A Look at Flink's Internal Data Structures for Efficient Checkpointing

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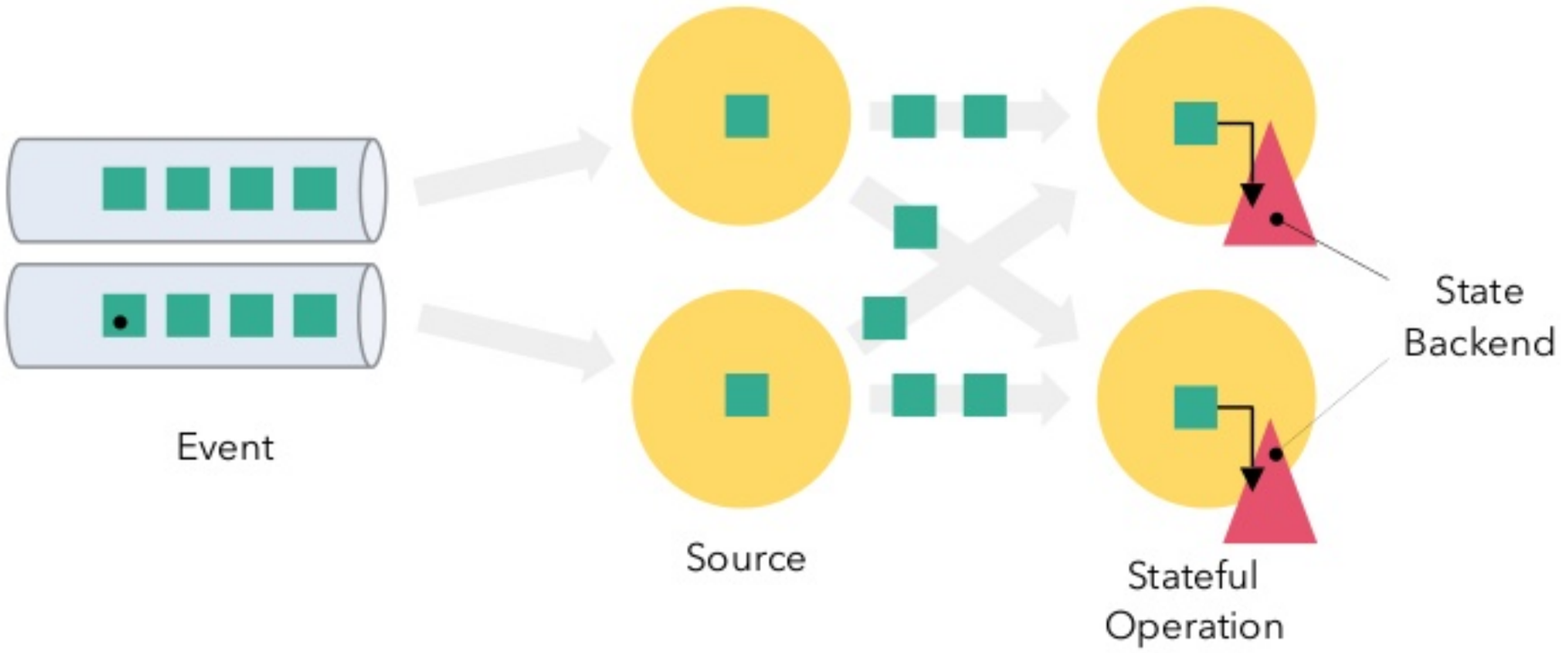
Flink State and Distributed Snapshots



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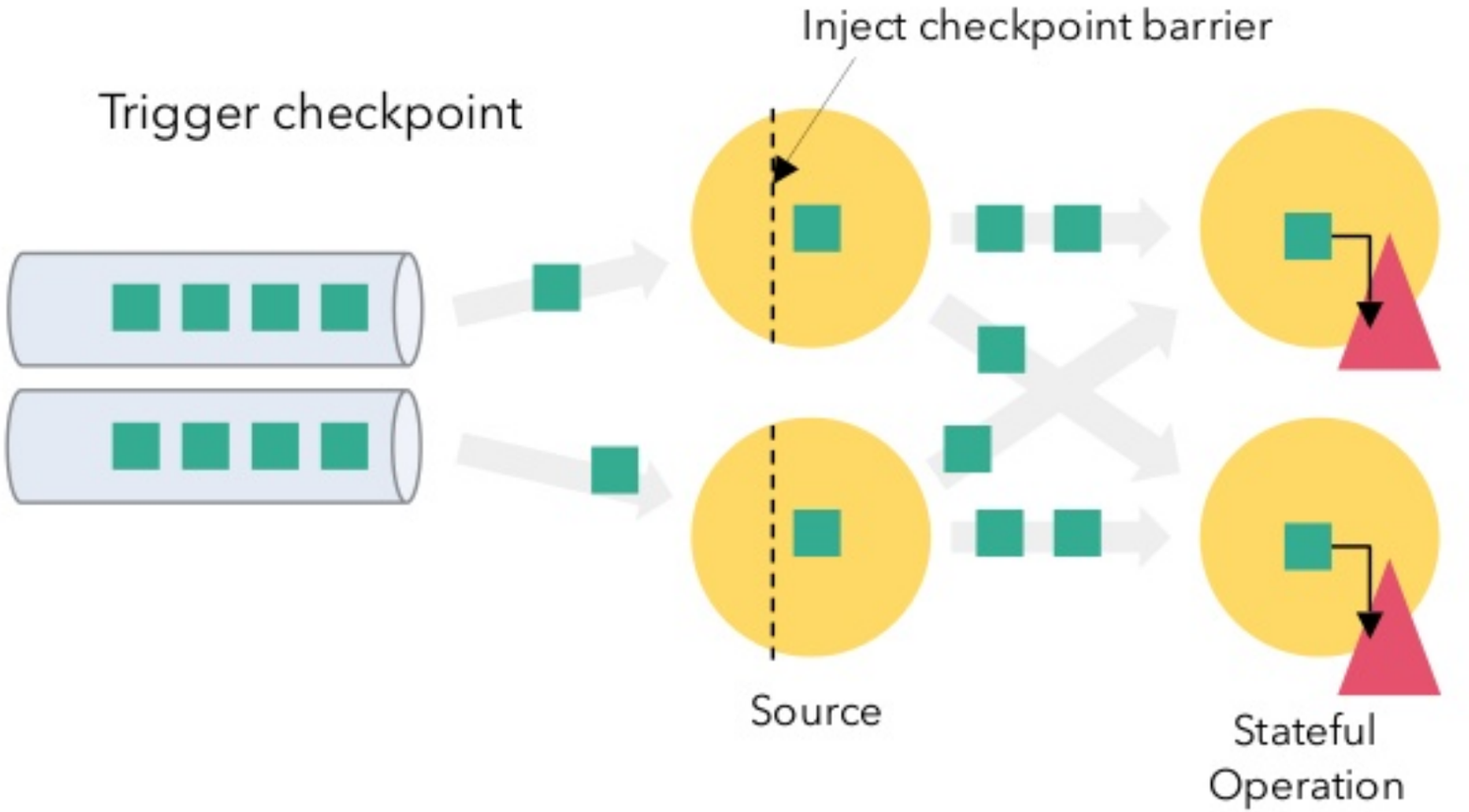
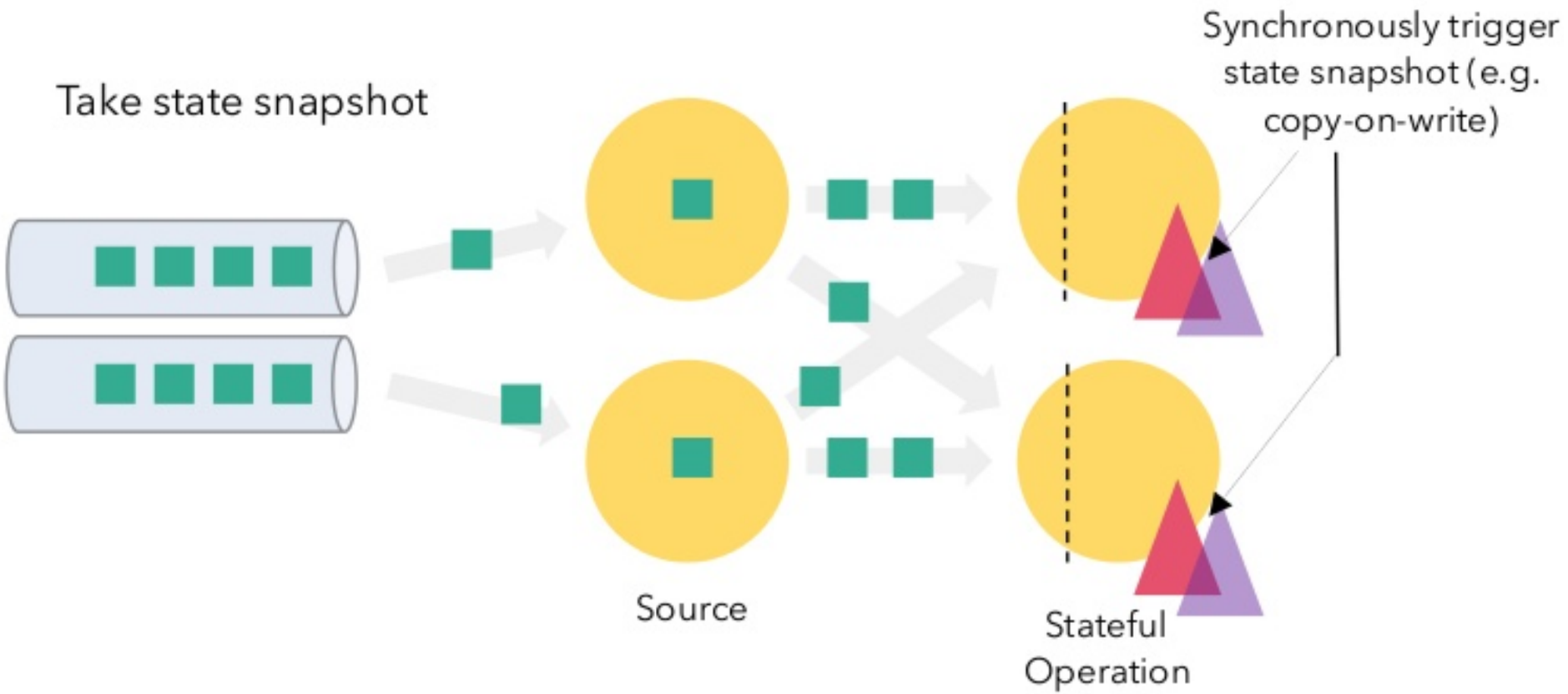


„Asynchronous Barrier Snapshotting“

Flink State and Distributed Snapshots



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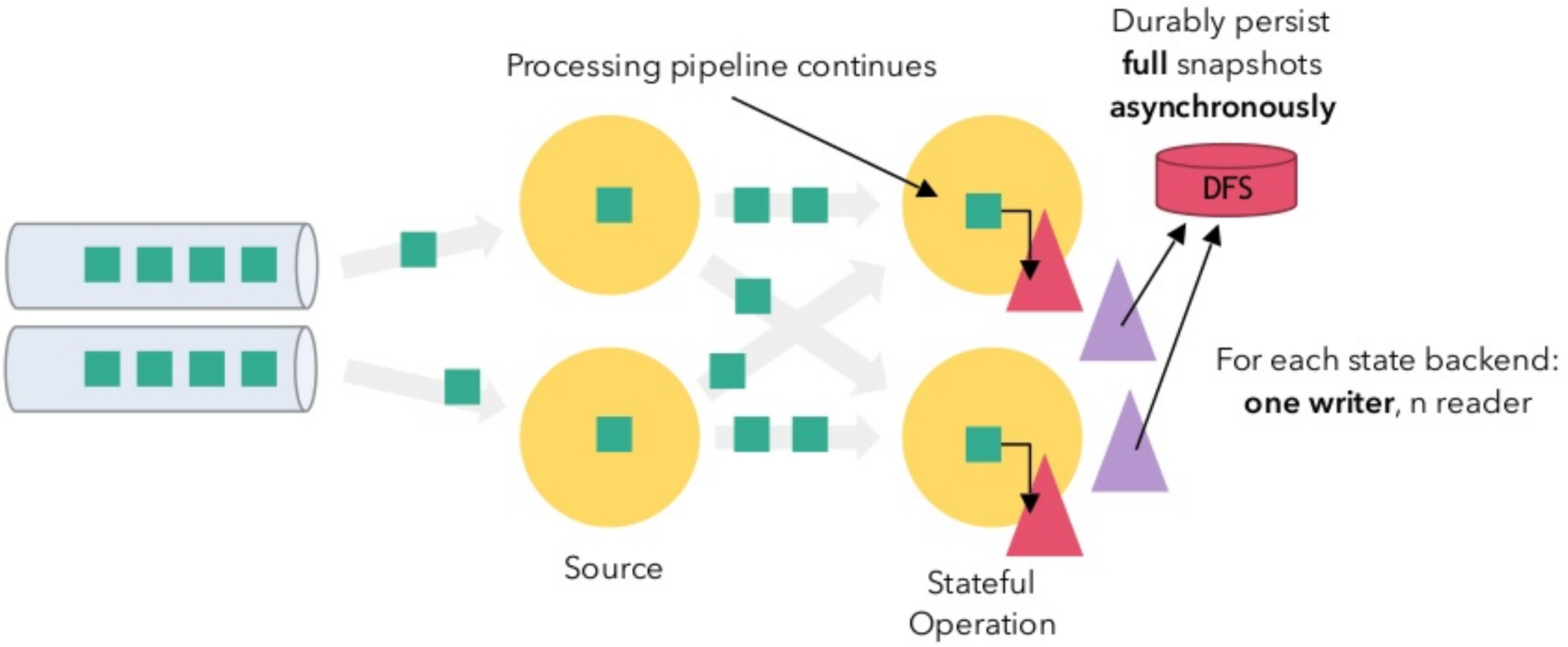
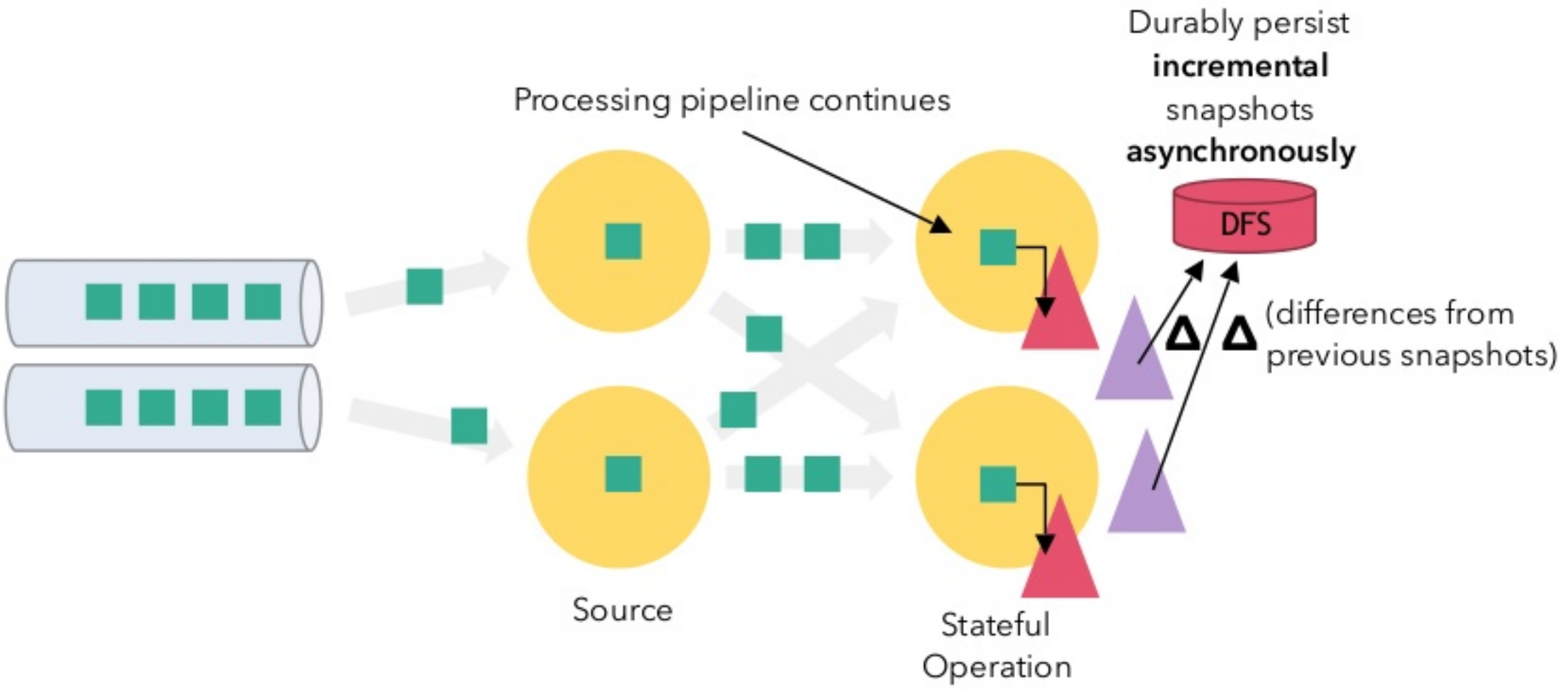


