FORD: Fast One-sided RDMA-based Distributed Transactions for Disaggregated Persistent Memory

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Huazhong University of Science and Technology, China

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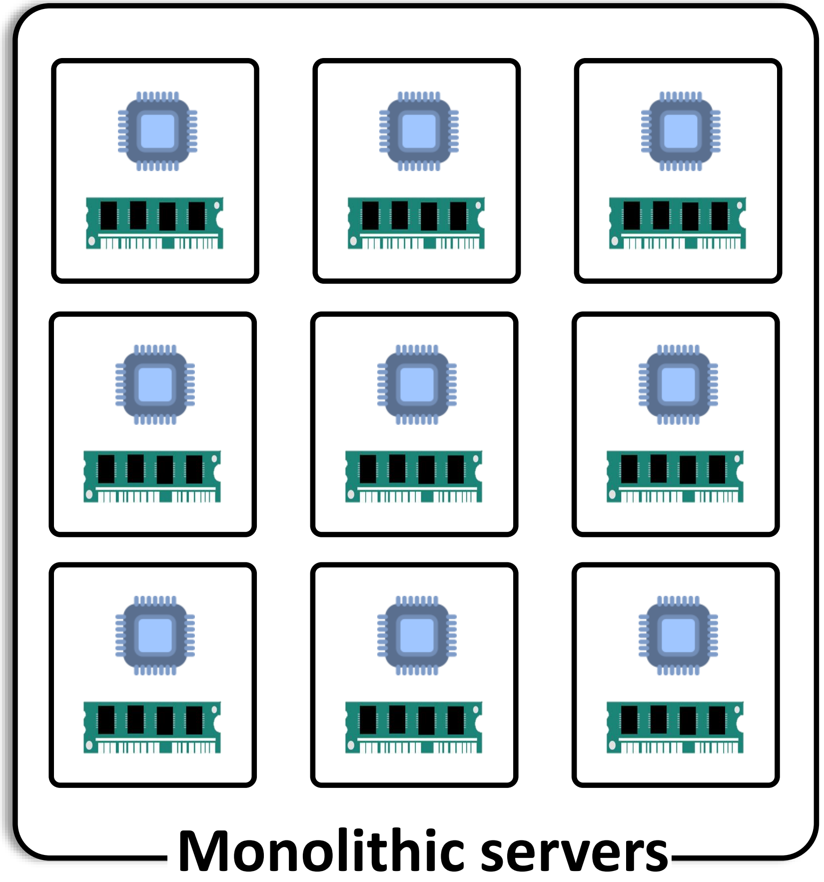
Disaggregated Persistent Memory

- Memory disaggregation



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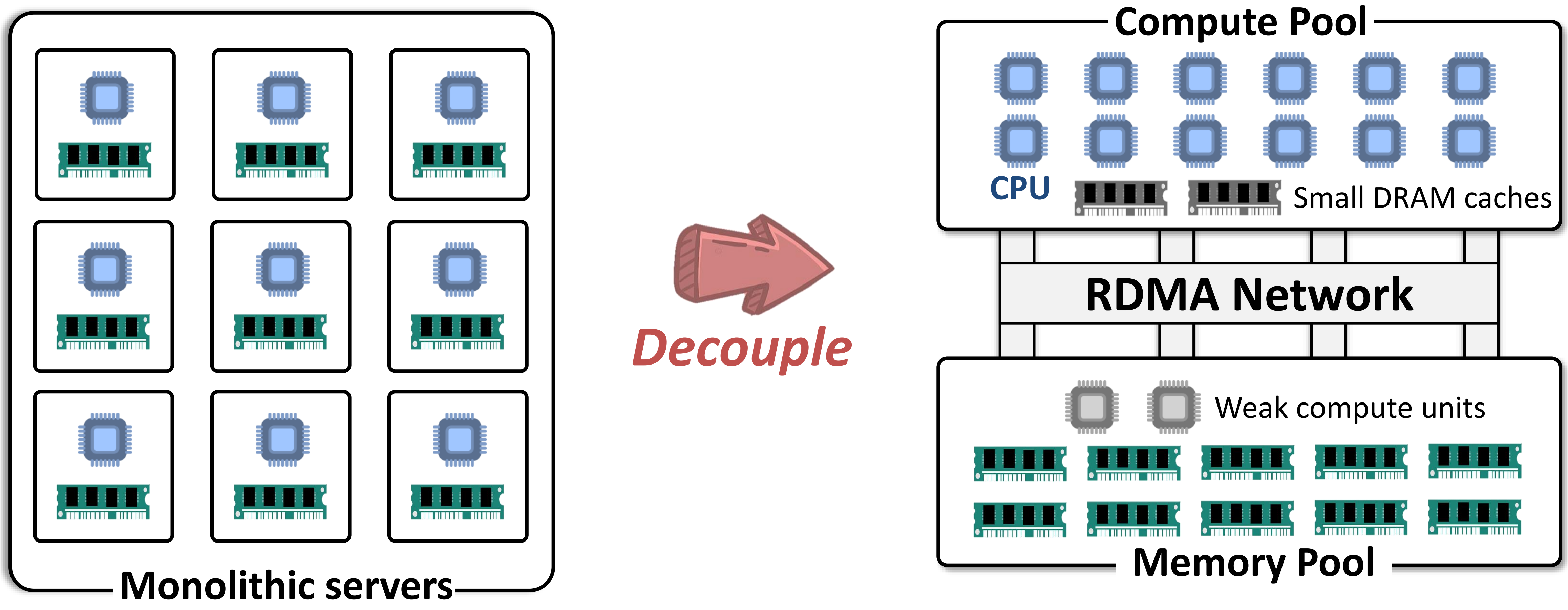

