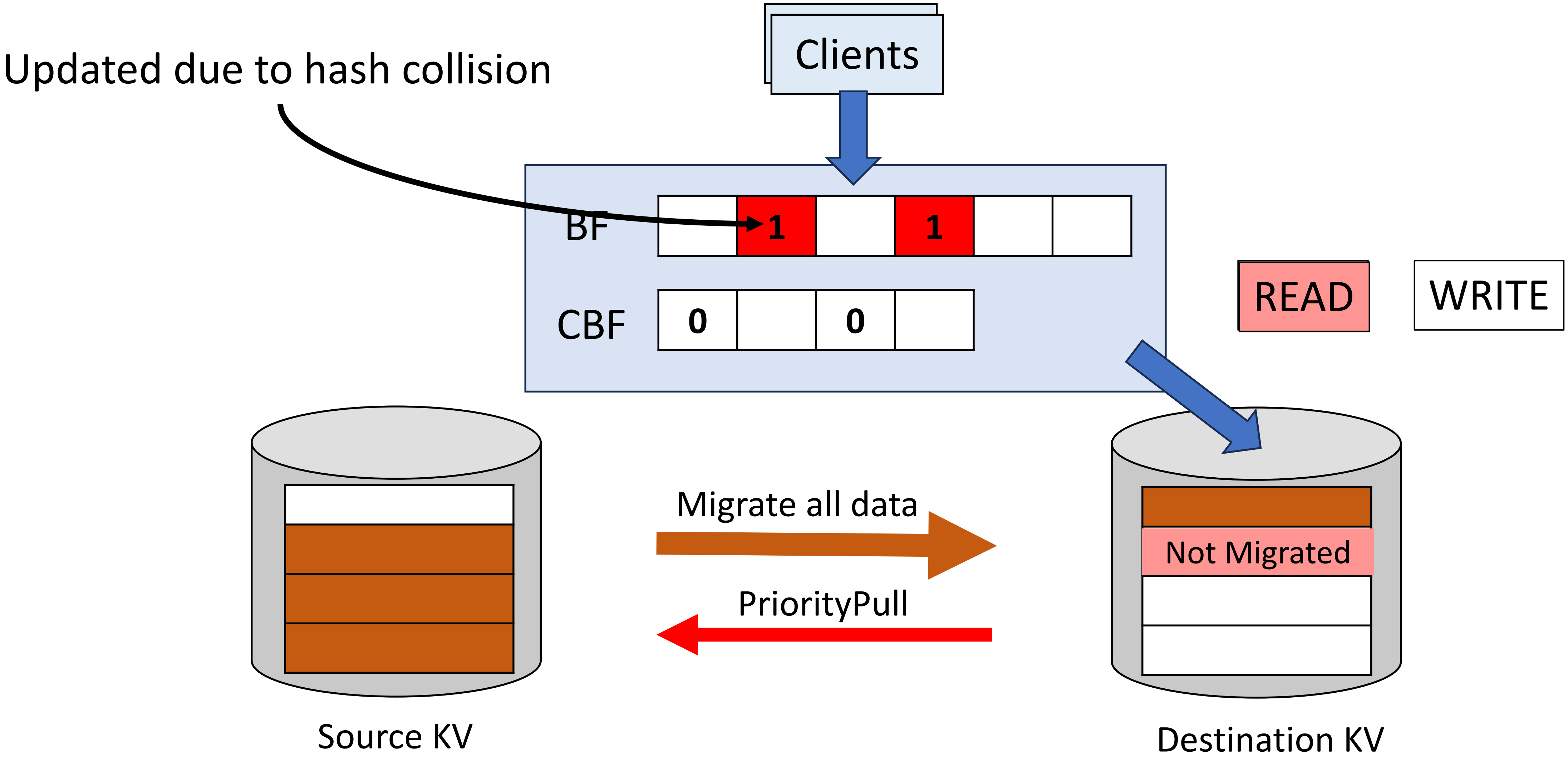


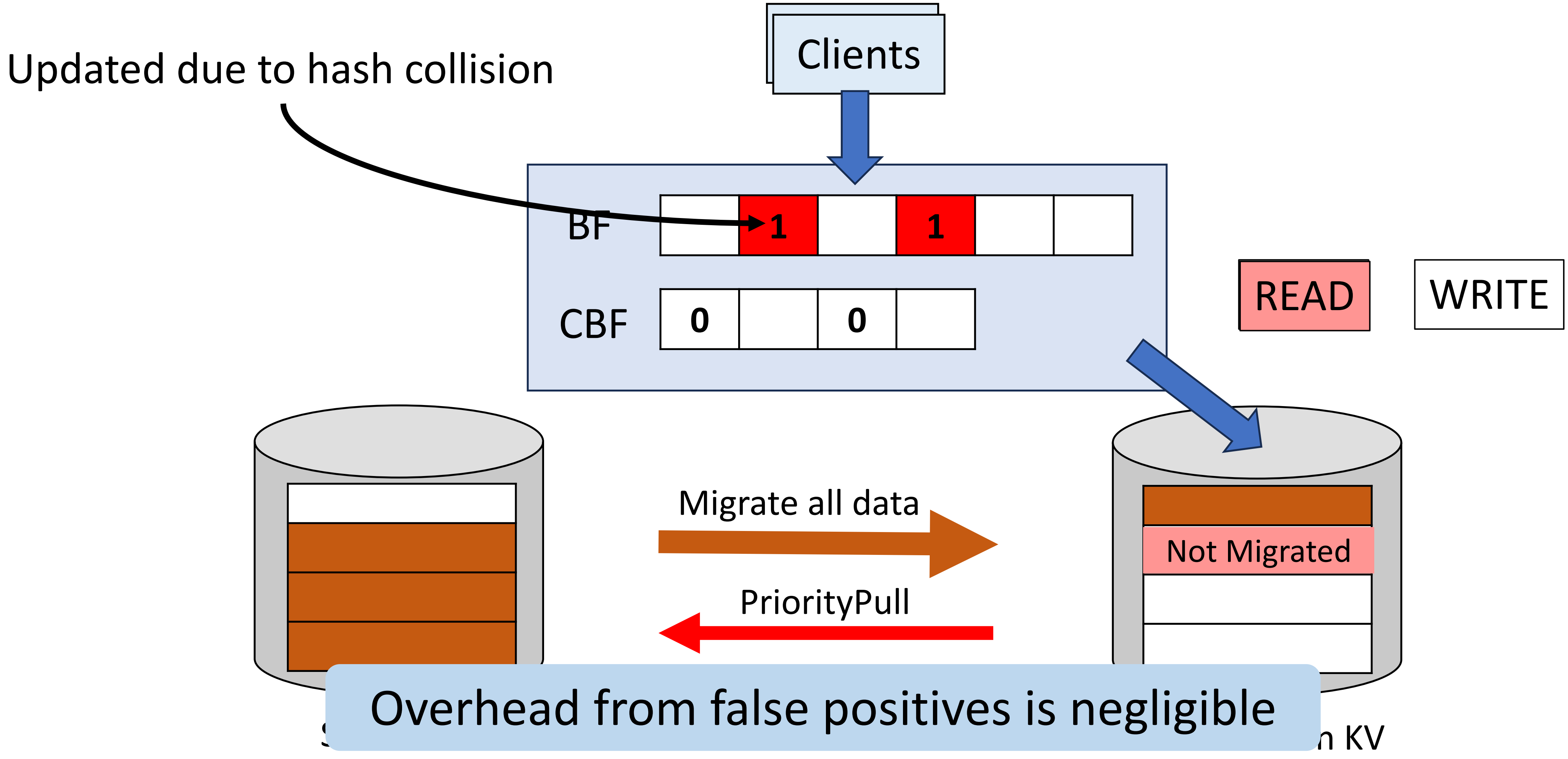
- Data consistency is maintained by Double-READ.
- Overhead caused by Double-READ is negligible.