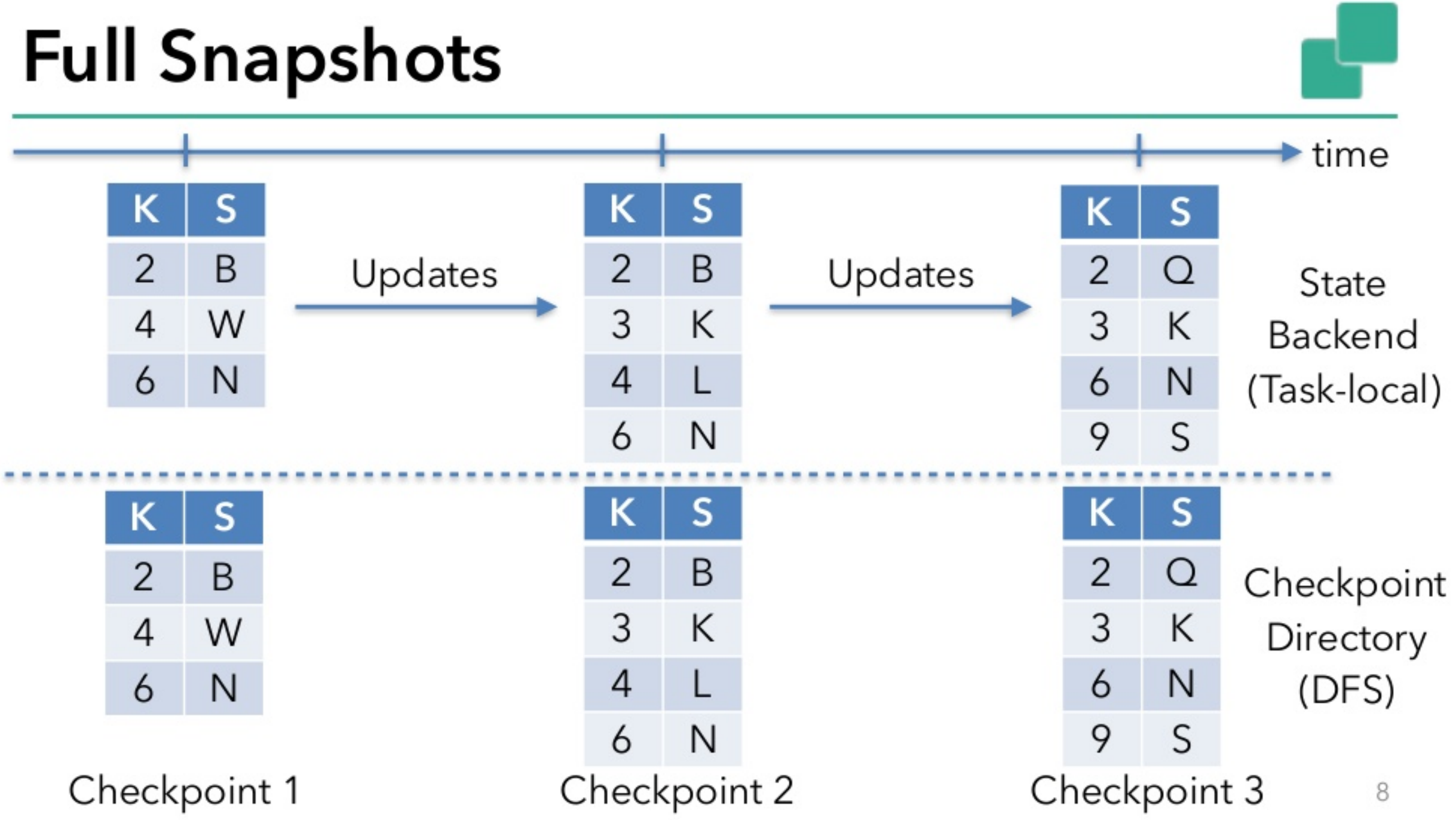
Challenges for Data Structures

- Asynchronous Checkpoints:
  - Minimize pipeline stall time while taking the snapshot.
  - Keep overhead (memory, CPU,…) as low as possible while writing the snapshot.
  - Support multiple parallel checkpoints.

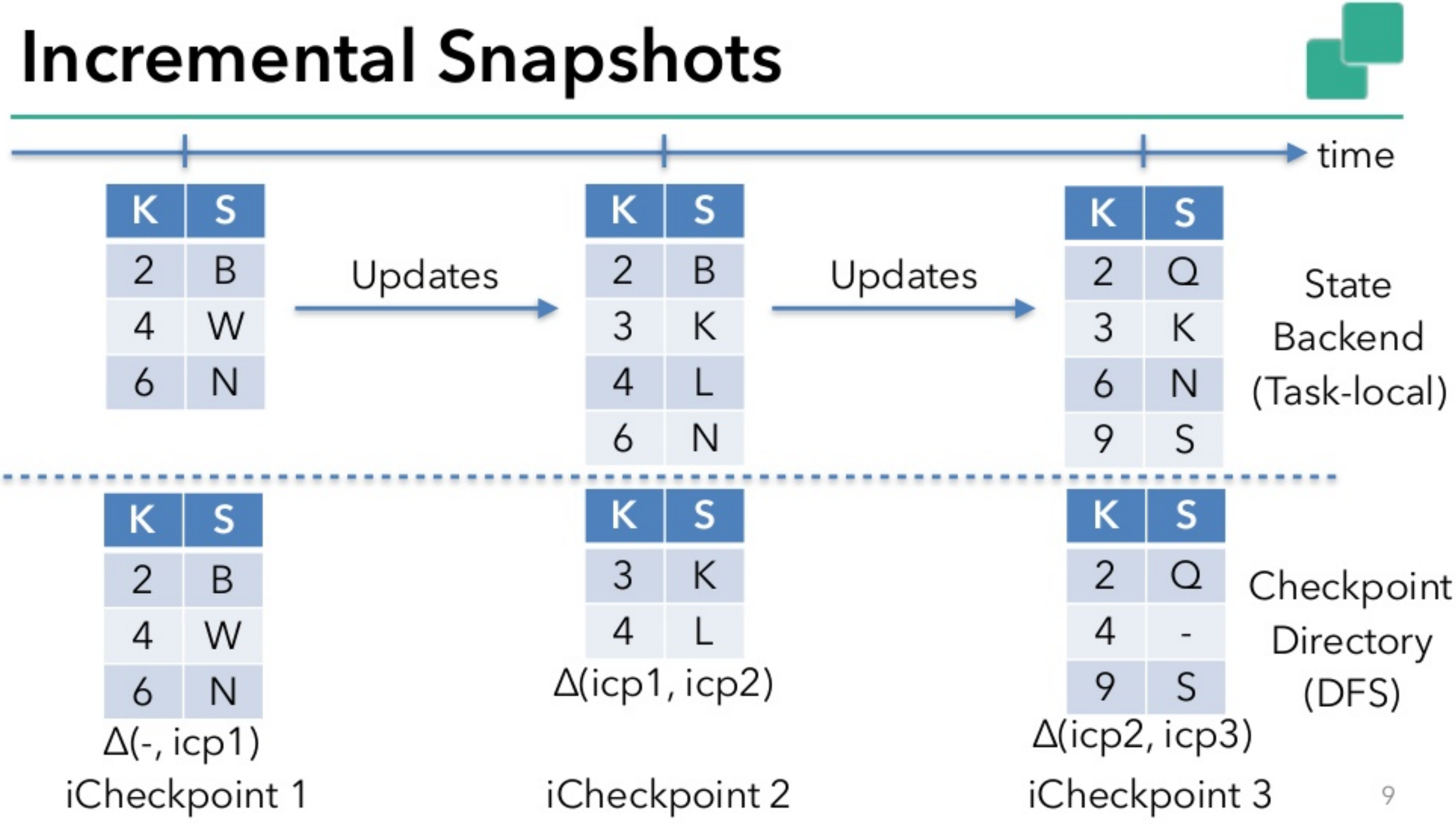
Flink State and Distributed Snapshots



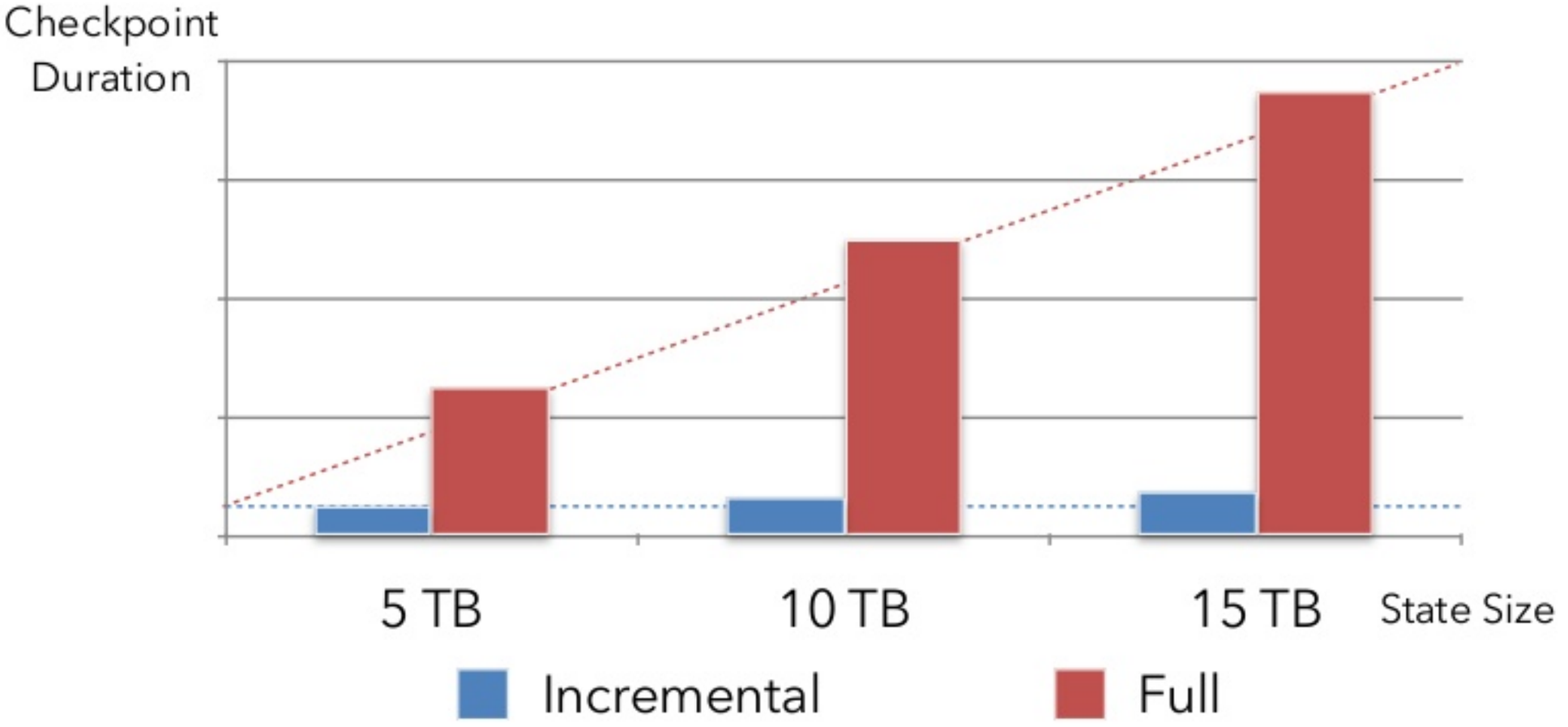
Full Snapshots



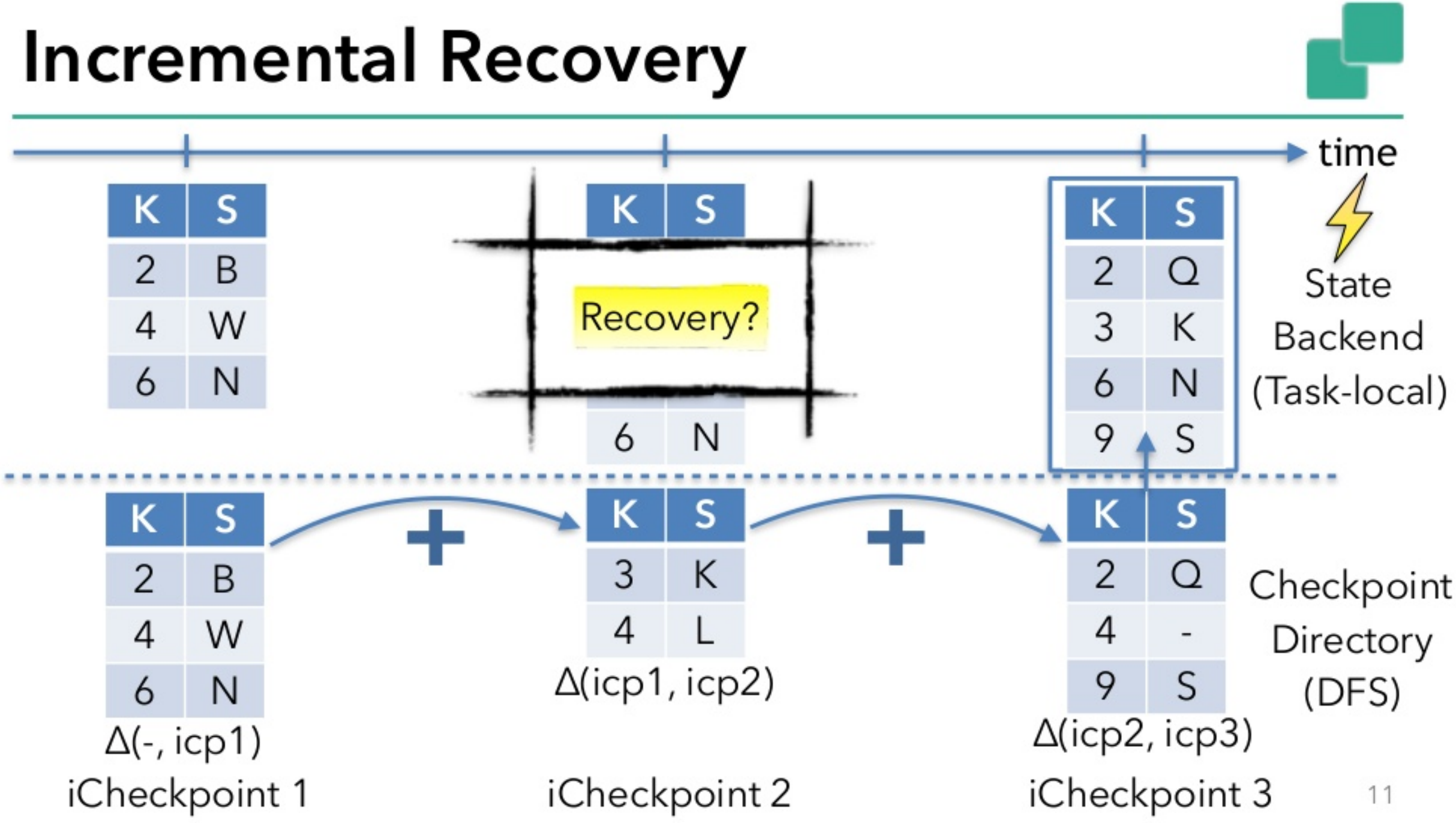
Incremental Snapshots



Incremental vs Full Snapshots



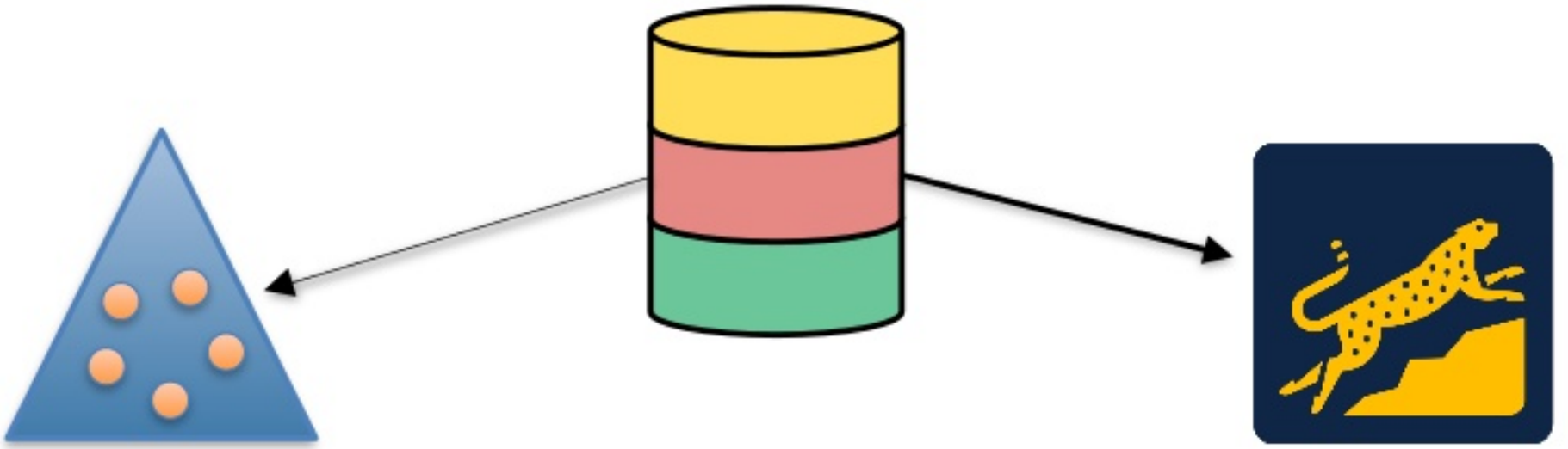
Incremental Recovery



Challenges for Data Structures

- Incremental checkpoints:
  - Efficiently detect the (minimal) set of state changes between two checkpoints.
  - Avoid unbounded checkpoint history.

Two Keyed State Backends



HeapKeyedStateBackend

- State lives in memory, on Java heap.
- Operates on objects.
- Think of a hash map {key obj -> state obj}.
- **Goes through ser/de during snapshot/restore.**
- **Async snapshots supported.**

RocksDBKeyedStateBackend

- State lives in off-heap memory and on disk.
- Operates on serialized bytes.
- Think of K/V store {key bytes -> state bytes}.
- Based on log-structured-merge (LSM) tree.
- **Goes through ser/de for each state access.**
- **Async and incremental snapshots.**

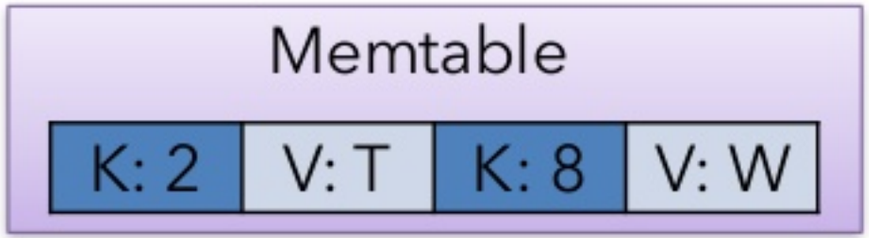
Asynchronous and Incremental Checkpoints with the RocksDB Keyed-State Backend

What is RocksDB

- Ordered Key/Value store (bytes).
- Based on LSM trees.
- Embedded, written in C++, used via JNI.
- Write optimized (all bulk sequential), with acceptable read performance.