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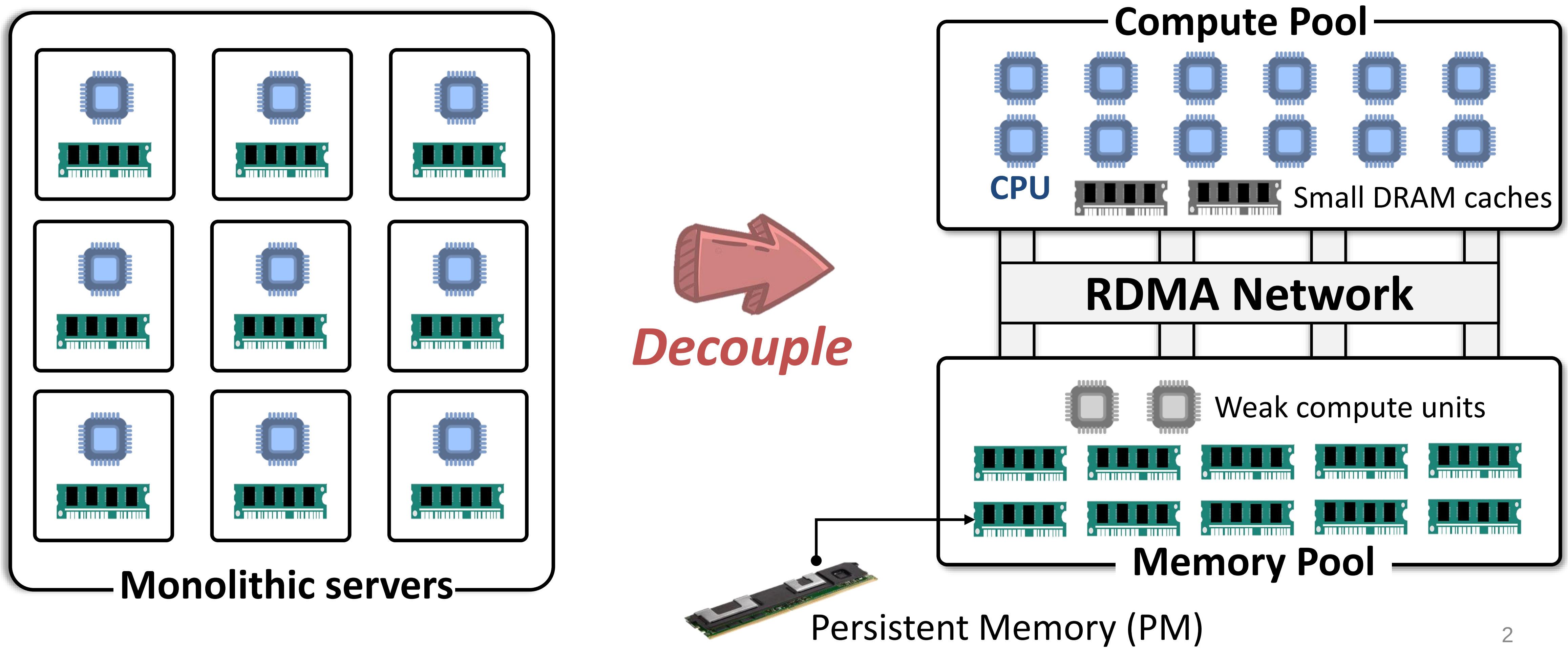
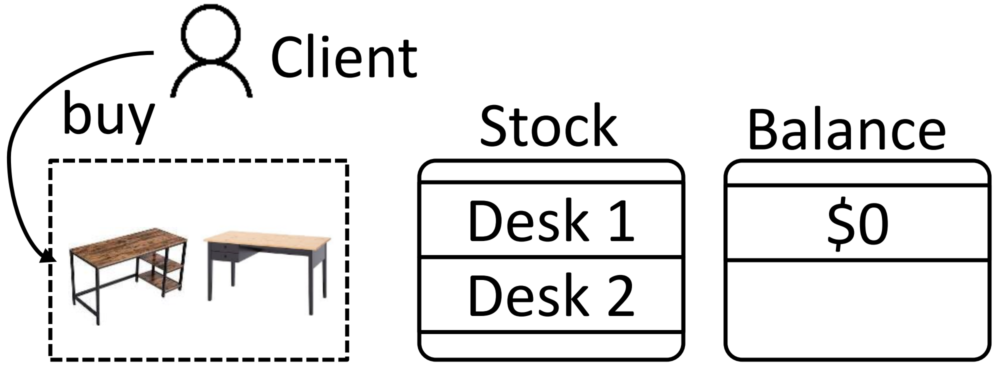


Transaction



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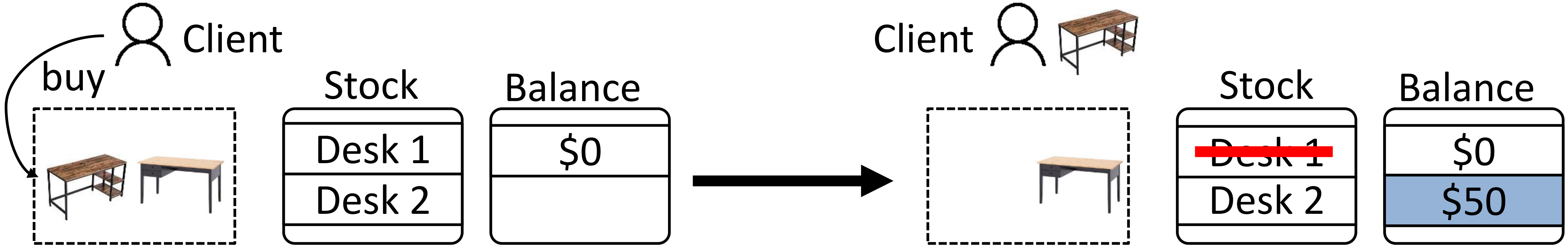

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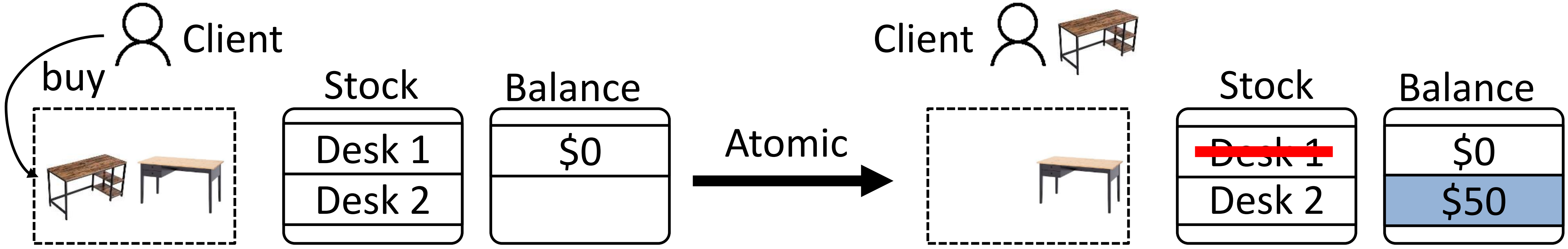