Data is Consistent even with False Positives



(check more details in our paper)

Data is Consistent even with False Positives



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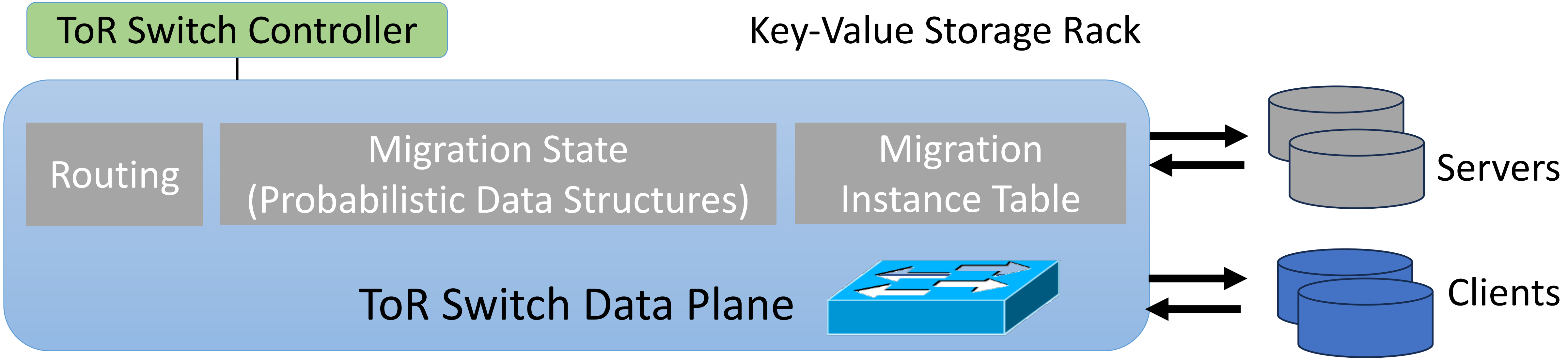
Putting It Together: NetMigrate



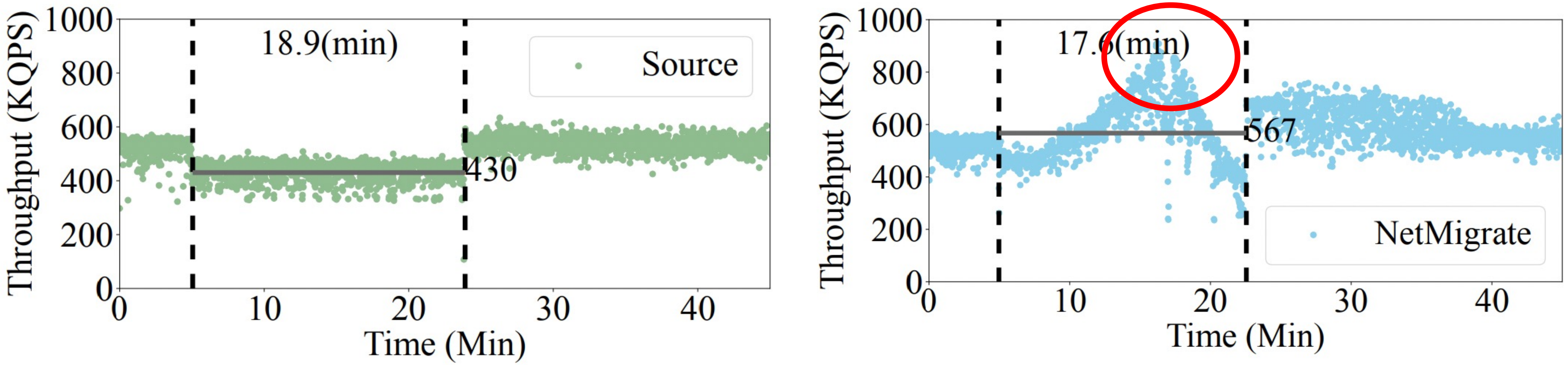
- Leveraging probabilistic data structures on the switch to track three migration states.
- Query protocol guaranteeing consistency.
- The overhead caused by false positives and unsure states is small.

Evaluation

- Testbed
  - 6.5 Tbps Intel Tofino switch
  - 3 servers each with an 8-core CPU, a 40G NIC, and 64GB memory
- Baselines
  - Source-based migration protocol, Rocksteady, Fulva
- Workloads
  - Migrating 256 million KV pairs (~16GB), with 4B key, 64B value
  - YCSB with 0%, 5%, 10%, 20%, 30% write ratio
  - Source CPU budgets: 100%, 70%, 40%