RocksDB Architecture (simplified)

Memory



- Mutable Memory Buffer for K/V Pairs (bytes)
- All reads / writes go here first
- Aggregating (overrides same unique keys)
- Asynchronously flushed to disk when full

Local Disk

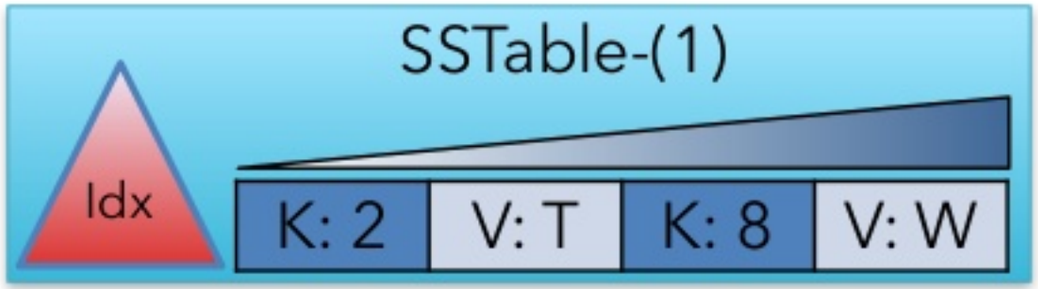
RocksDB Architecture (simplified)

Memory

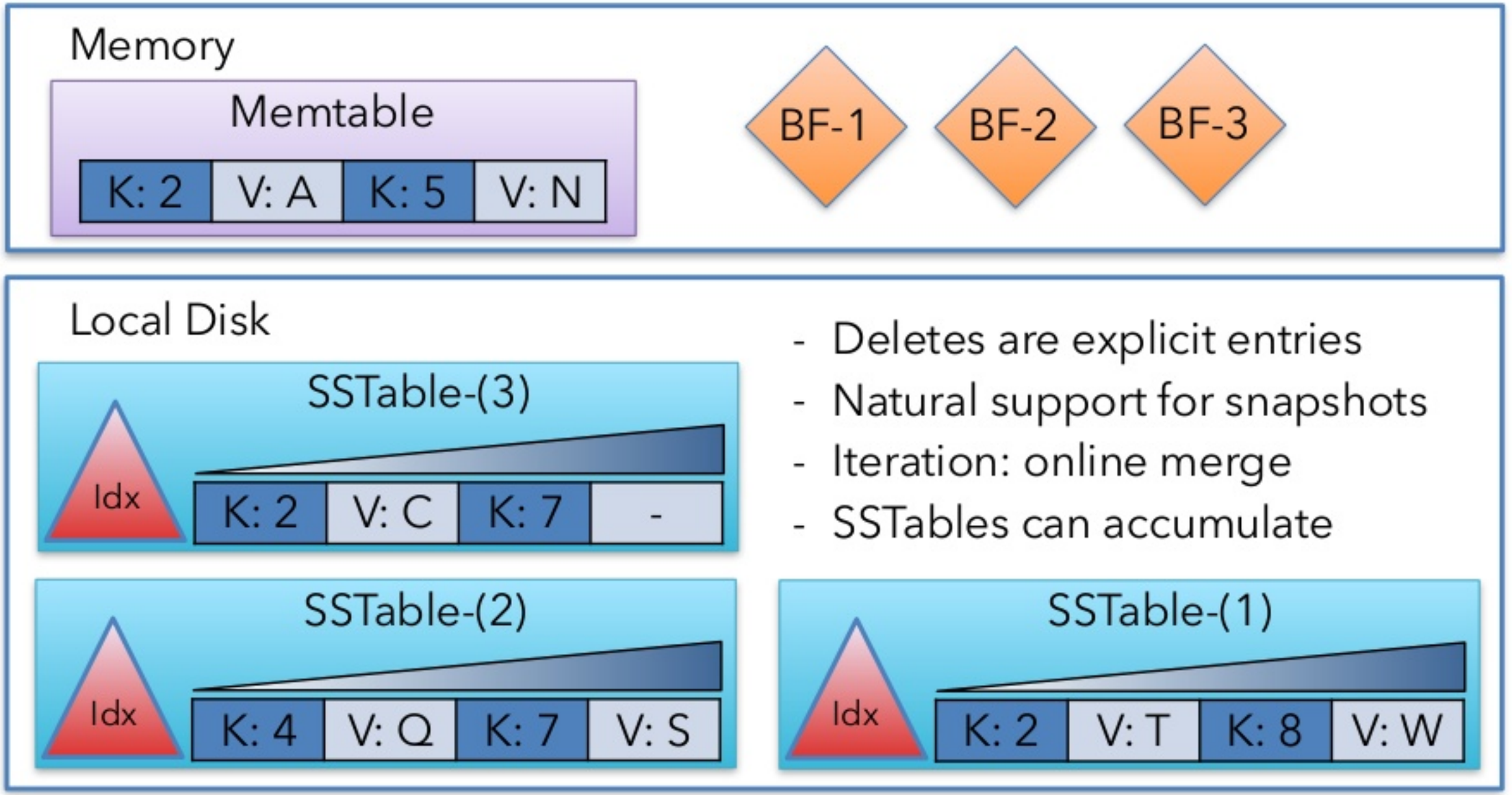
Memtable

Local Disk

- Flushed Memtable becomes **immutable**
- Sorted By Key (unique)
- Read: first check Memtable, then SSTable
- Bloomfilter & Index as optimisations

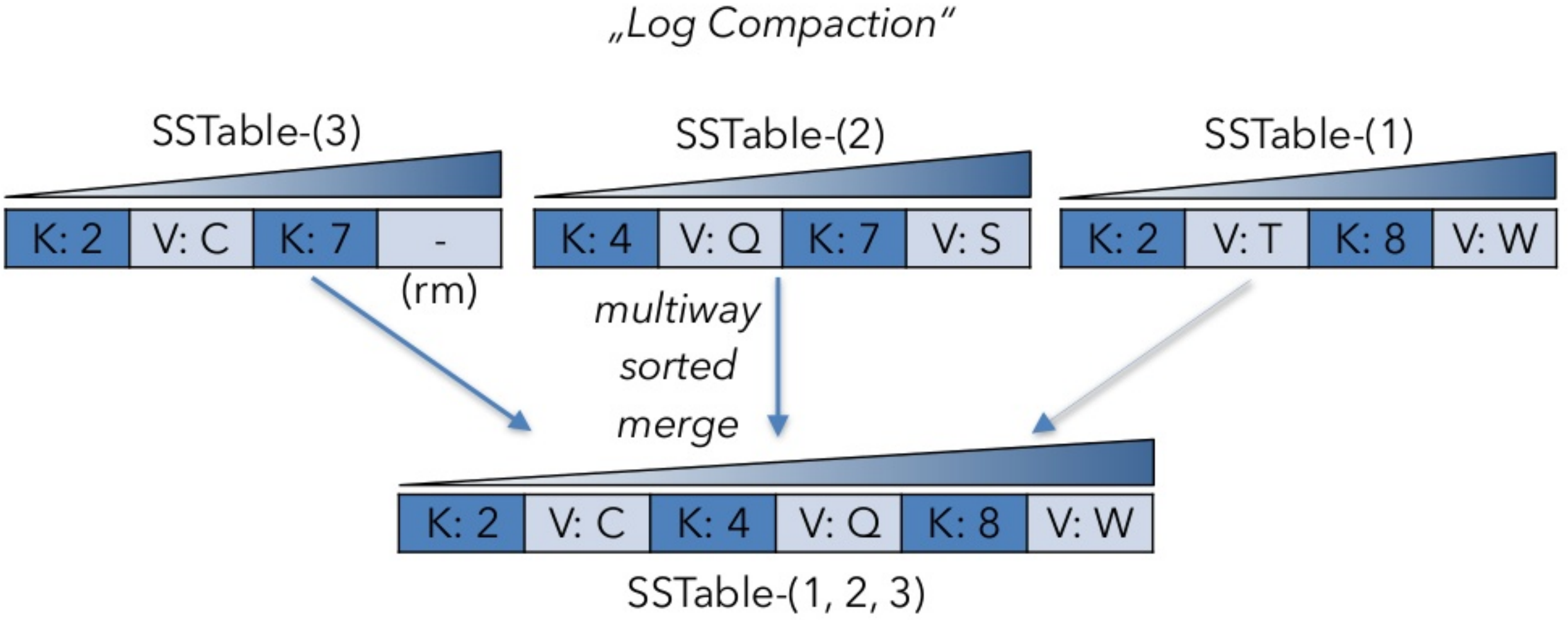


RocksDB Architecture (simplified)



- Deletes are explicit entries
- Natural support for snapshots
- Iteration: online merge
- SSTables can accumulate

RocksDB Compaction (simplified)



RocksDB Asynchronous Checkpoint

- Flush Memtable. (Simplified)
- Then create iterator over all current SSTables (they are immutable).
- New changes go to Memtable and future SSTables and are not considered by iterator.

RocksDB Incremental Checkpoint

- Flush Memtable.
- For all SSTable files in local working directory: upload new files since last checkpoint to DFS, re-reference other files.
- Do reference counting on JobManager for uploaded files.

Incremental Checkpoints - Example

- Illustrate interactions (simplified) between:
  - Local RocksDB instance
  - Remote Checkpoint Directory (DFS)
  - Job Manager (Checkpoint Coordinator)
- In this example: 2 latest checkpoints retained

Incremental Checkpoints - Example

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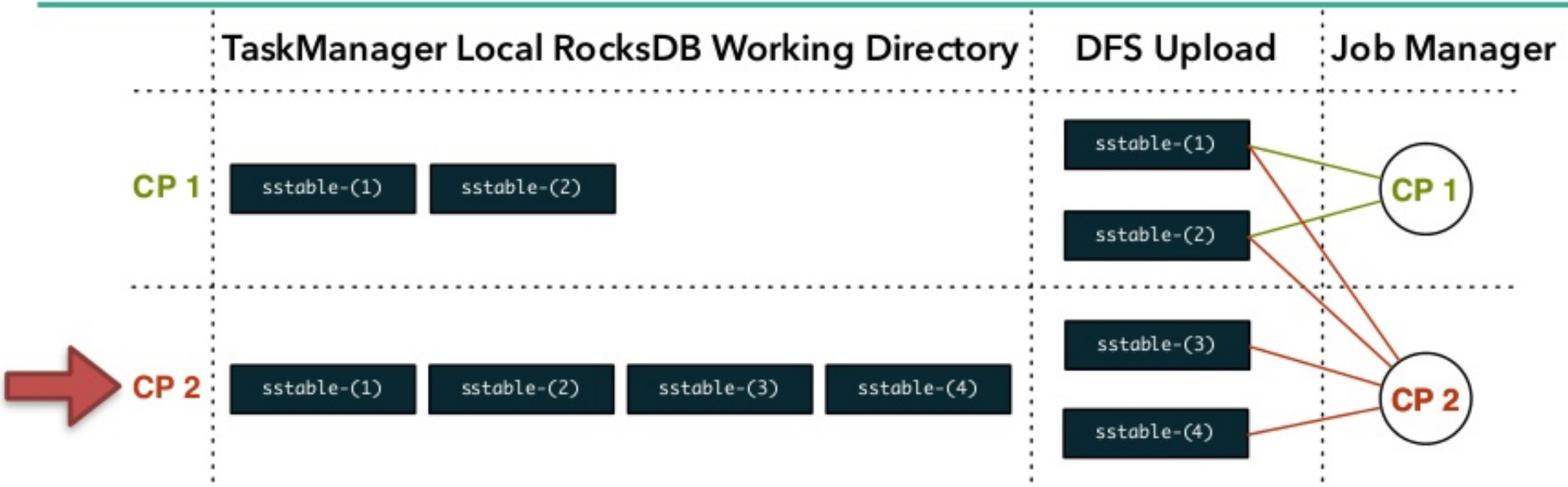
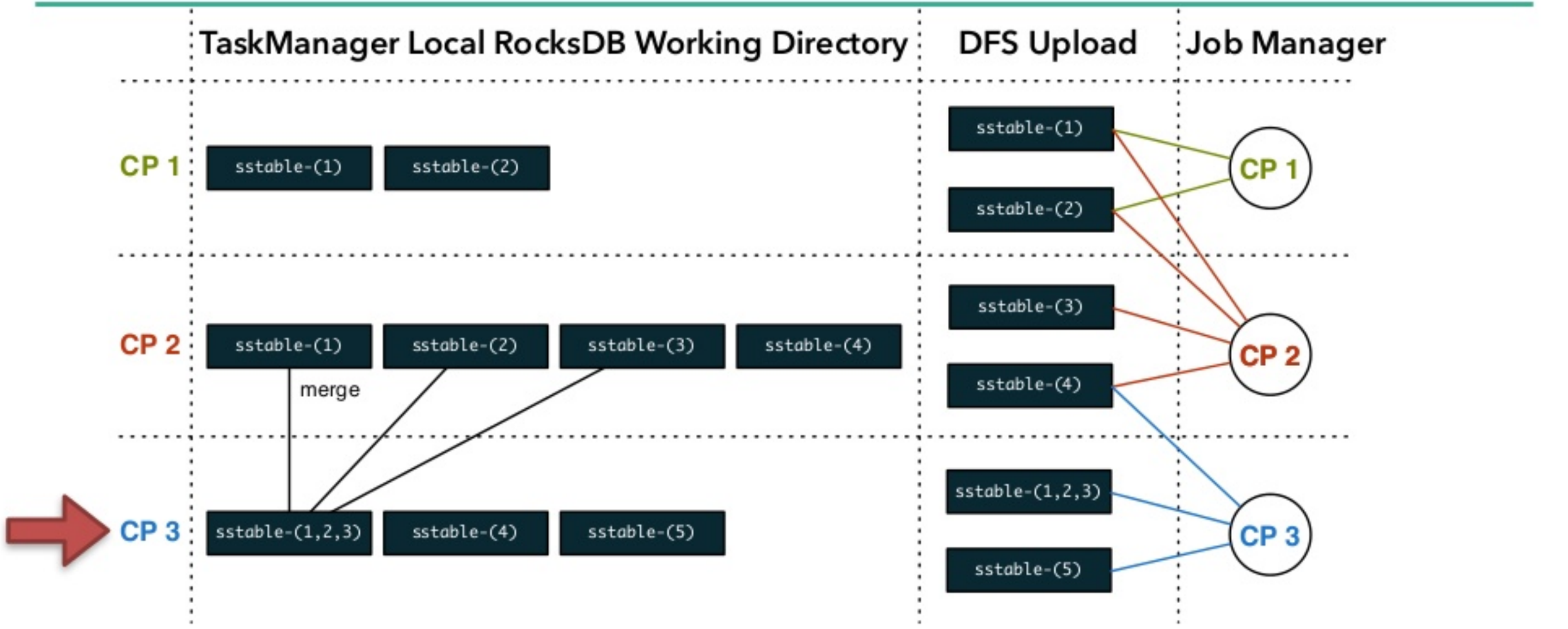
Incremental Checkpoints - Example



Incremental Checkpoints - Example



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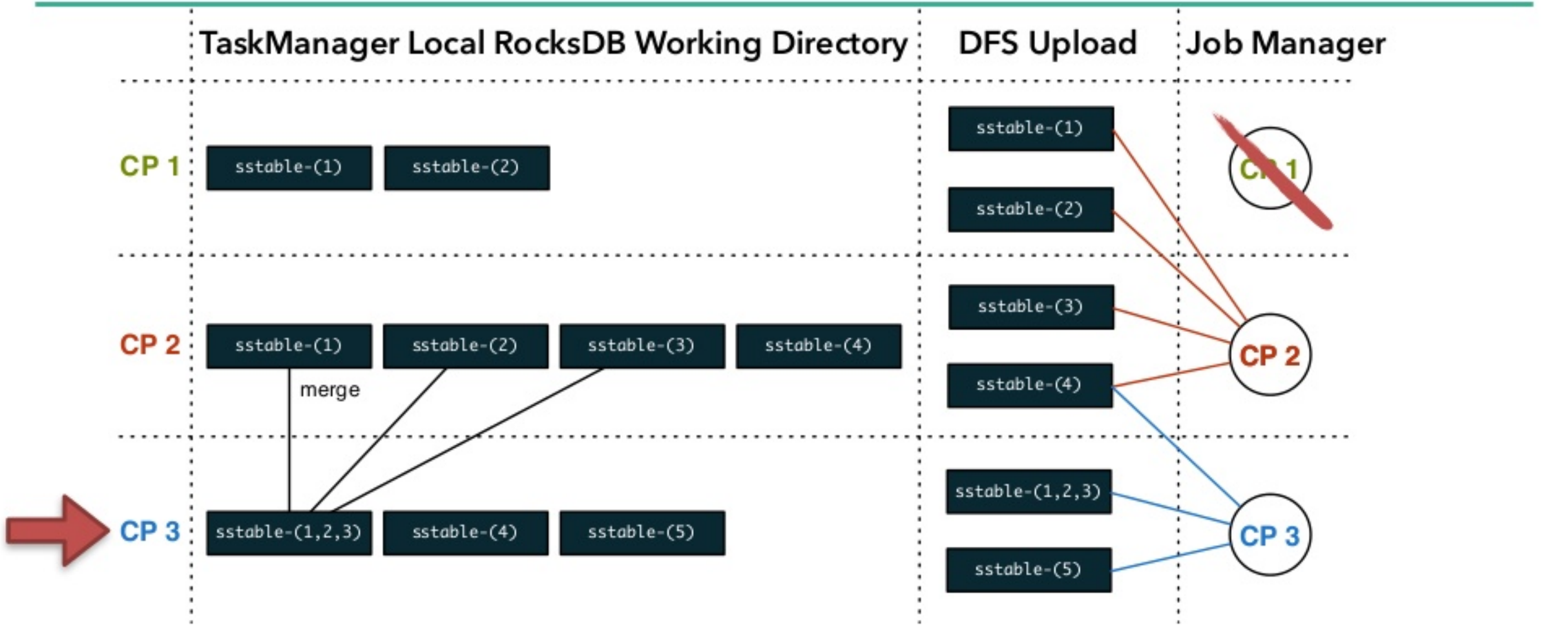