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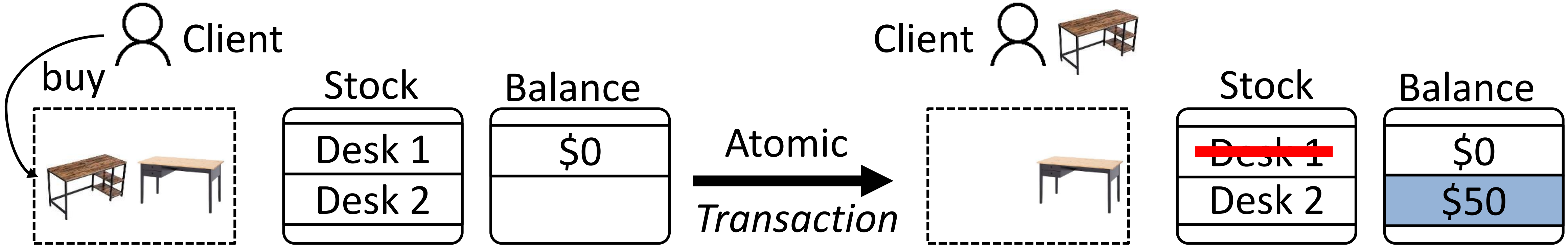
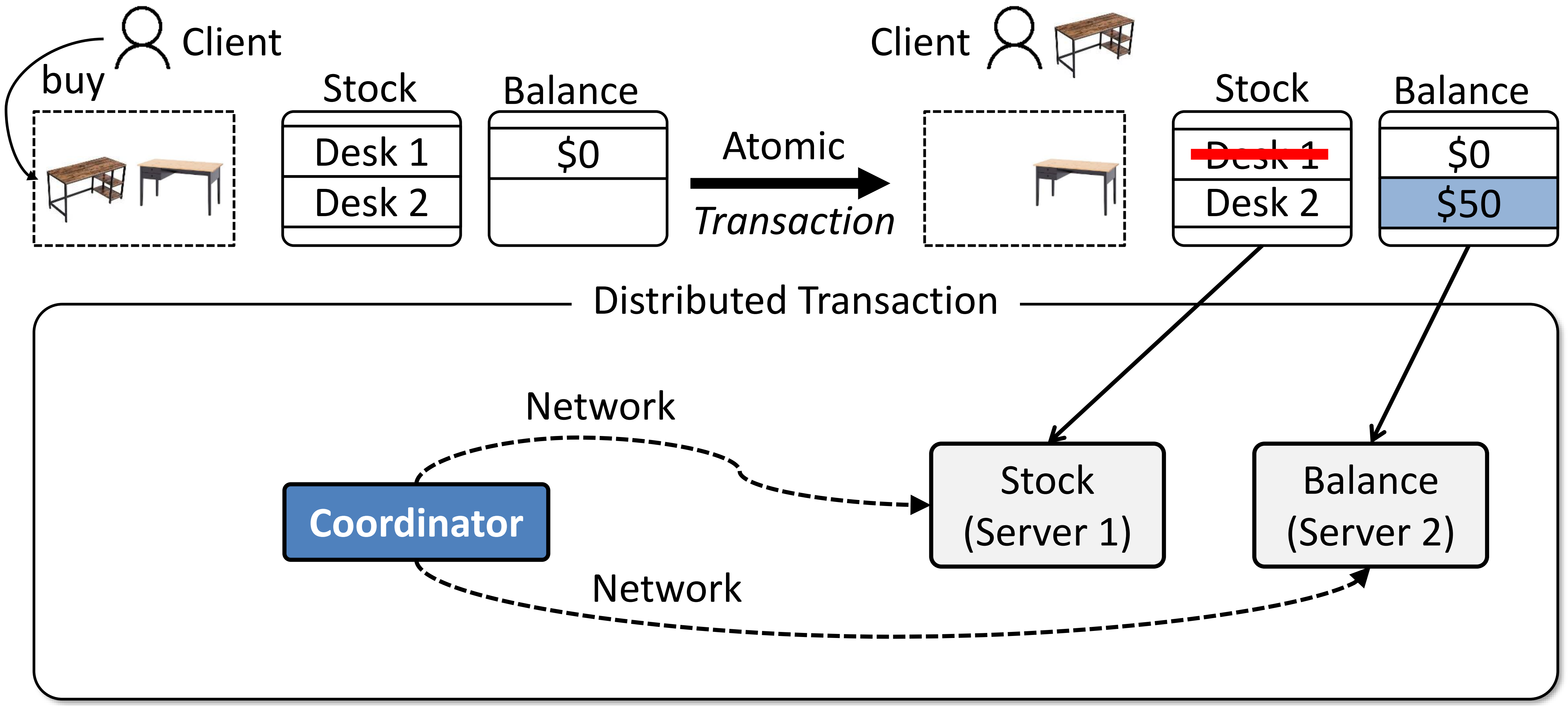


Distributed Transaction



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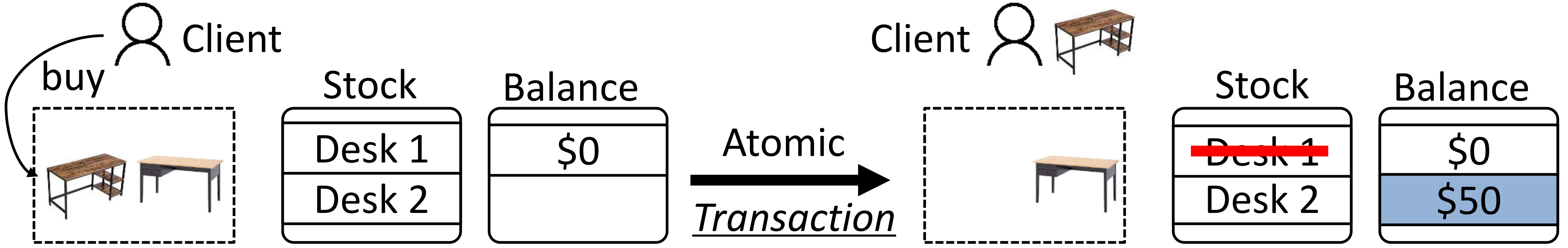