Overall performance -- Throughput

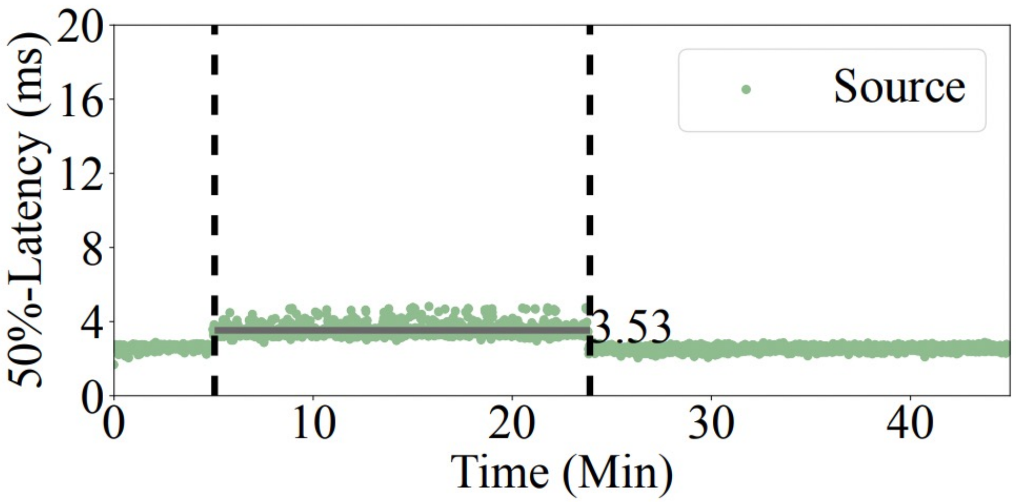
Setting: YCSB-B (5%) write ratio, source node is not overloaded (100%)

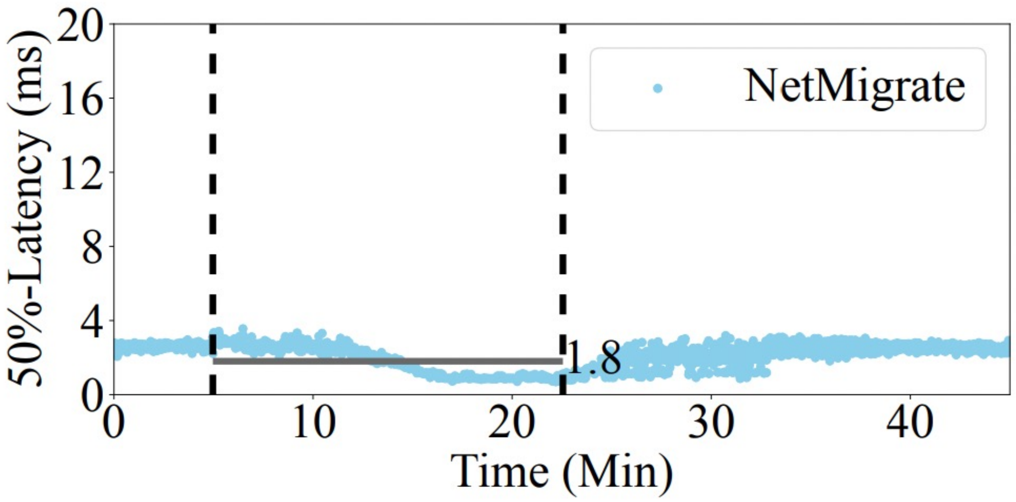


32% to 78% average throughput improvement compared to Source-based, Rocksteady, Fulva with similar migration time.

Overall performance – Median Latency

Setting: YCSB-B (5%) write ratio, source node is not overloaded (100%)





49% to 65% average median latency reduction.
Up to 39% average 99% tail-latency reduction.

Network Overhead

Protocols/Overhead	Client-side	Server-side
Rocksteady	7%~12%	0
Source-based	0	Proportional to write ratio
Fulva	~50%	0
NetMigrate	<0.05%	$<5\times10^{-5}\%$

Extra network bandwidth overhead
between clients and servers (client-side)
or between servers (server-side)

Conclusions

- Existing KV store live migration techniques still suffer from low query-serving performance and high overhead.
- We propose NetMigrate, a network-based hybrid live migration approach.
  - Track fine-grained migration states in programmable data plane.
  - Provide enhanced throughput and low migration overheads.
- Open-sourced at https://github.com/Froot-NetSys/NetMigrate.

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ARTIFACT EVALUATED usenix ASSOCIATION FUNCTIONAL

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Thank you! Q&A