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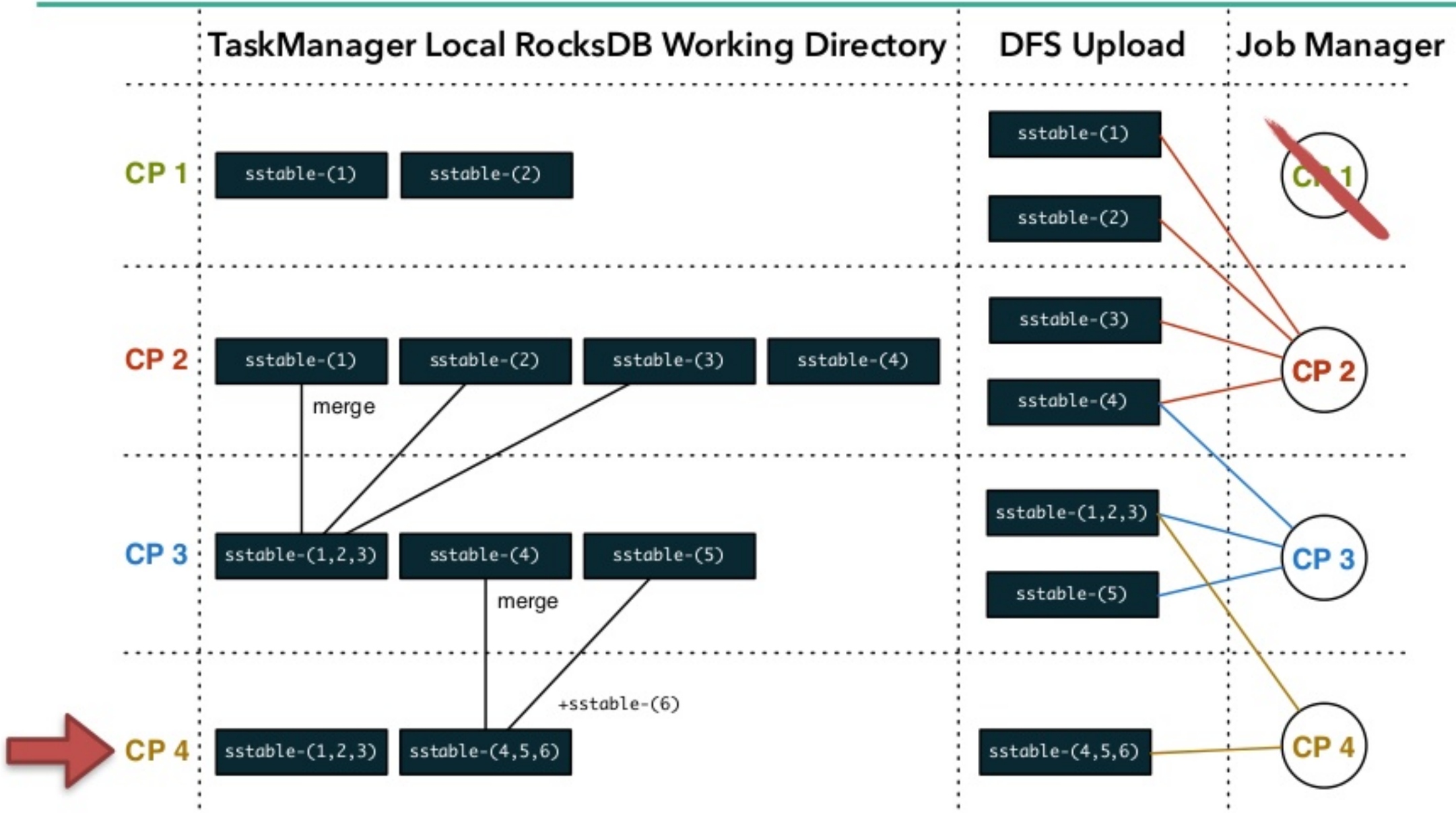

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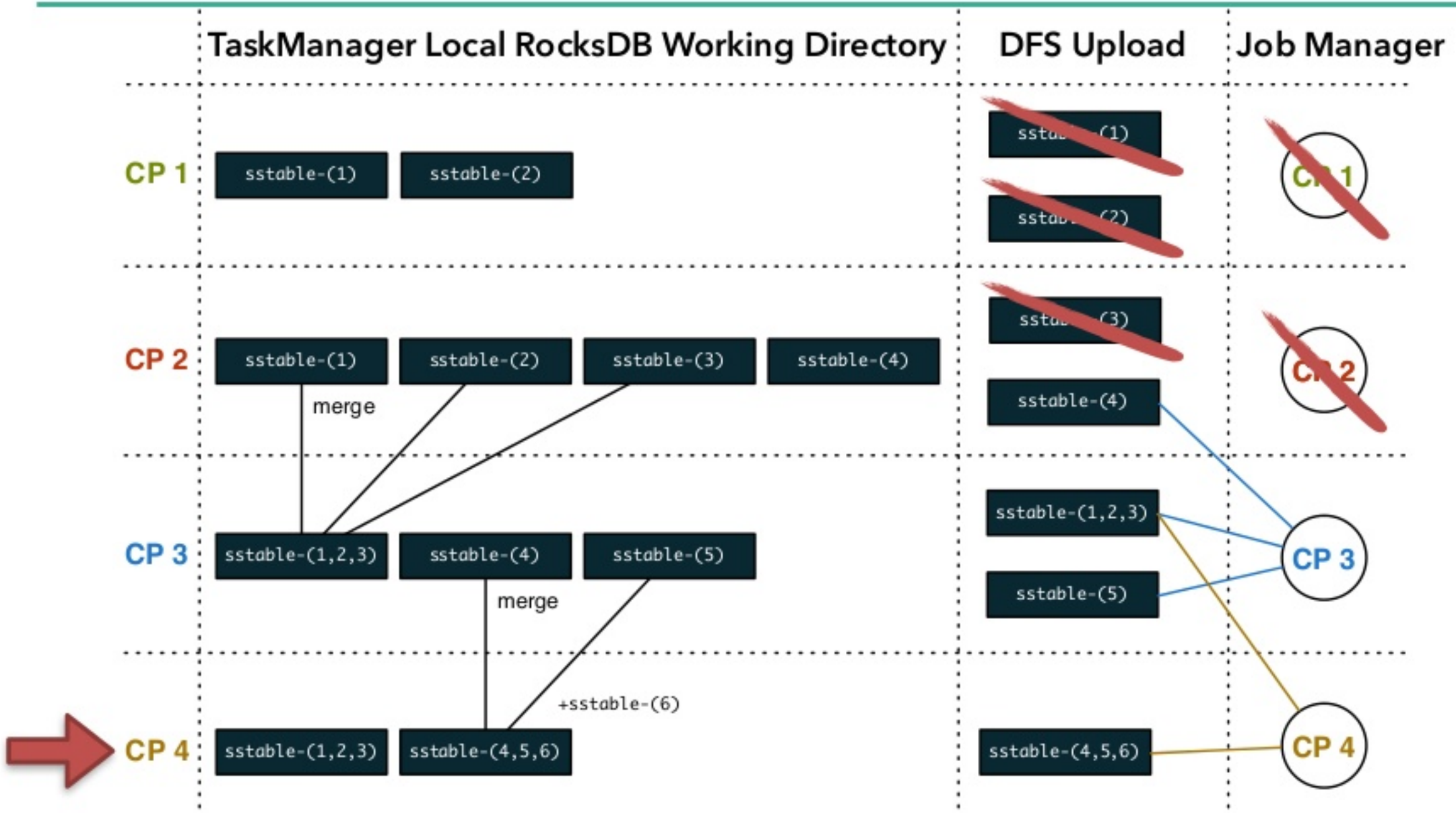
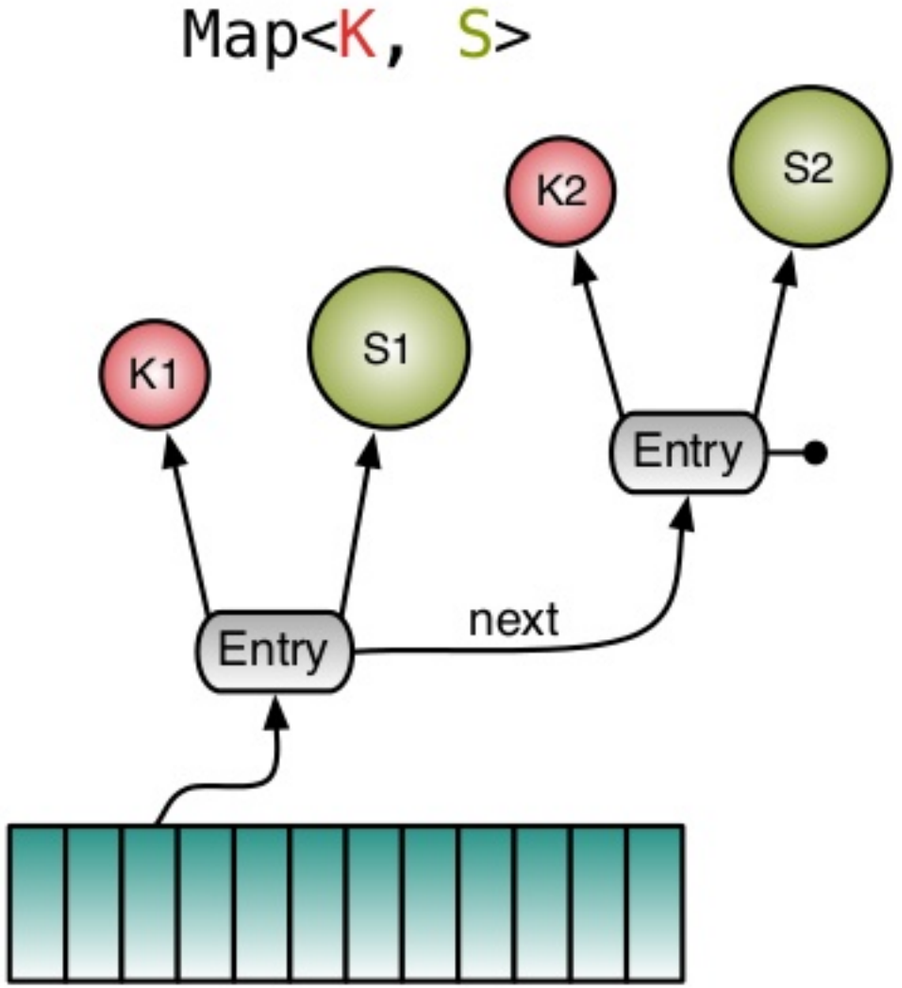


Summary RocksDB

- Asynchronous snapshots „for free“, immutable copy is already there.
- Trivially supports multiple concurrent snapshots.
- Detection of incremental changes easy: observe creation and deletion of SSTables.
- Bounded checkpoint history through compaction.

Asynchronous Checkpoints with the Heap Keyed-State Backend

Heap Backend: Chained Hash Map



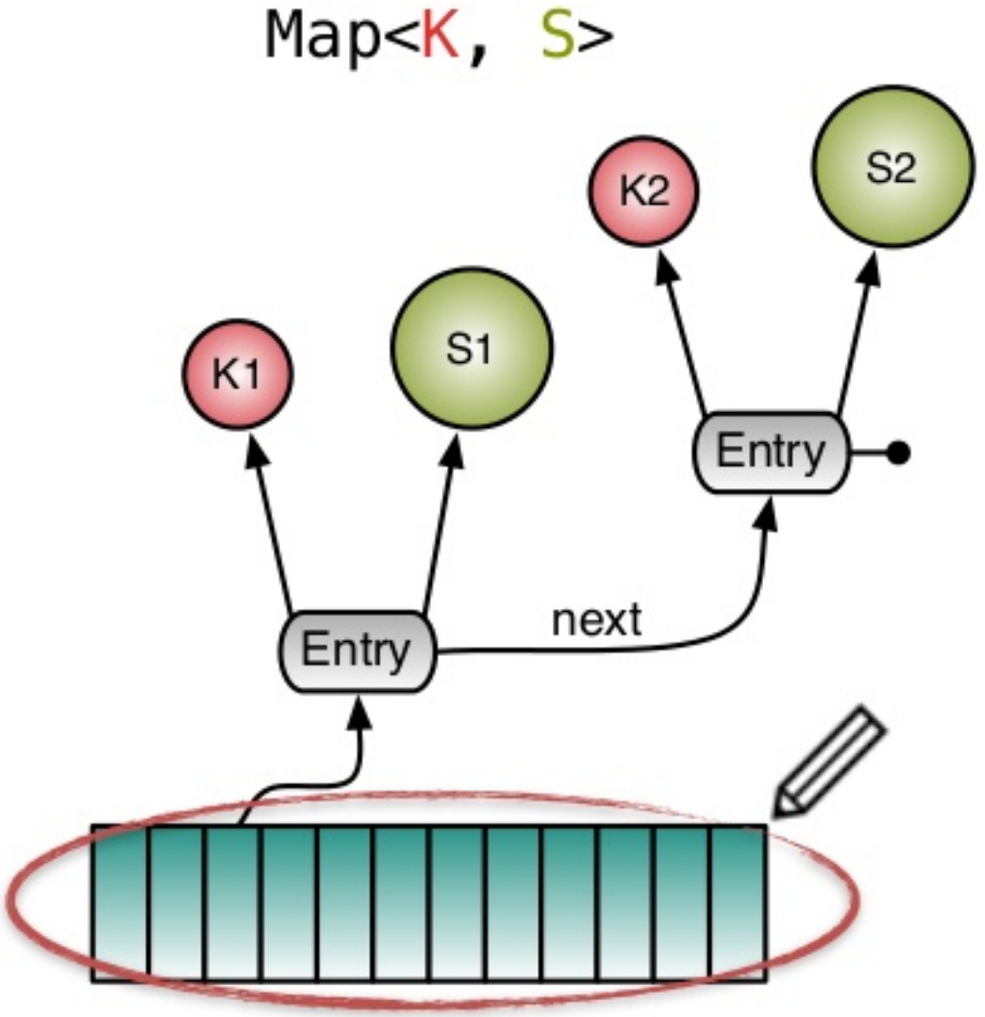

```
Map<K, S> {

    Entry<K, S>[] table;
}
```

```
Entry<K, S> {

    final K key;
    S state;
    Entry next;
}
```

Heap Backend: Chained Hash Map

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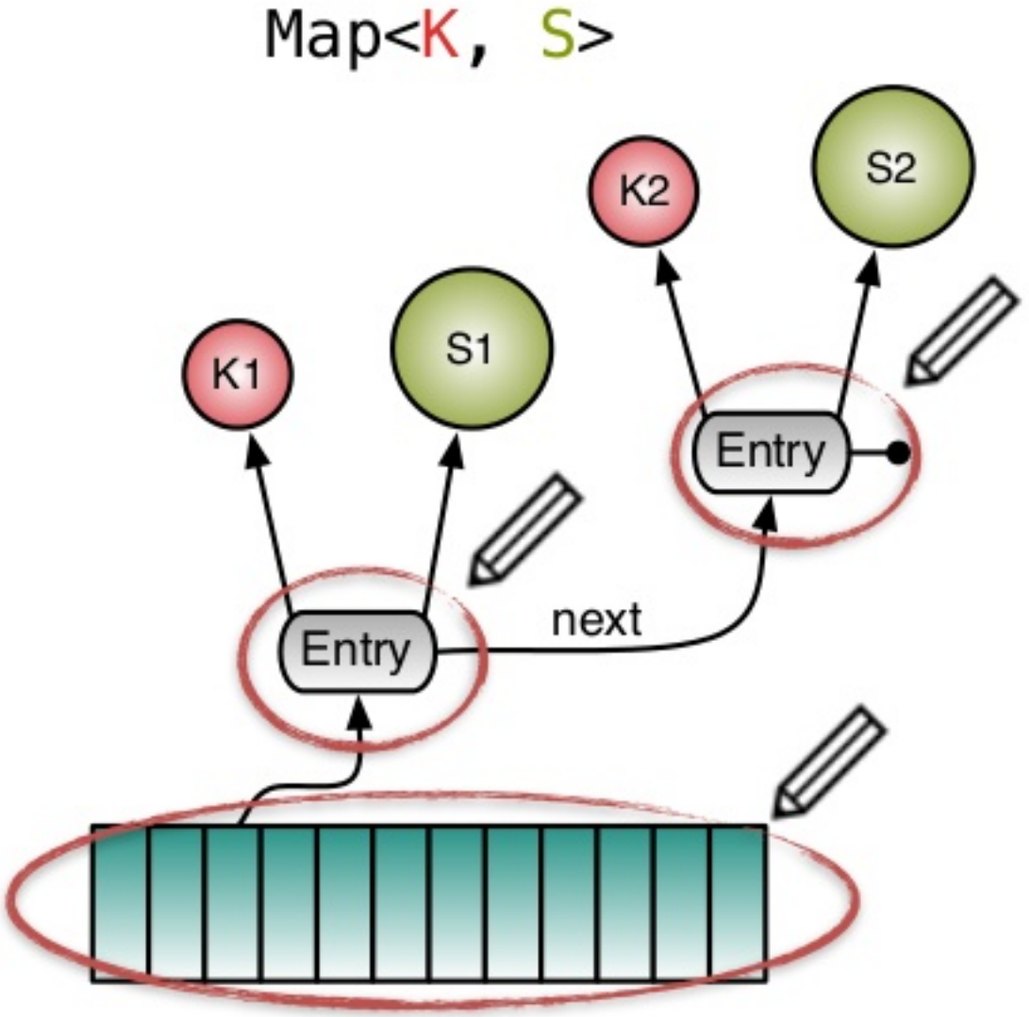