Distributed Transaction: **A key building block**

Google Cloud Spanner

Amazon Aurora

Microsoft Azure

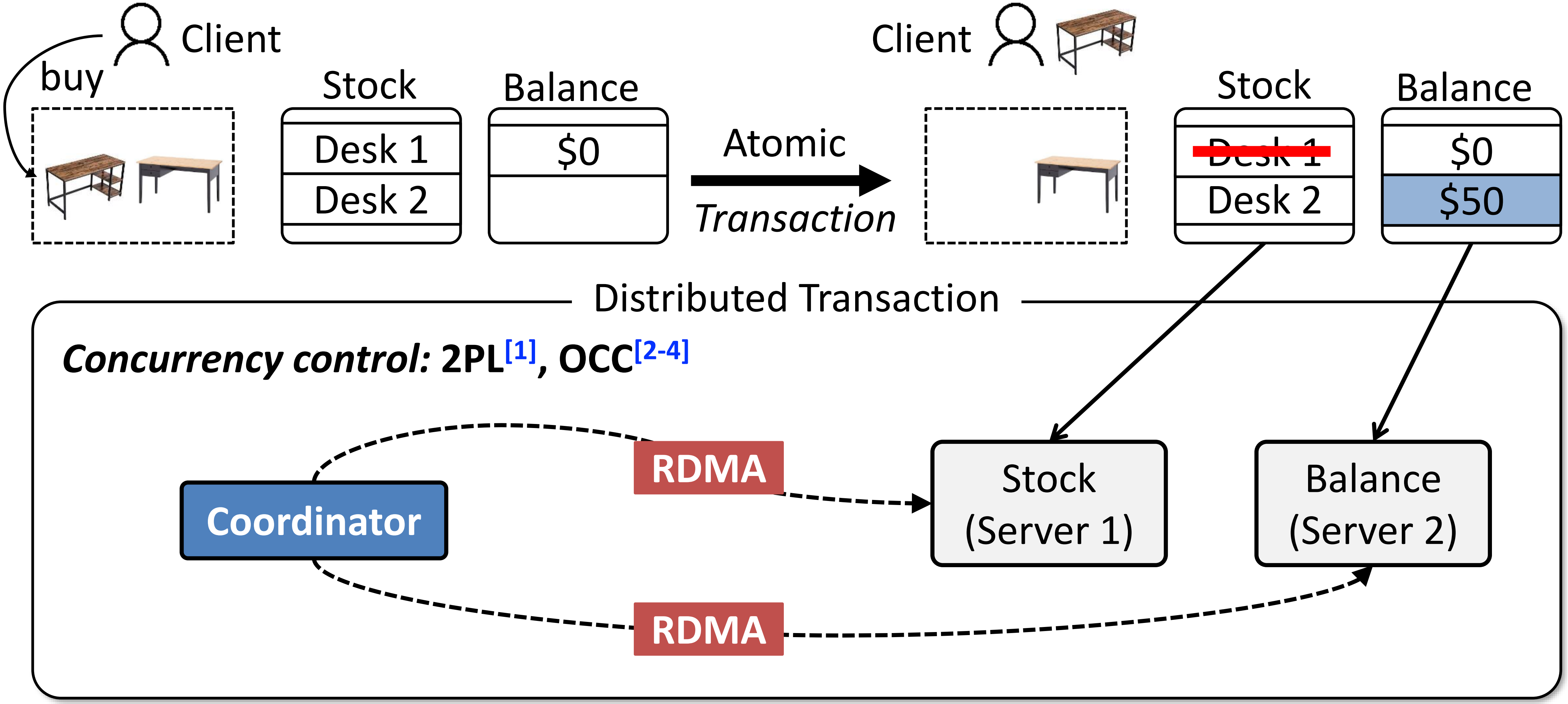
HUAWEI

HUAWEI CLOUD

Alibaba.com

PayPal

RDMA-based Distributed Transaction



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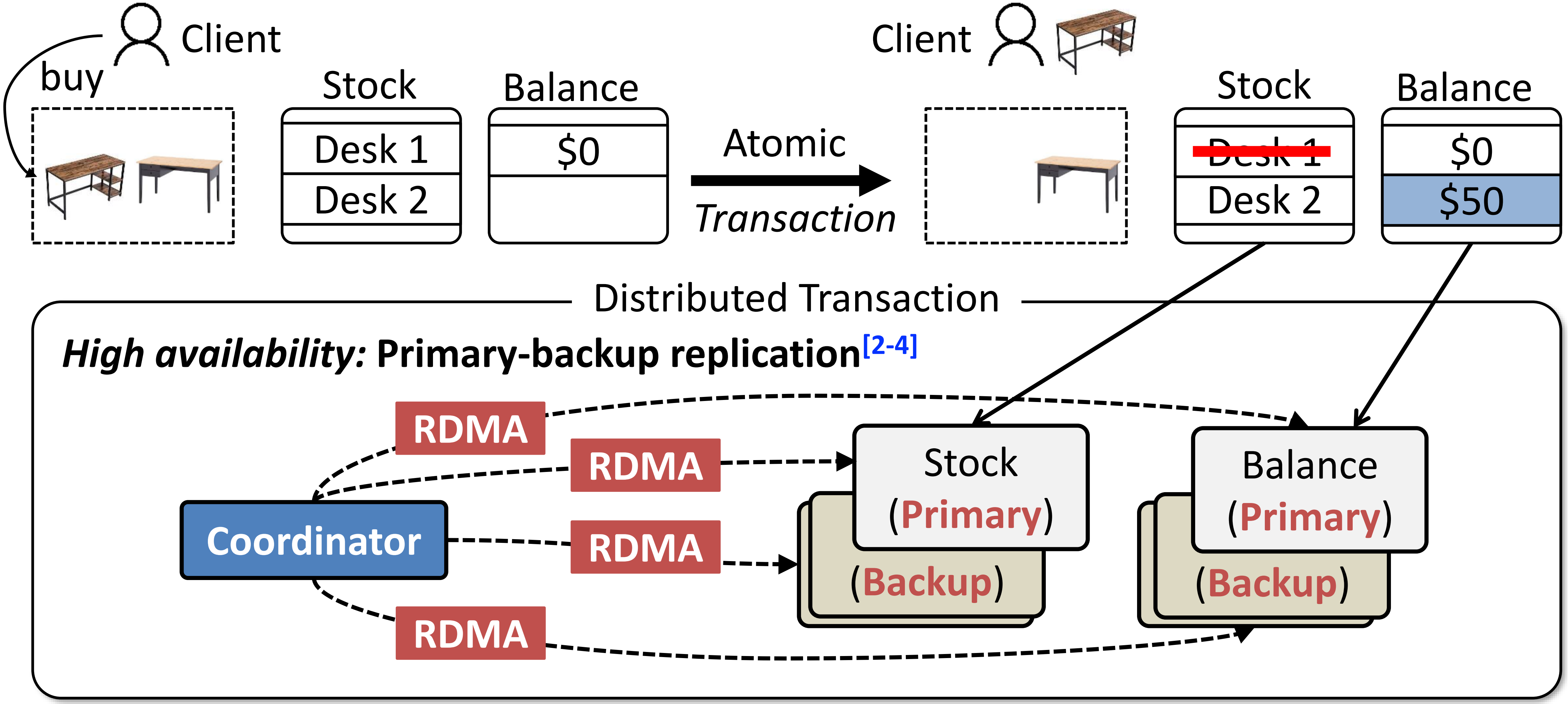

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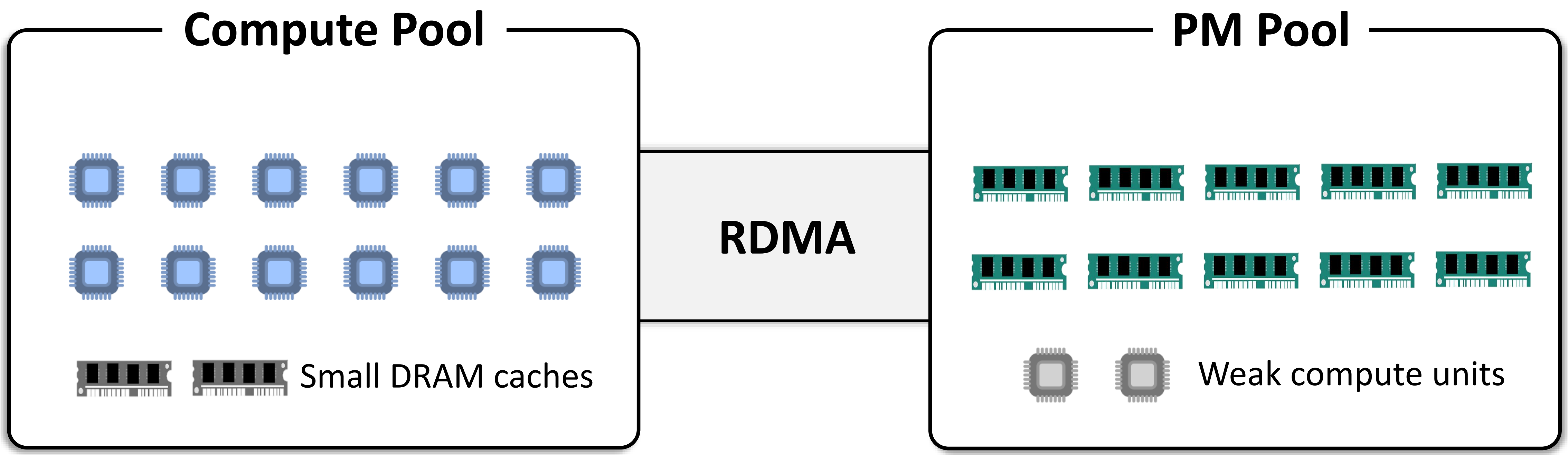
Transaction on Disaggregated PM



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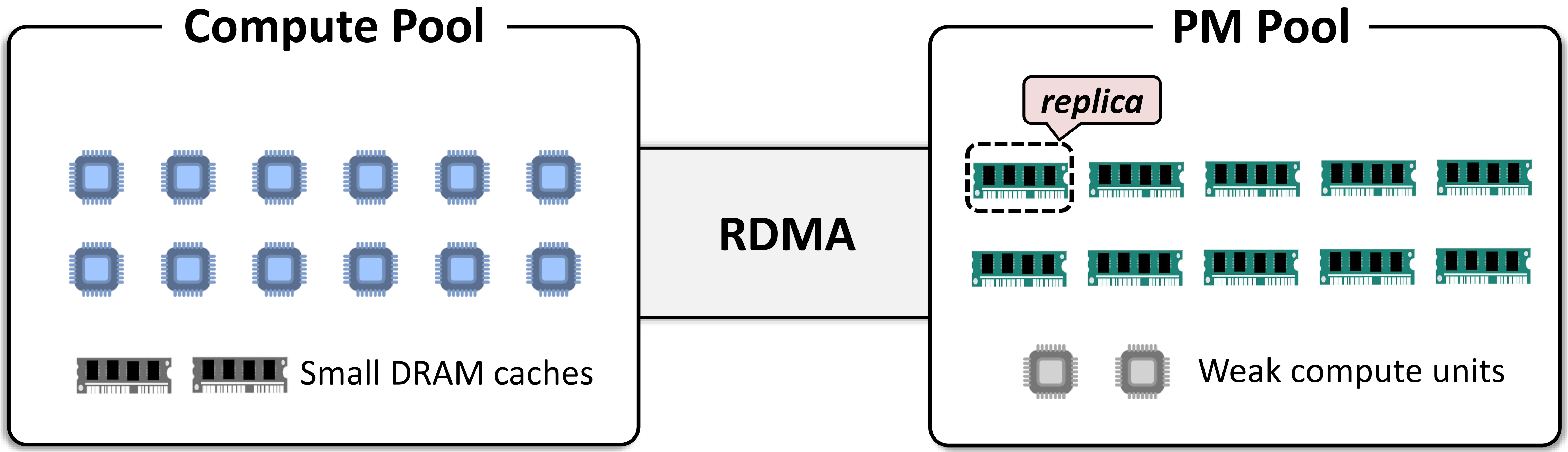