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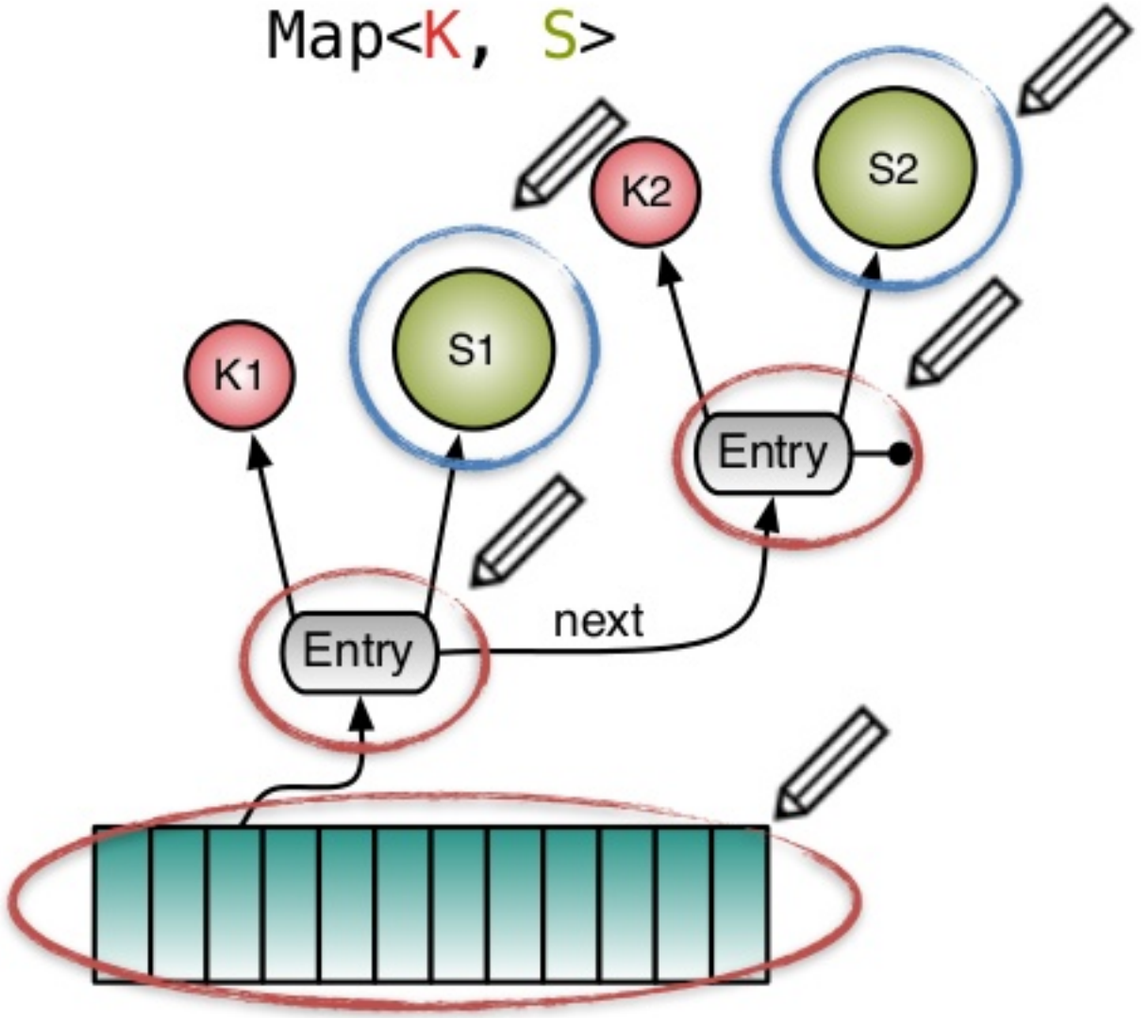


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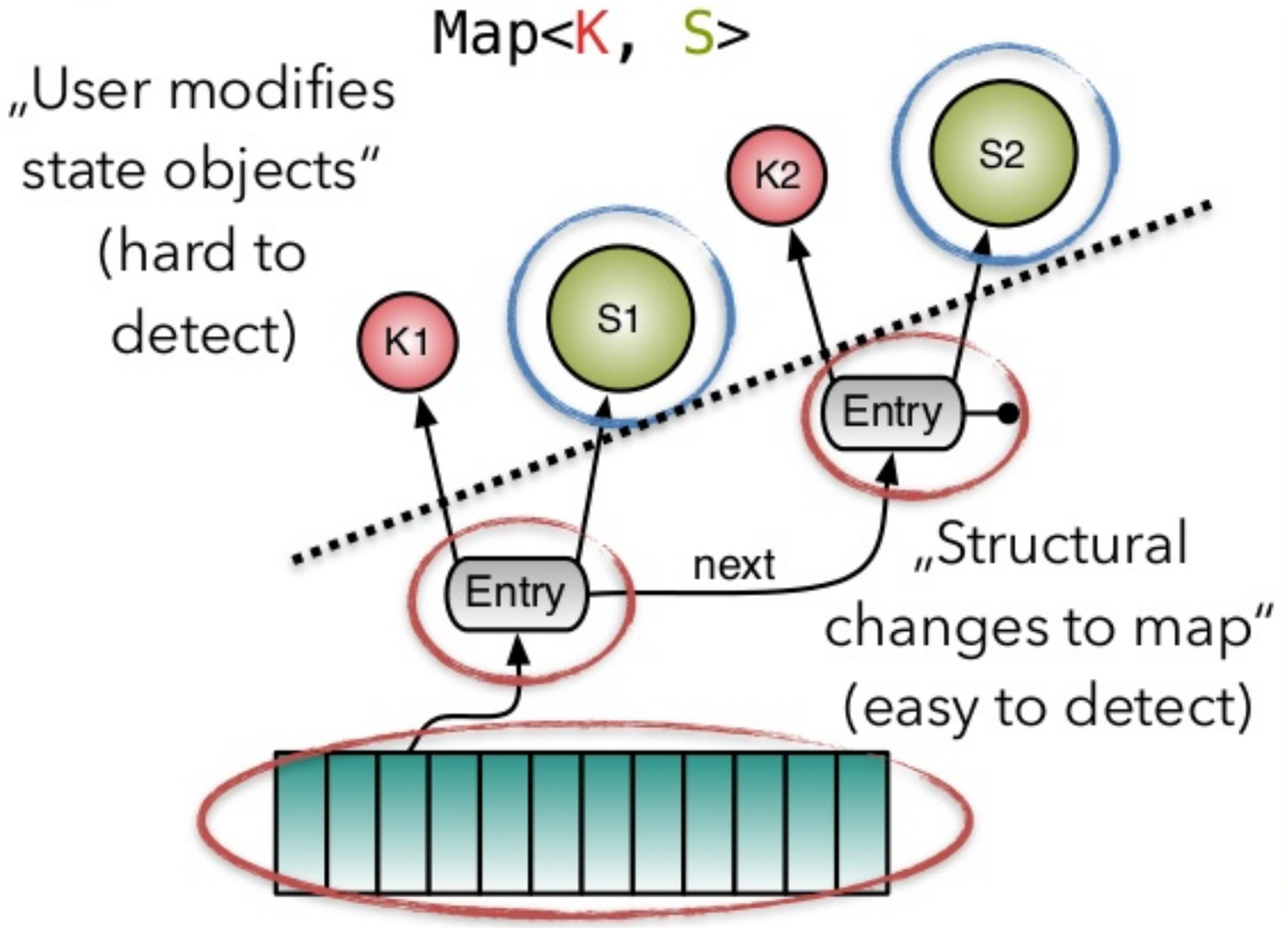


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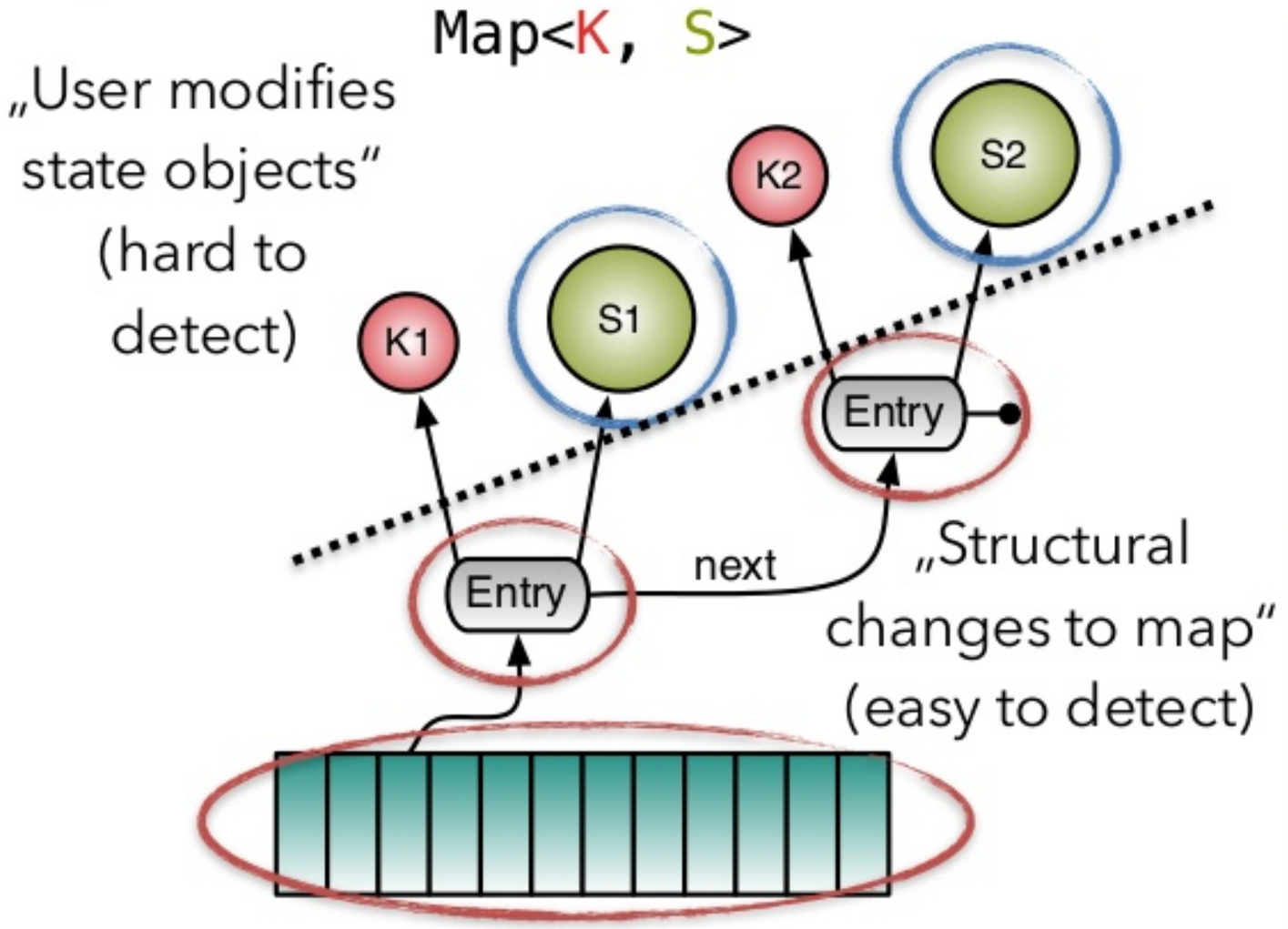
Copy-on-Write Hash Map




```
Map<K, S> {

    Entry<K, S>[] table;

    int mapVersion;
    int requiredVersion;

    OrderedSet<Integer> snapshots;
}
```

```
Entry<K, S> {

    final K key;
    S state;
    Entry next;

    int stateVersion;
    int entryVersion;
}
```

Copy-on-Write Hash Map - Snapshots

Create Snapshot:

1. Flat array-copy of table array
2. snapshots.add(mapVersion);
3. ++mapVersion;
4. requiredVersion = mapVersion;

Release Snapshot:

1. snapshots.remove(snapVersion);
2. requiredVersion = snapshots.getMax();

```
Map<K, S> {

   Entry<K, S>[] table;

   int mapVersion;
   int requiredVersion;

   OrderedSet<Integer> snapshots;
}

Entry<K, S> {

   final K key;
   S state;
   Entry next;

   int stateVersion;
   int entryVersion;
}
```

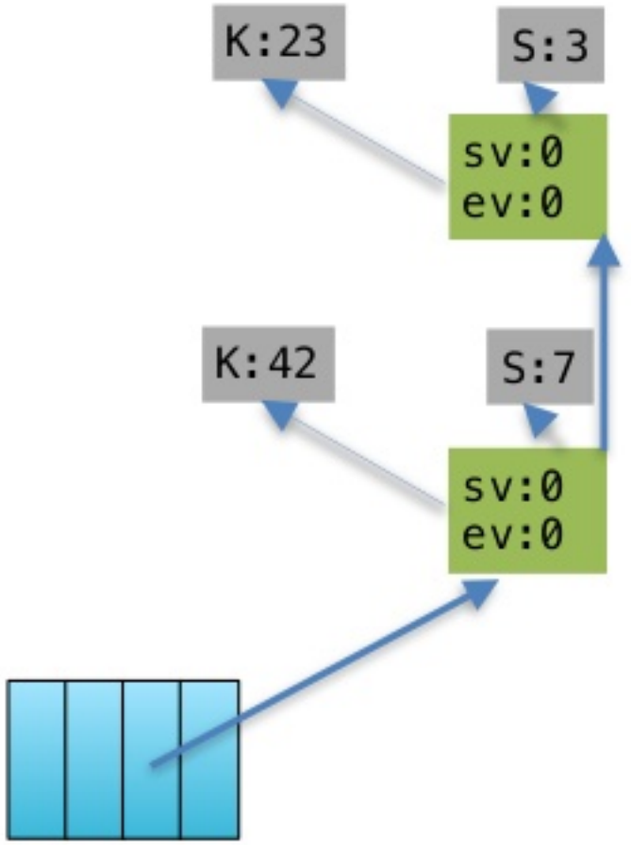
Copy-on-Write Hash Map - 2 Golden Rules

1. *Whenever a map entry* `e` *is modified and* `e.entryVersion < map.requiredVersion`*, first copy the entry and redirect pointers that are reachable through snapshot to the copy. Set* `e.entryVersion = map.mapVersion`*. Pointer redirection can trigger recursive application of rule 1 to other entries.*

2. *Before returning the state object* `s` *of entry* `e` *to a caller, if* `e.stateVersion < map.requiredVersion`*, create a deep copy of* `s` *and redirect the pointer in* `e` *to the copy. Set* `e.stateVersion = map.mapVersion`. Then return the copy to the caller. *Applying rule 2 can trigger rule 1.*

Copy-on-Write Hash Map - Example

```
mapVersion: 0
requiredVersion: 0
```



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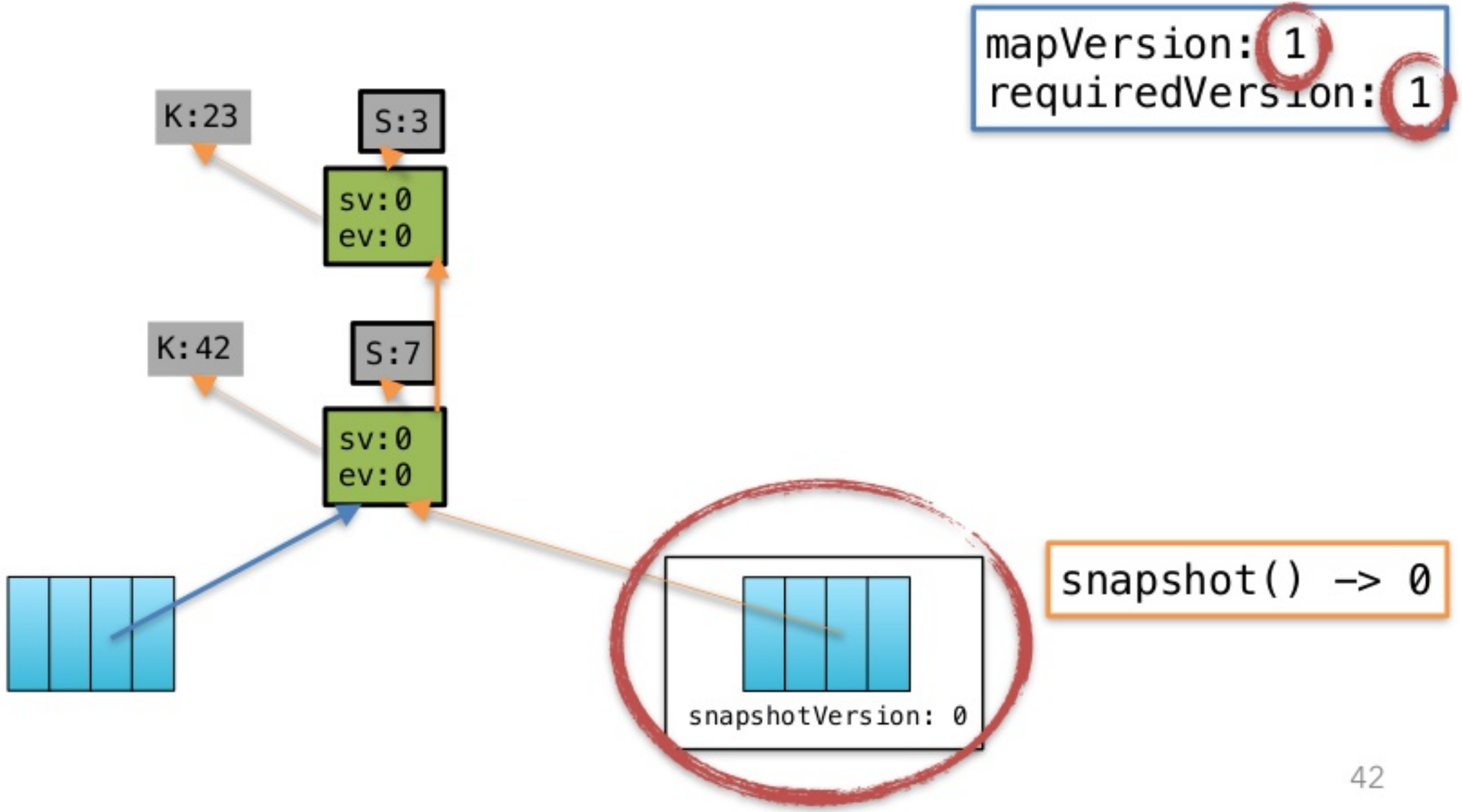