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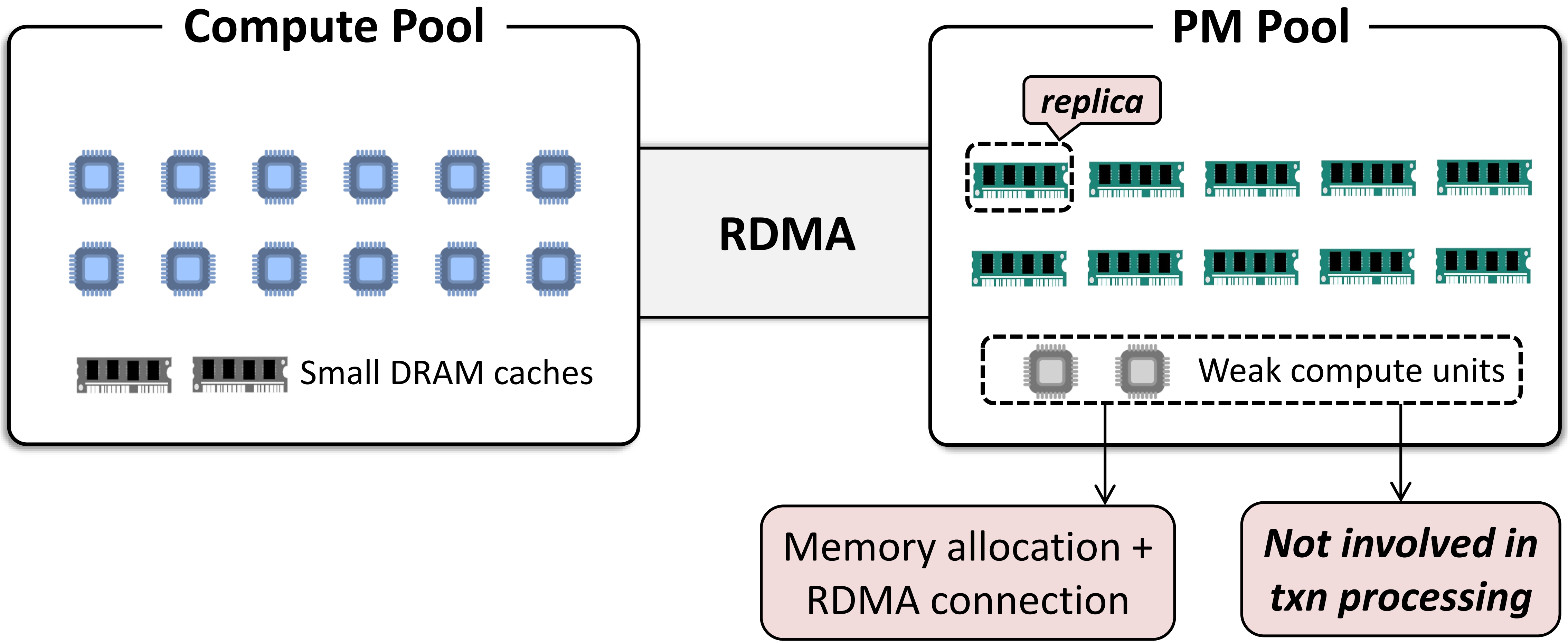

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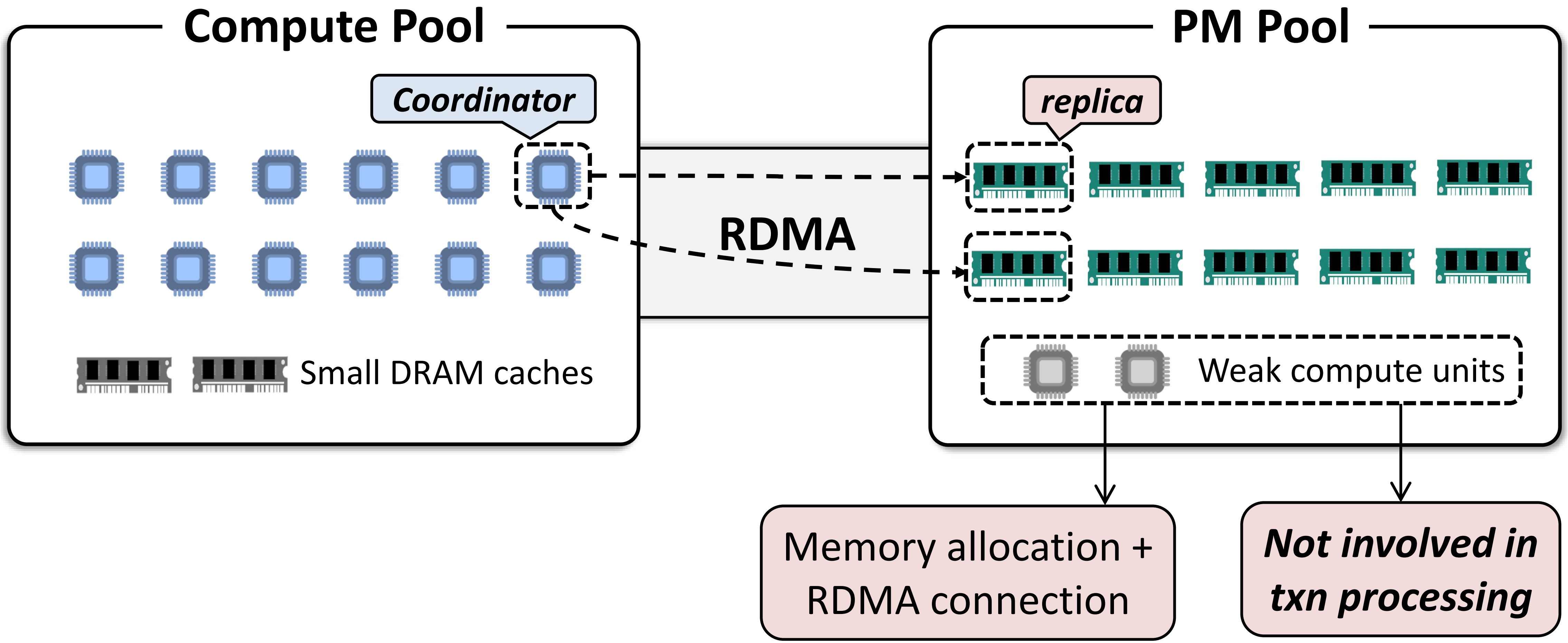

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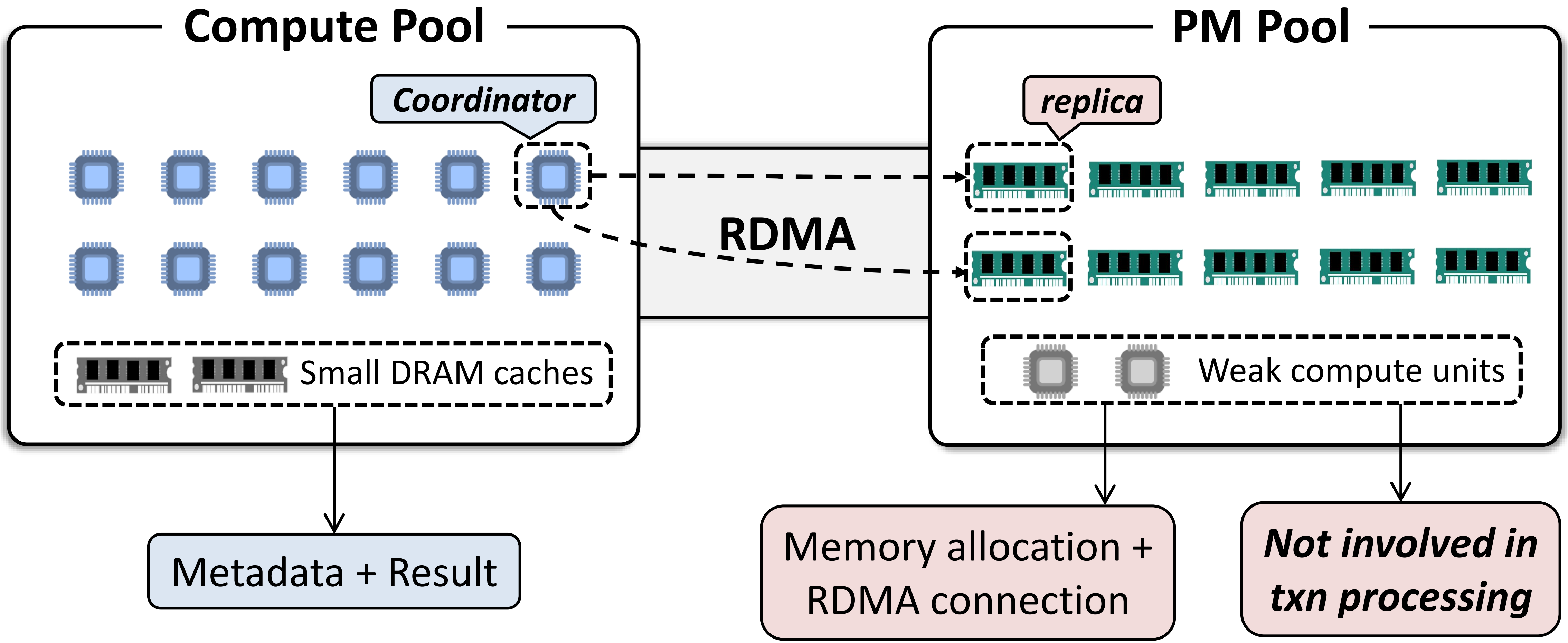
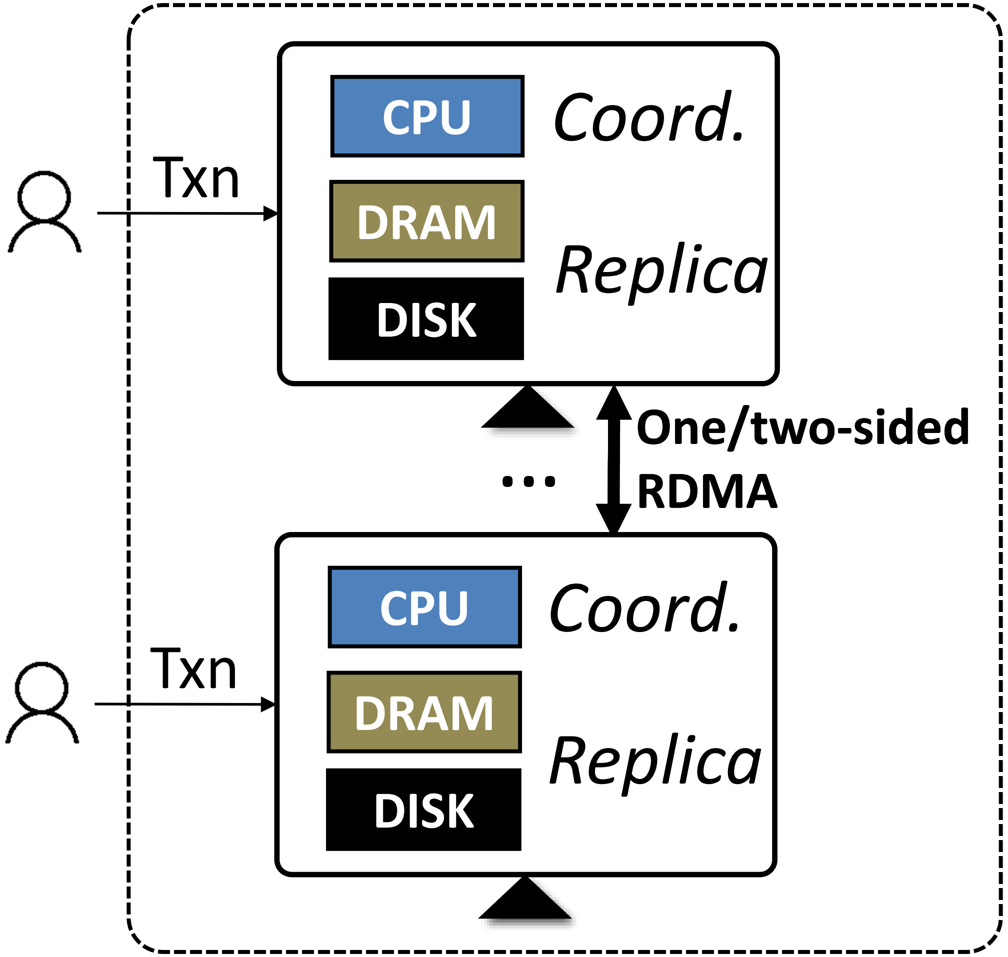


State-of-the-art



Monolithic architecture[1-4]