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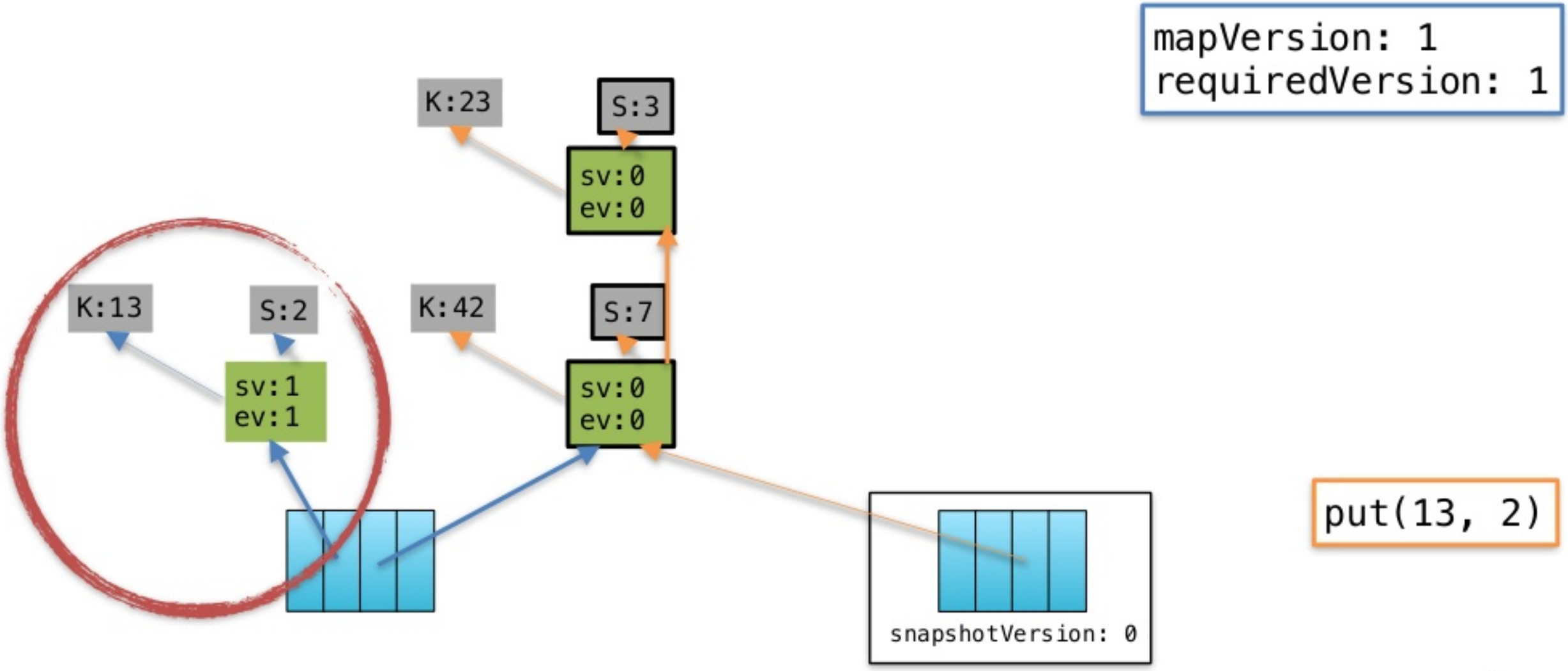

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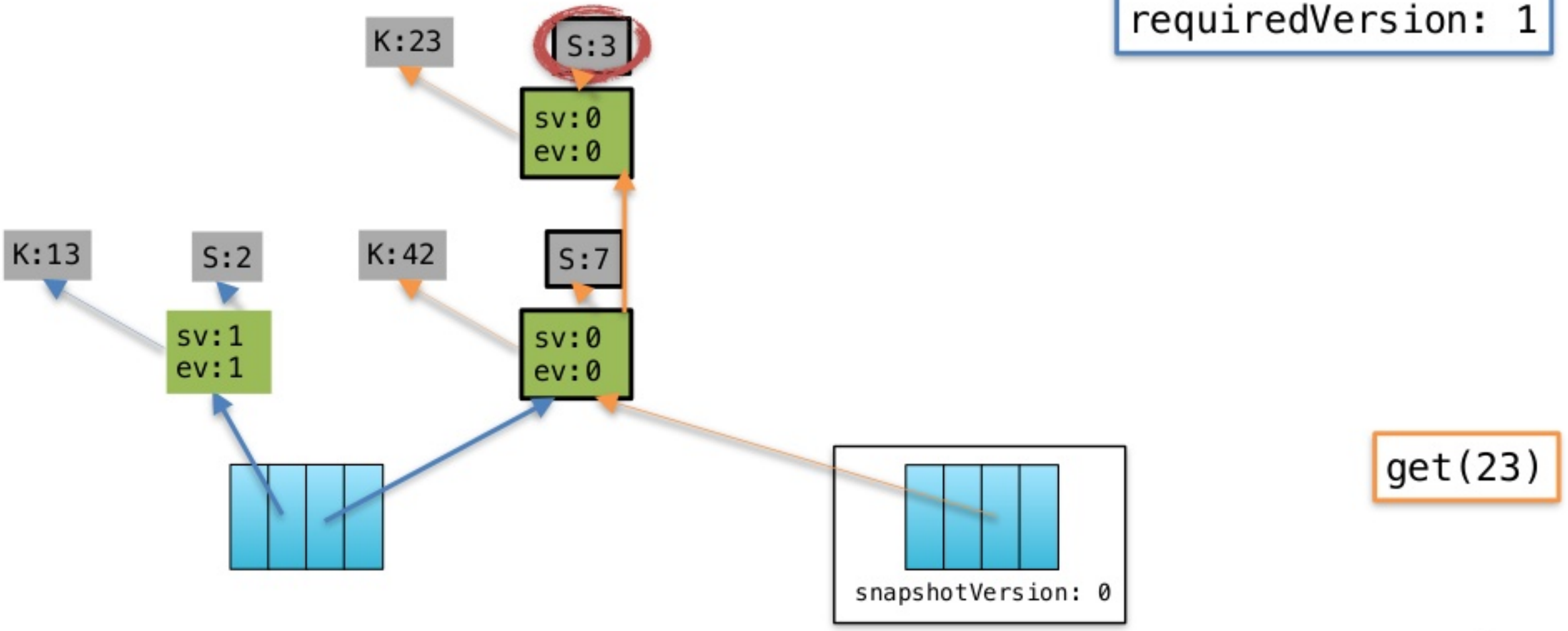

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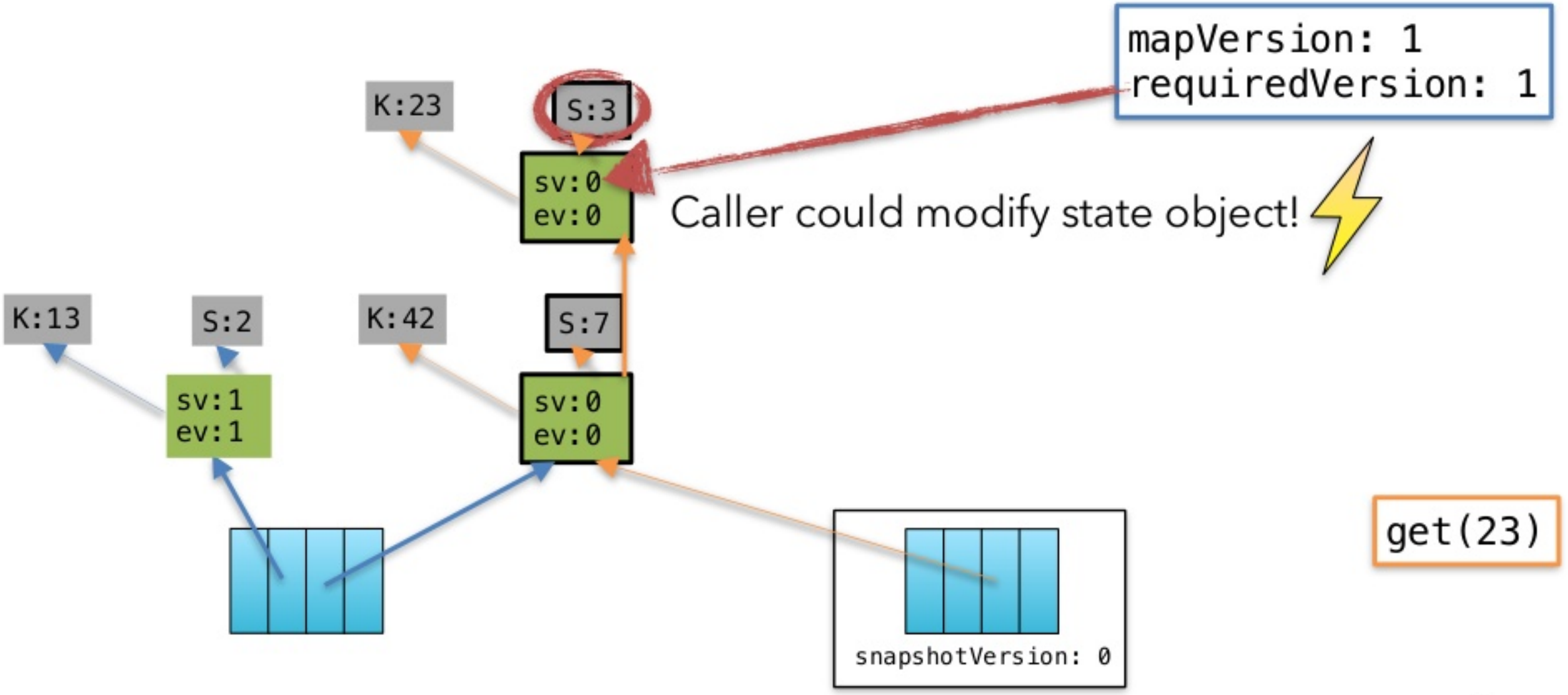

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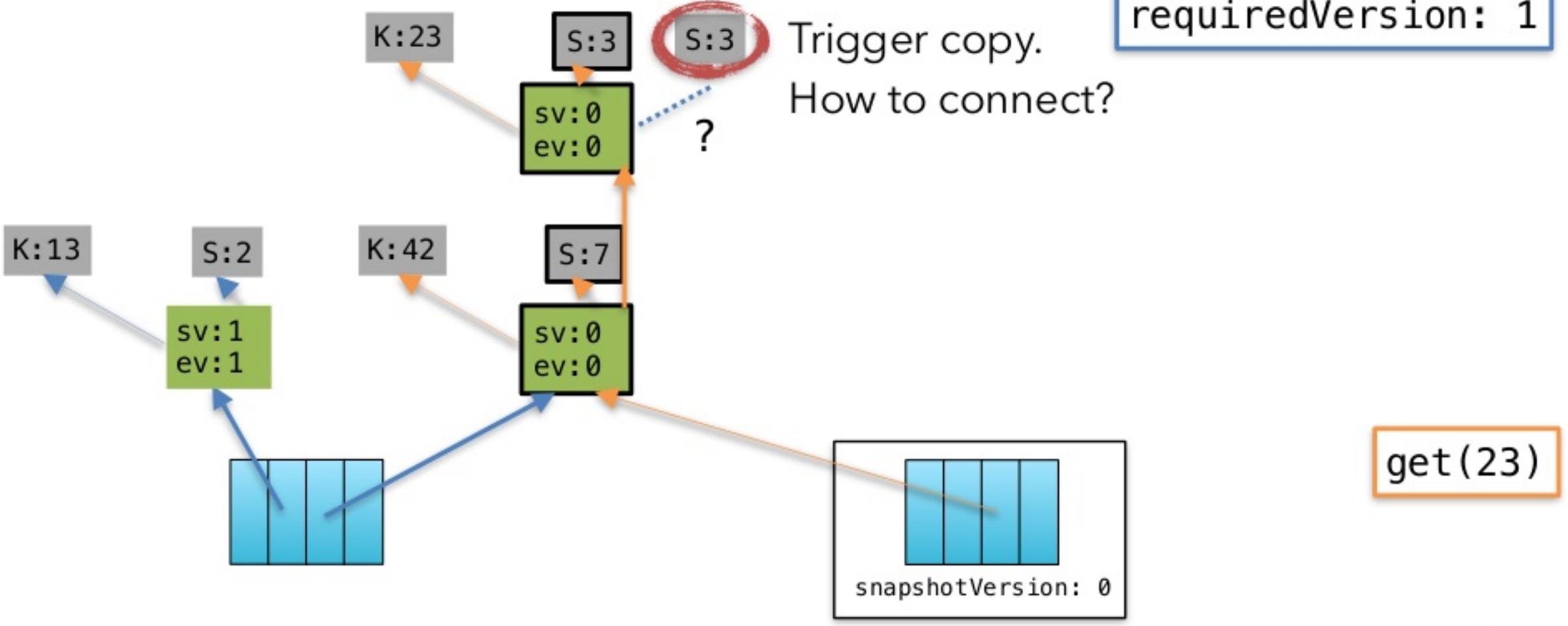

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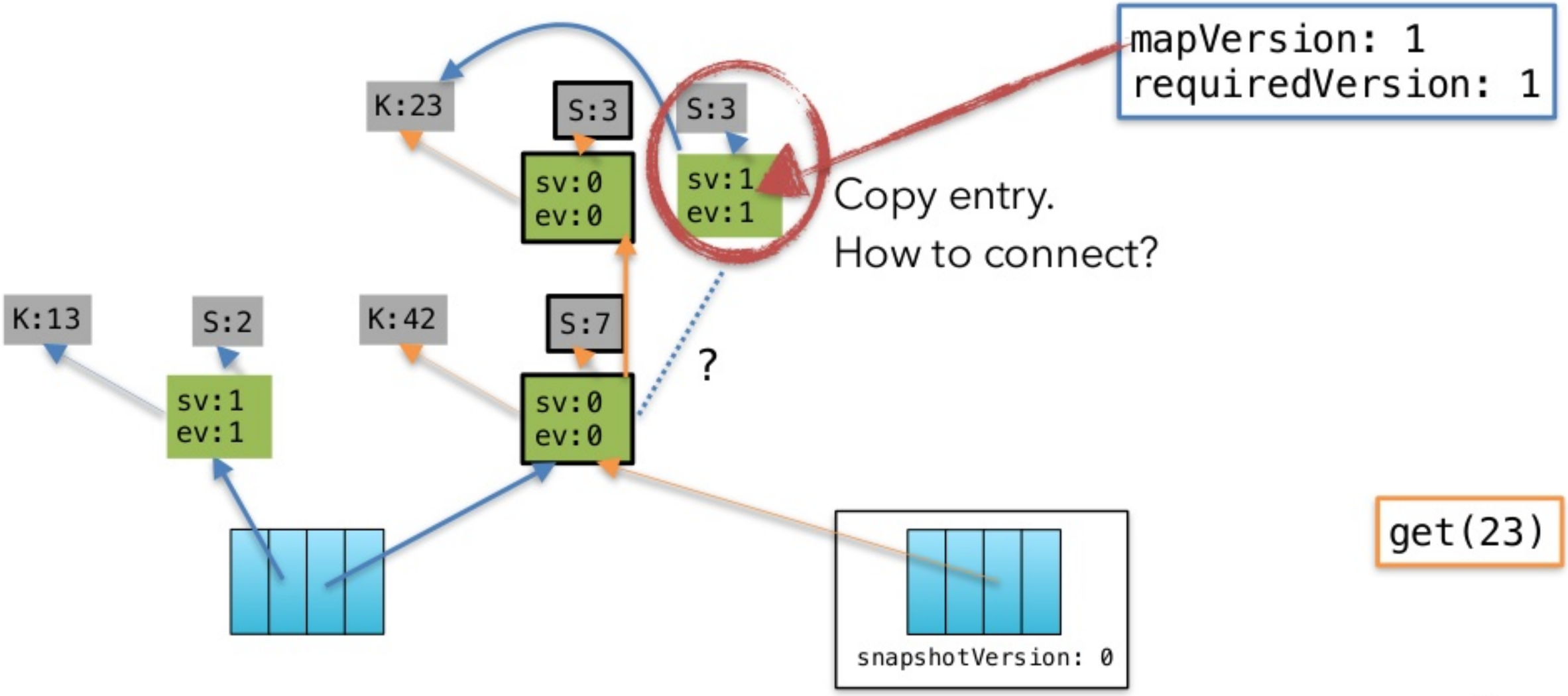

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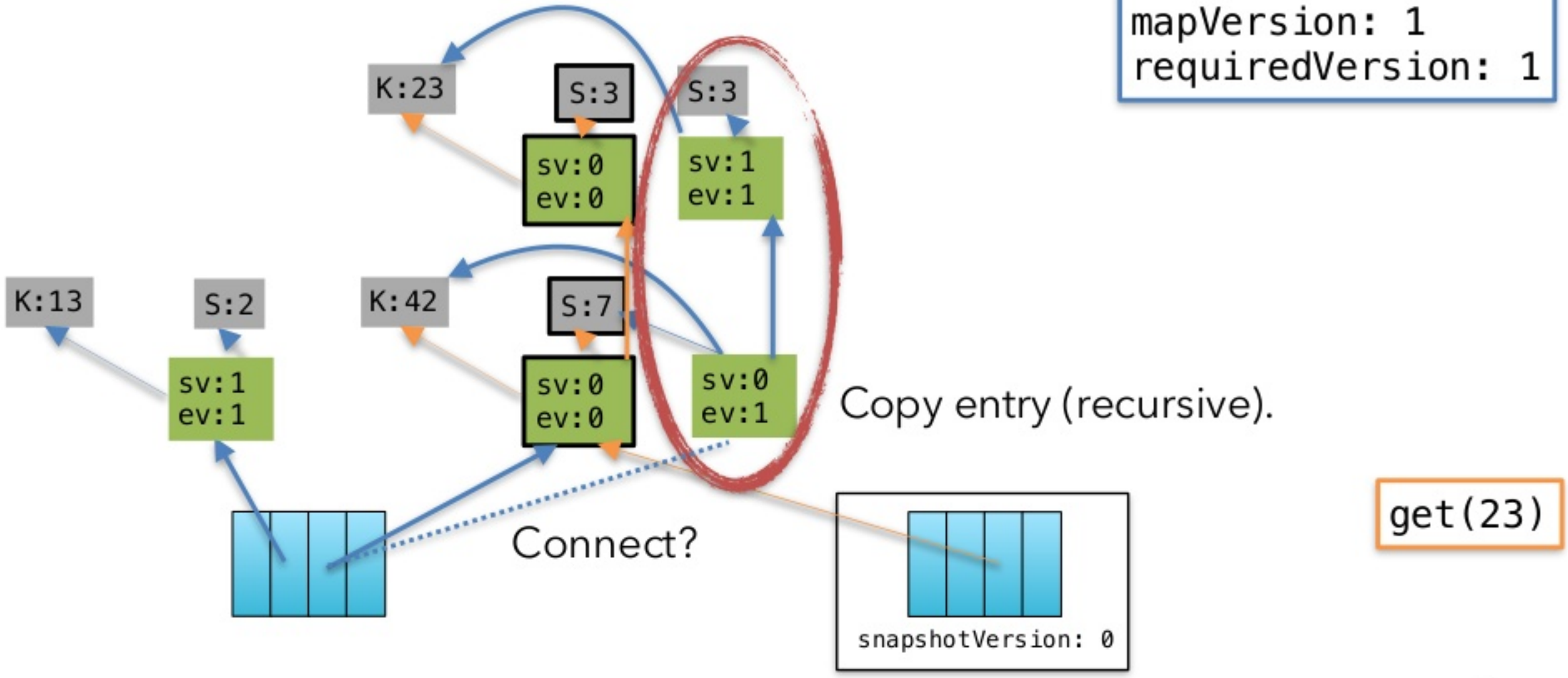