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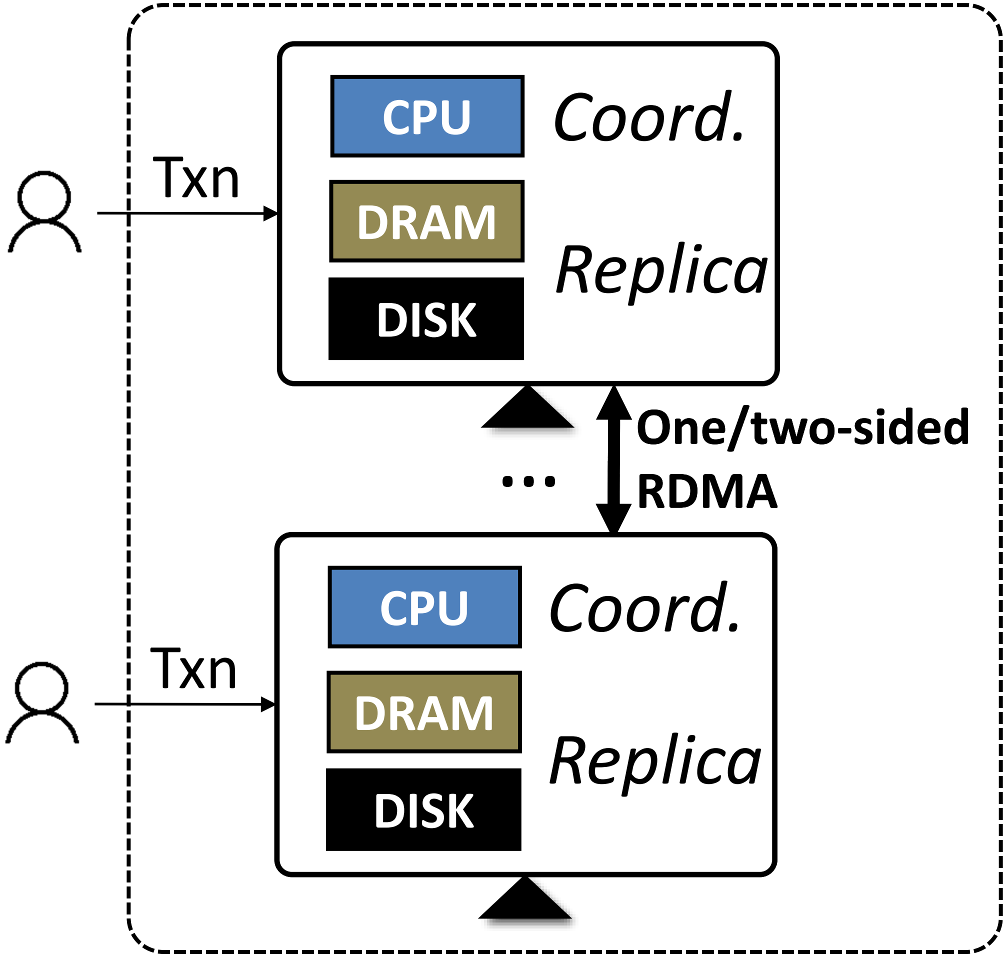

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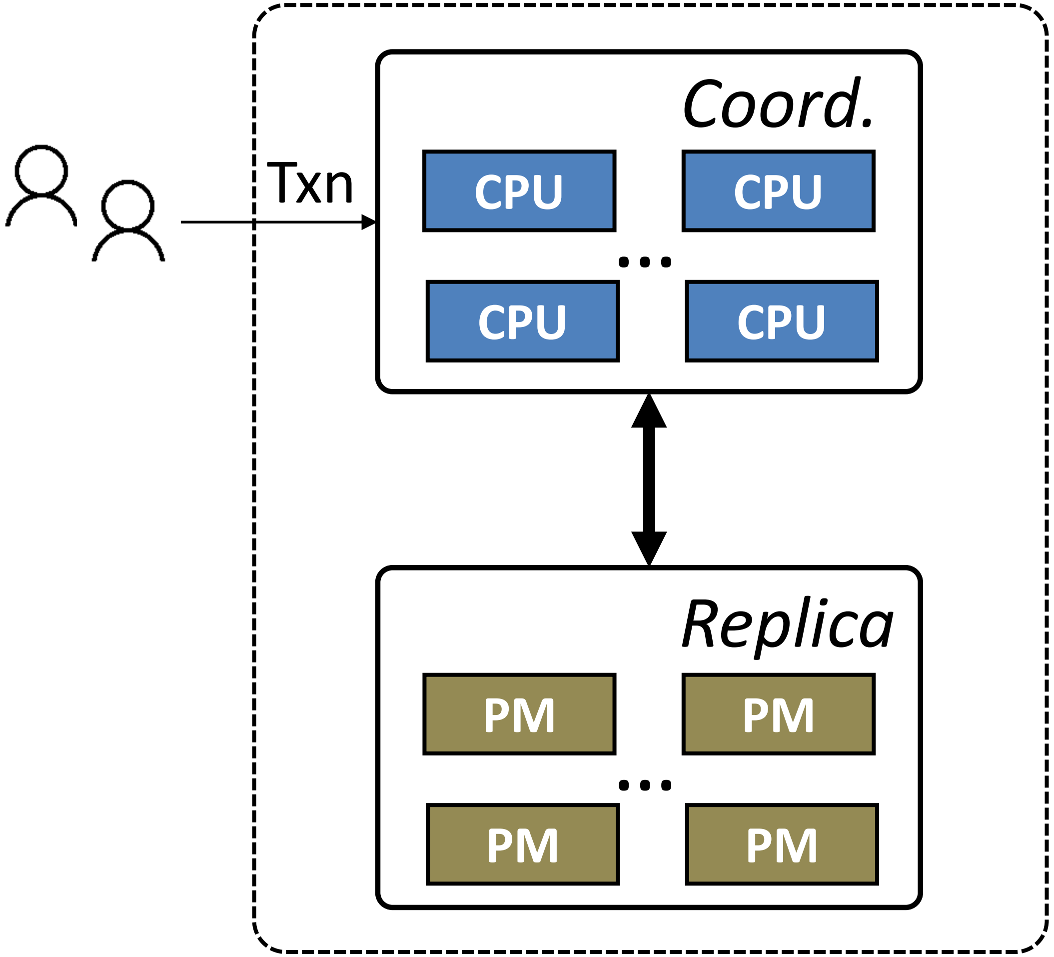

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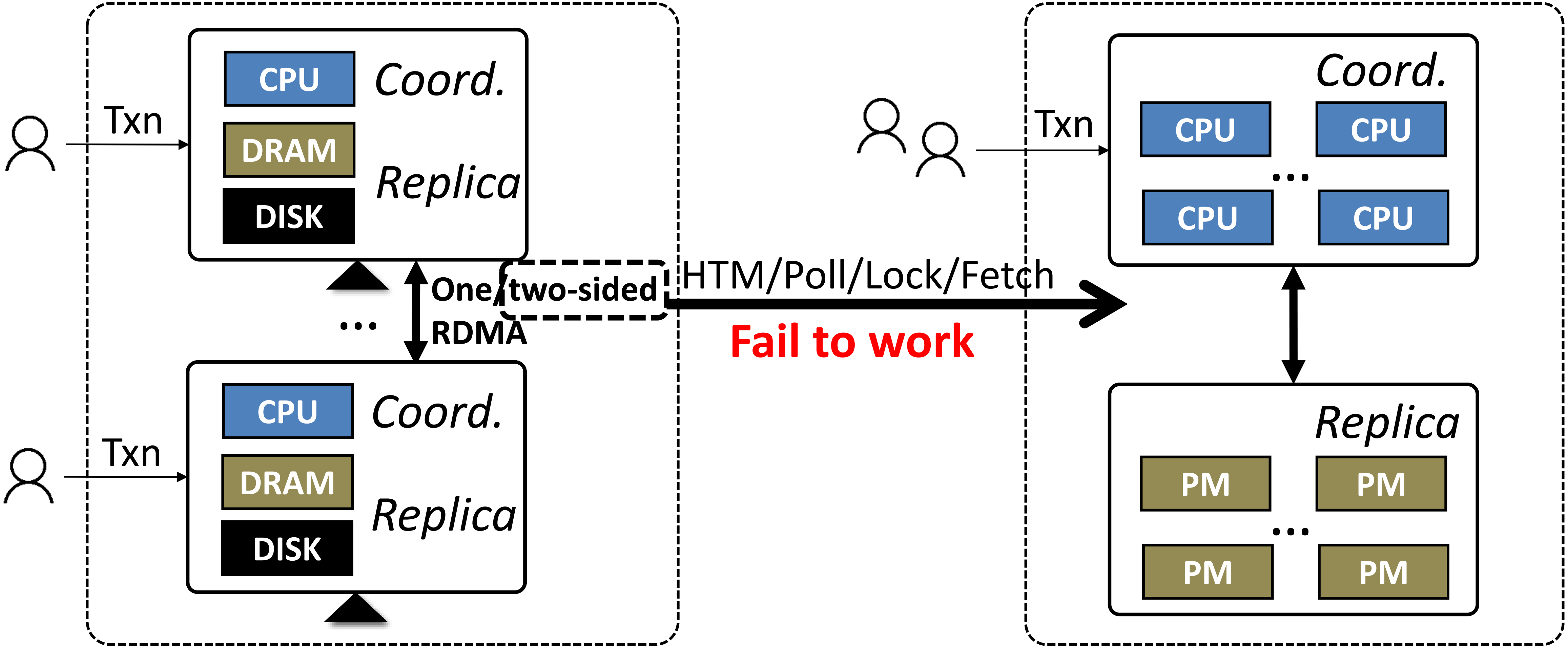