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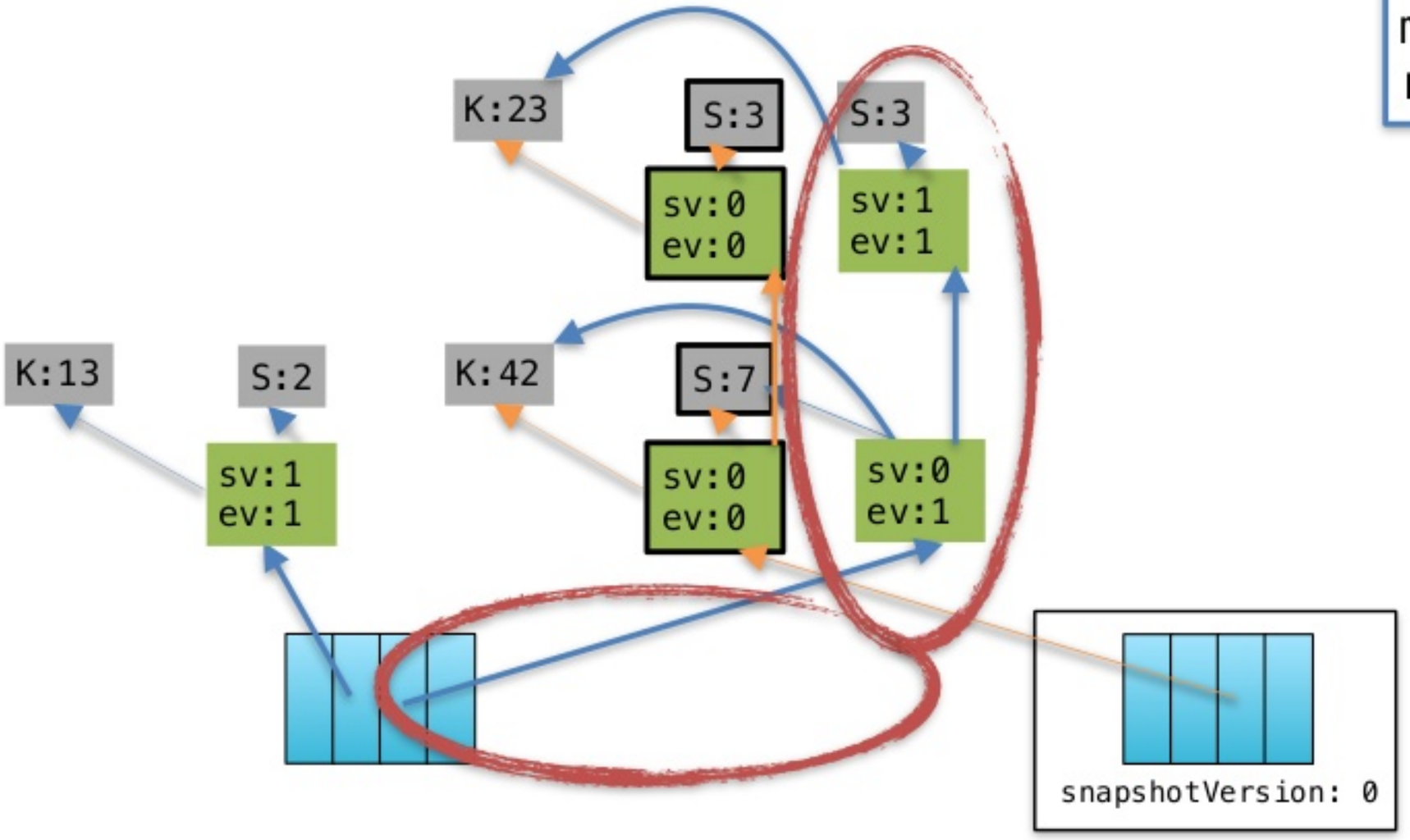

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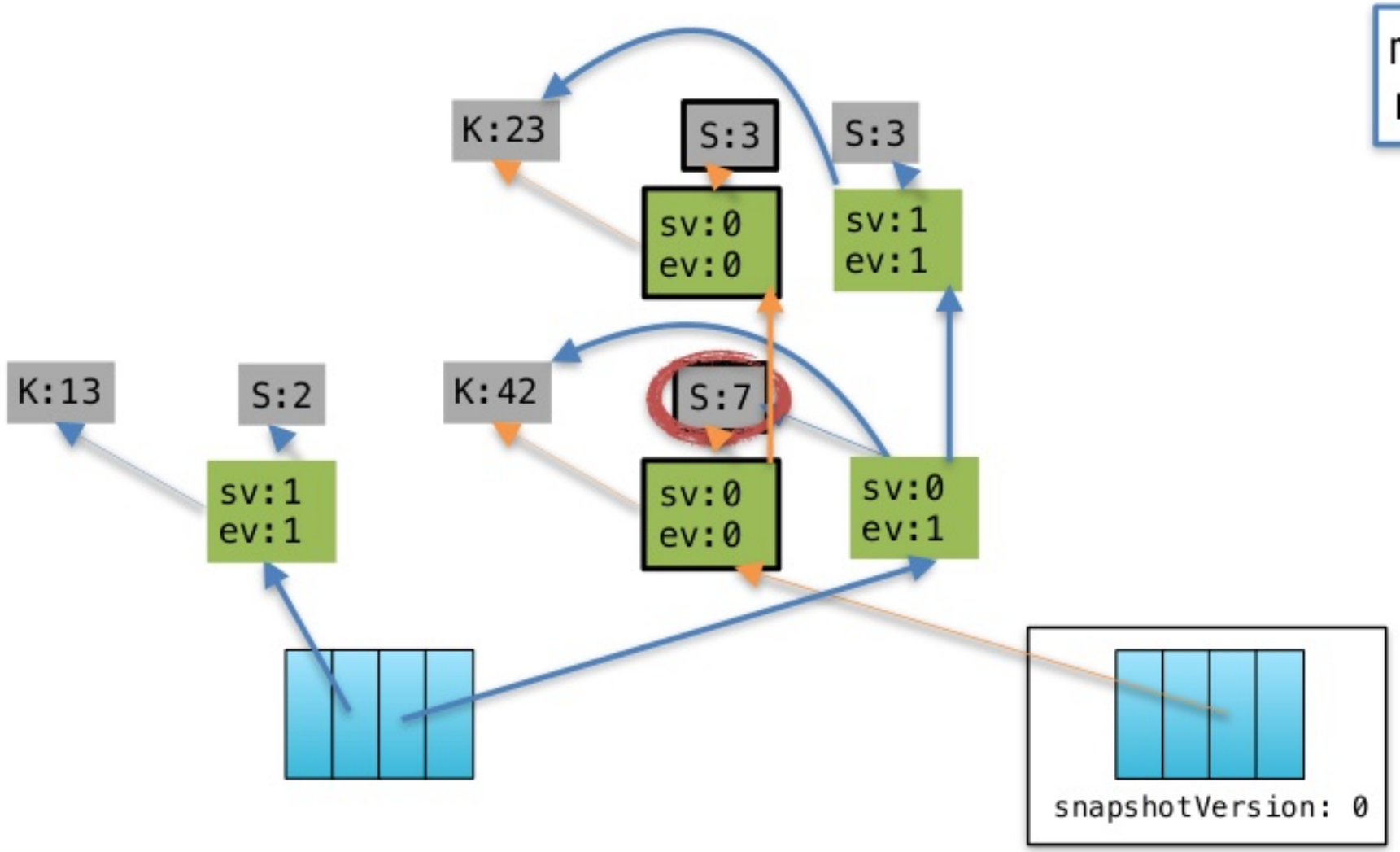

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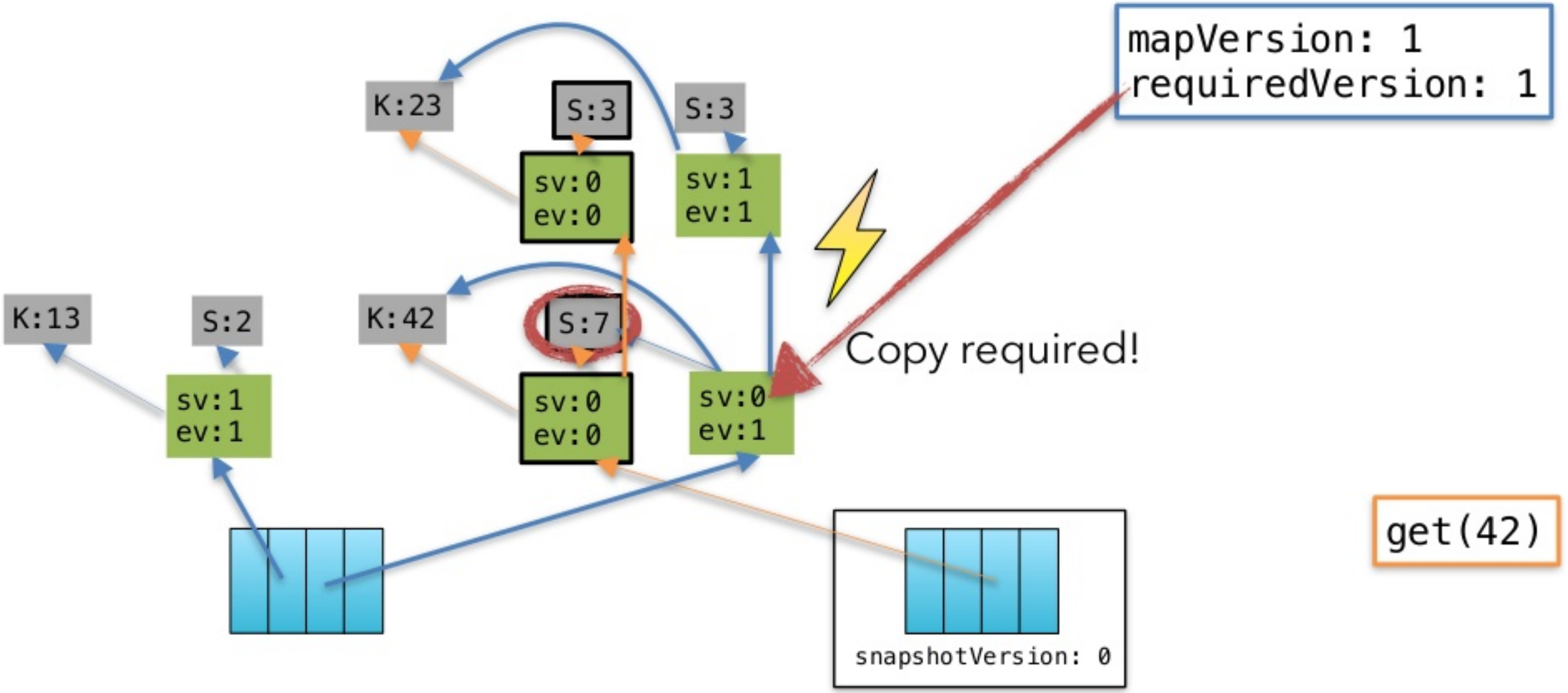

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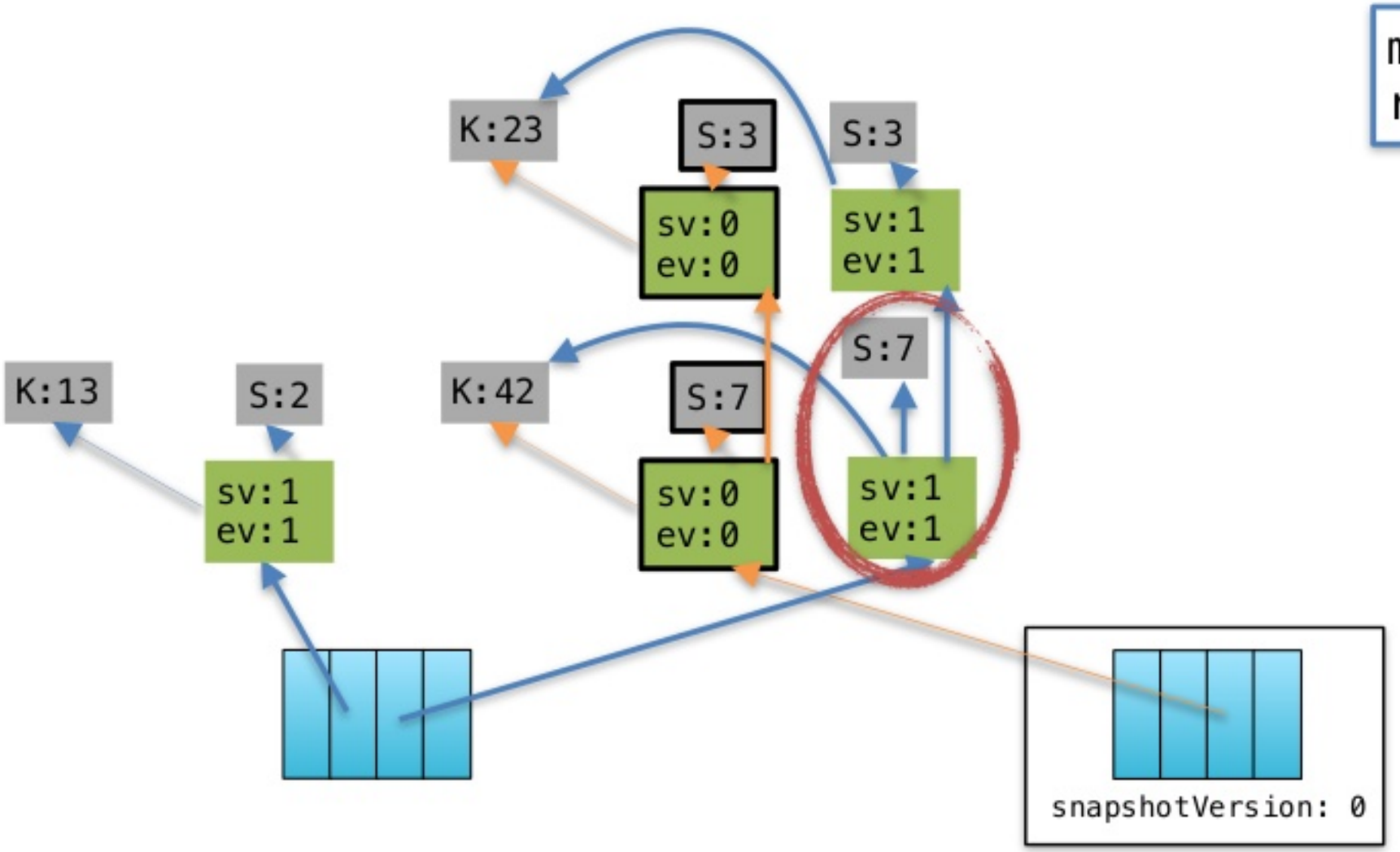

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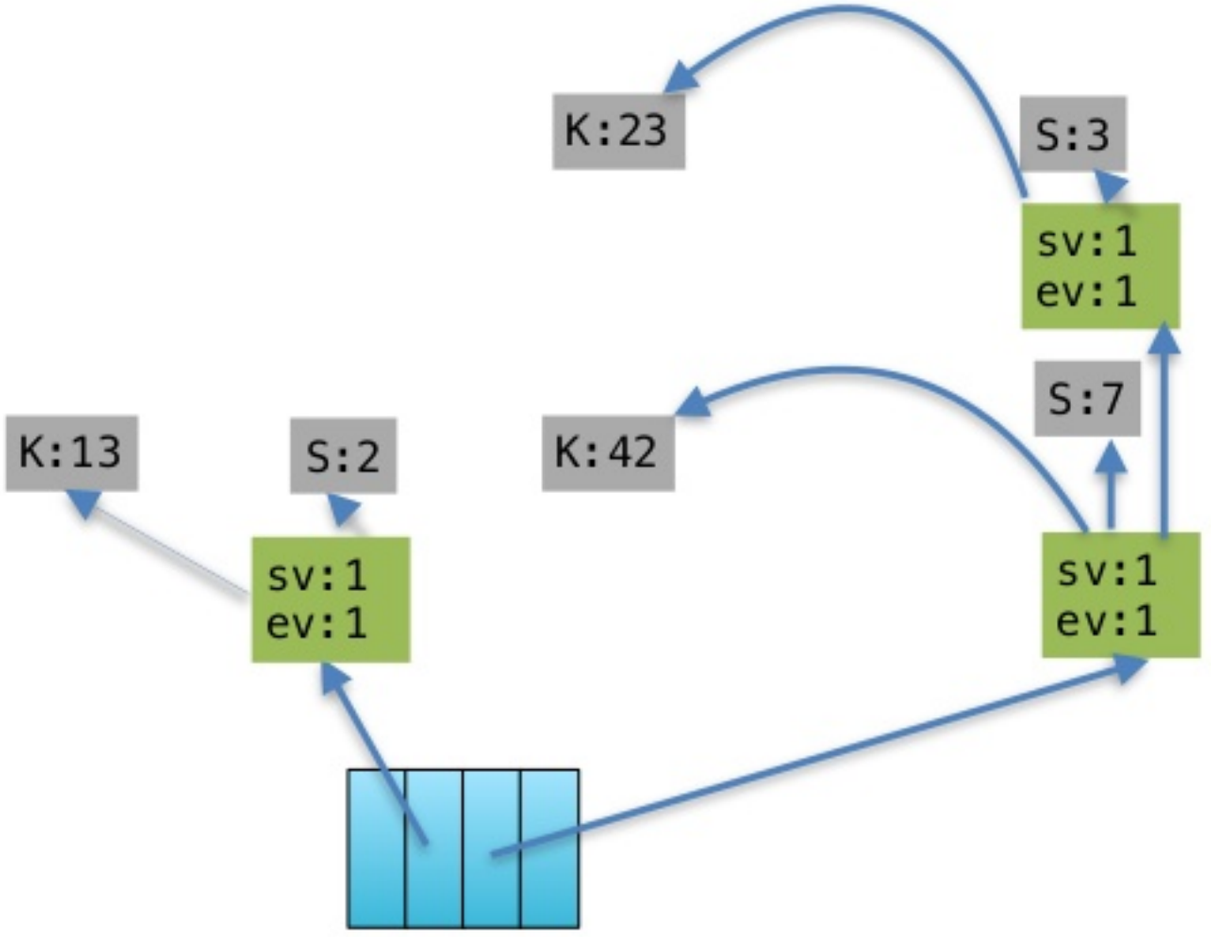


```
mapVersion: 1
requiredVersion: 0
```

```
release(0)
```

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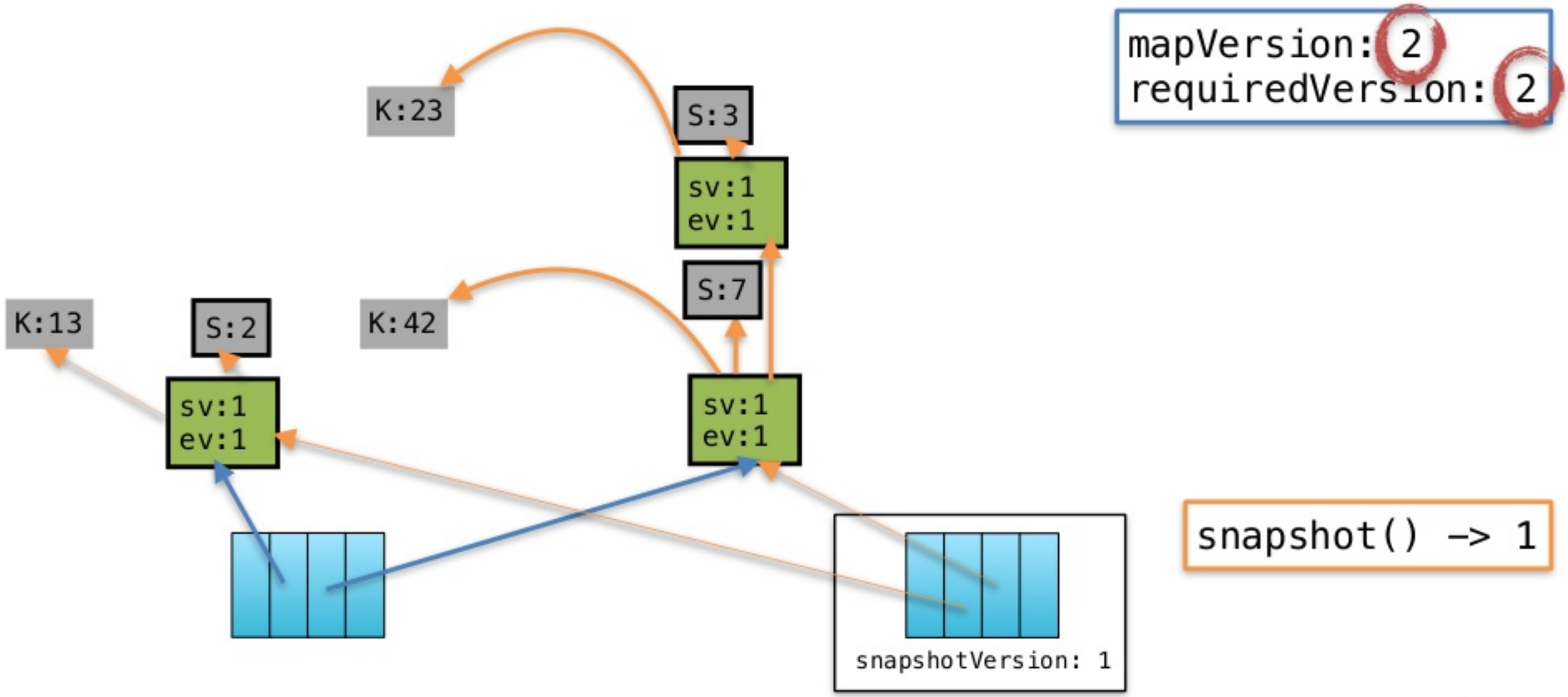

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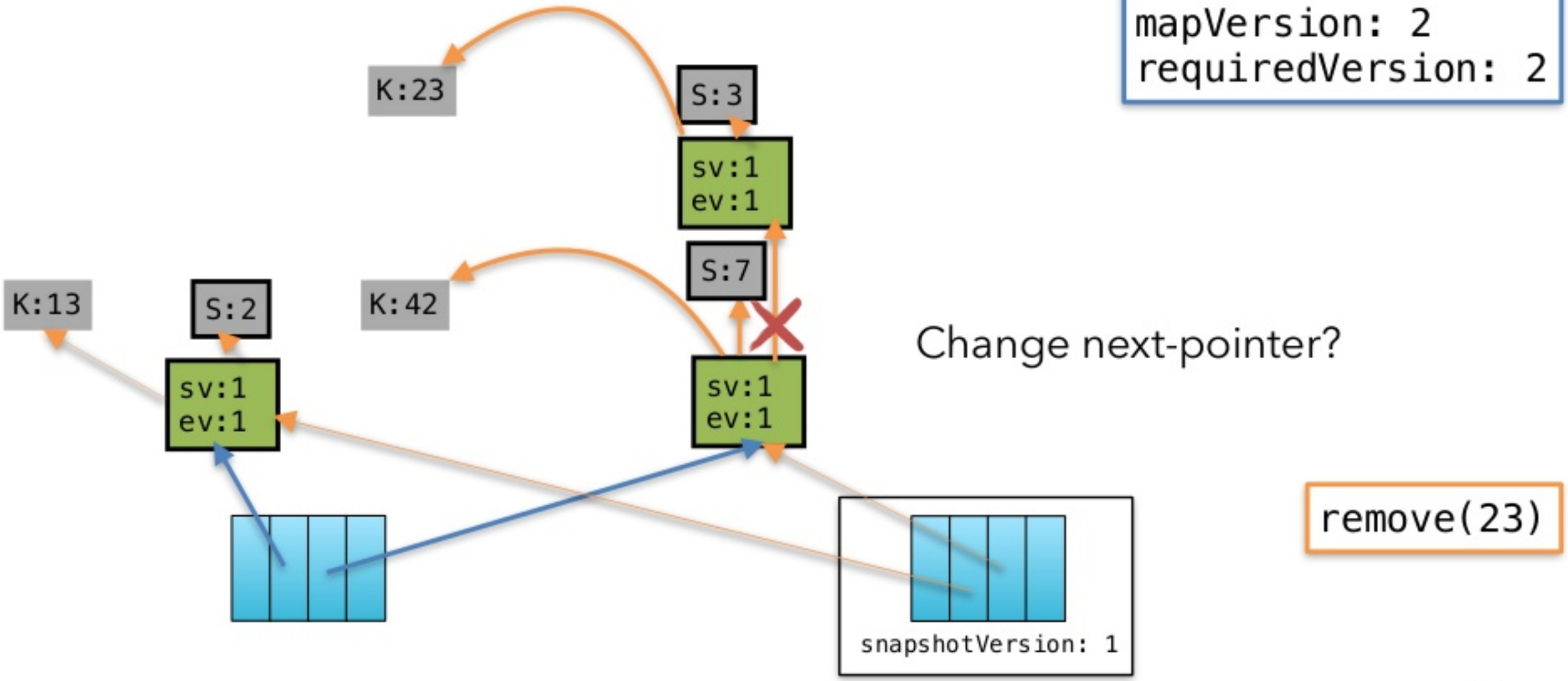
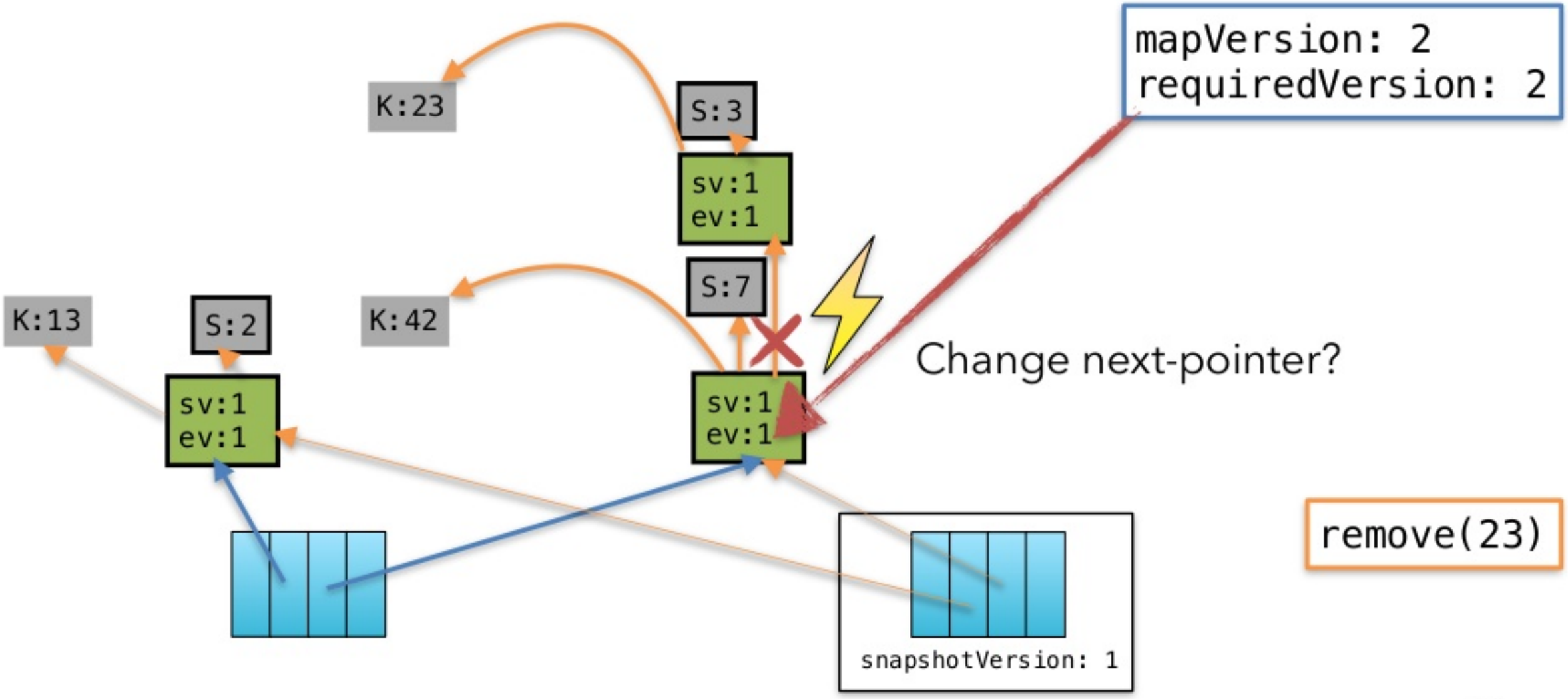
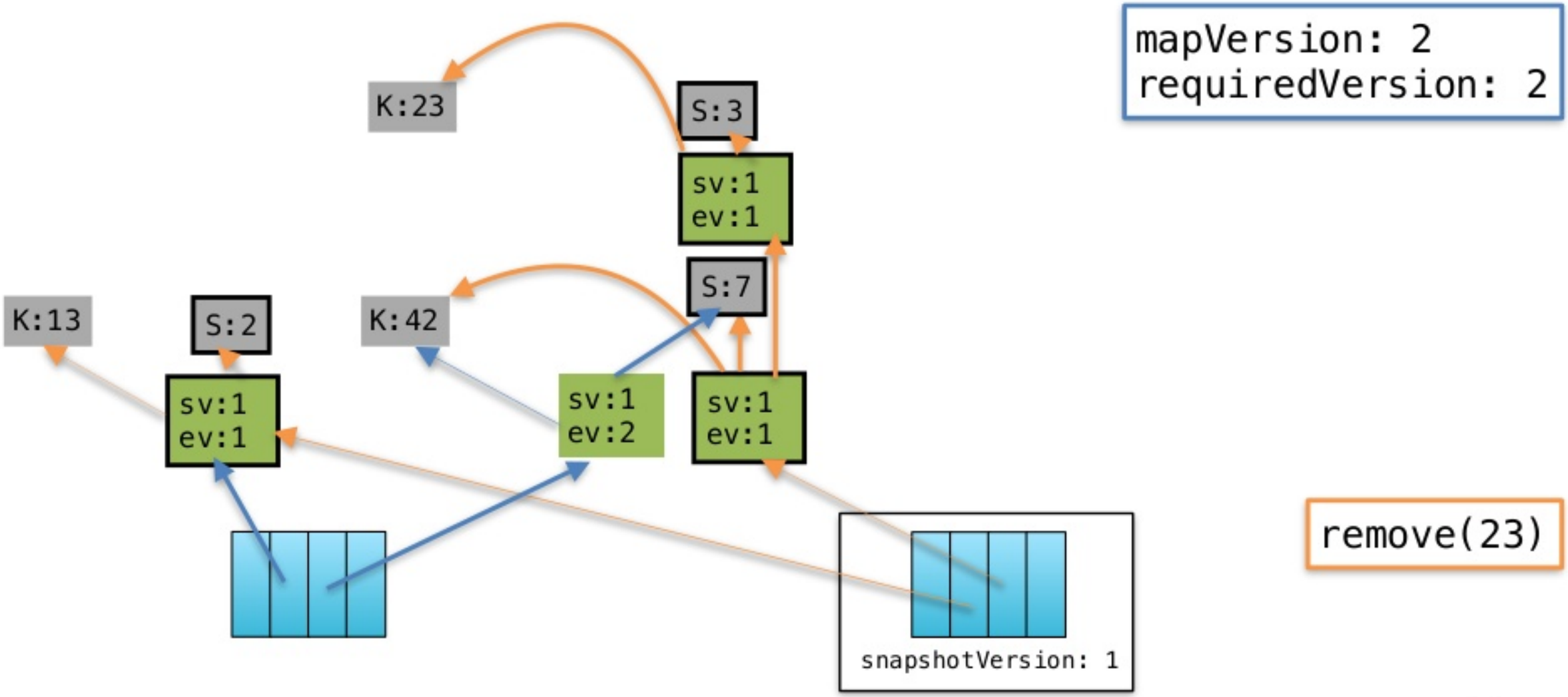


Copy-on-Write Hash Map - Example

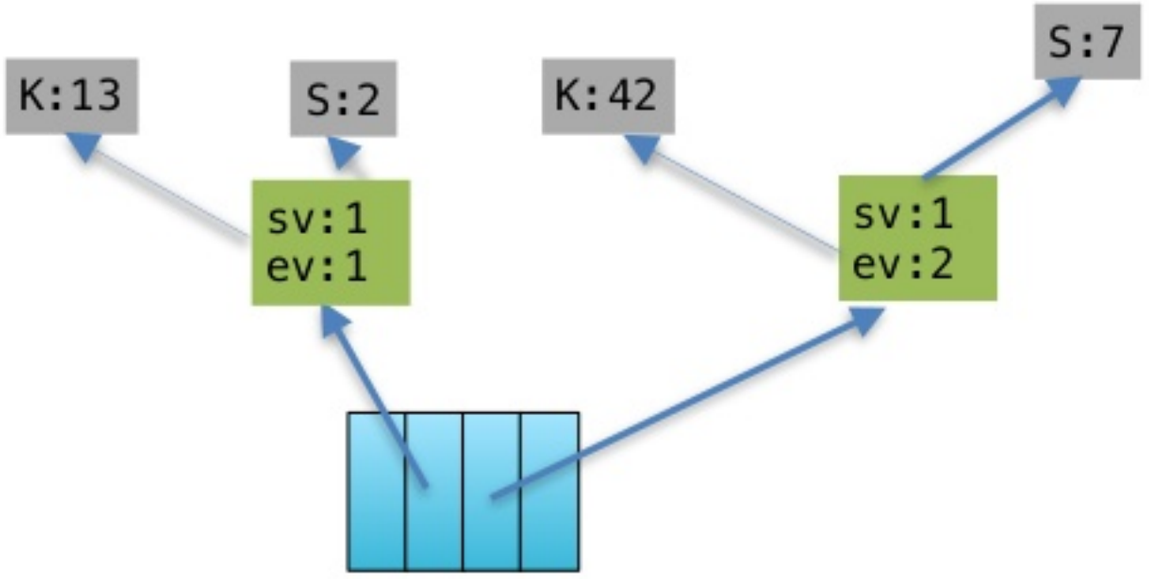


Copy-on-Write Hash Map - Example



Copy-on-Write Hash Map - Example

```
mapVersion: 2
requiredVersion: 0
```




```
release(1)
```

Copy-on-Write Hash Map Benefits

- Fine granular, lazy copy-on-write.
- At most one copy per object, per snapshot.
- No thread synchronisation between readers and writer after array-copy step.
- Supports multiple concurrent snapshots.
- Also implements efficient incremental rehashing.
- Future: Could serve as basis for incremental snapshots.

Questions?