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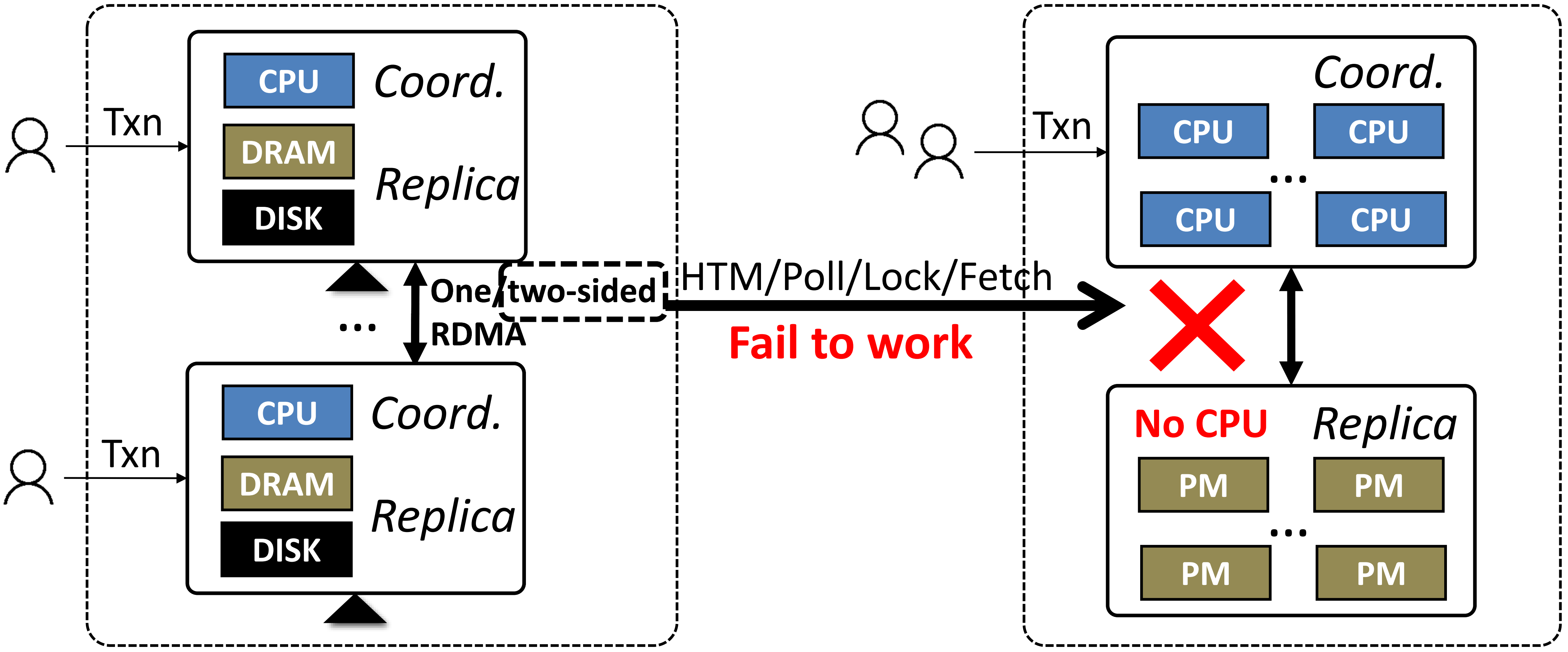

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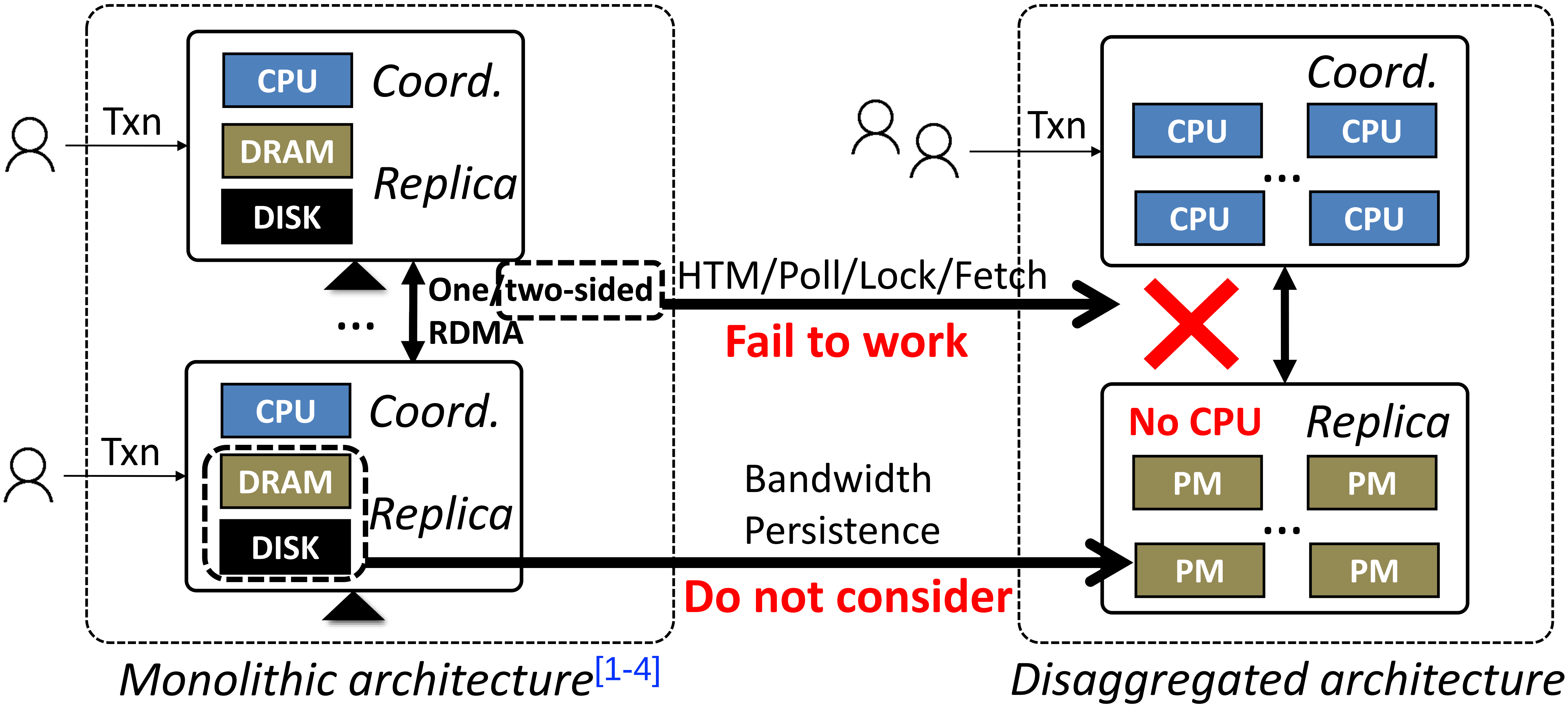

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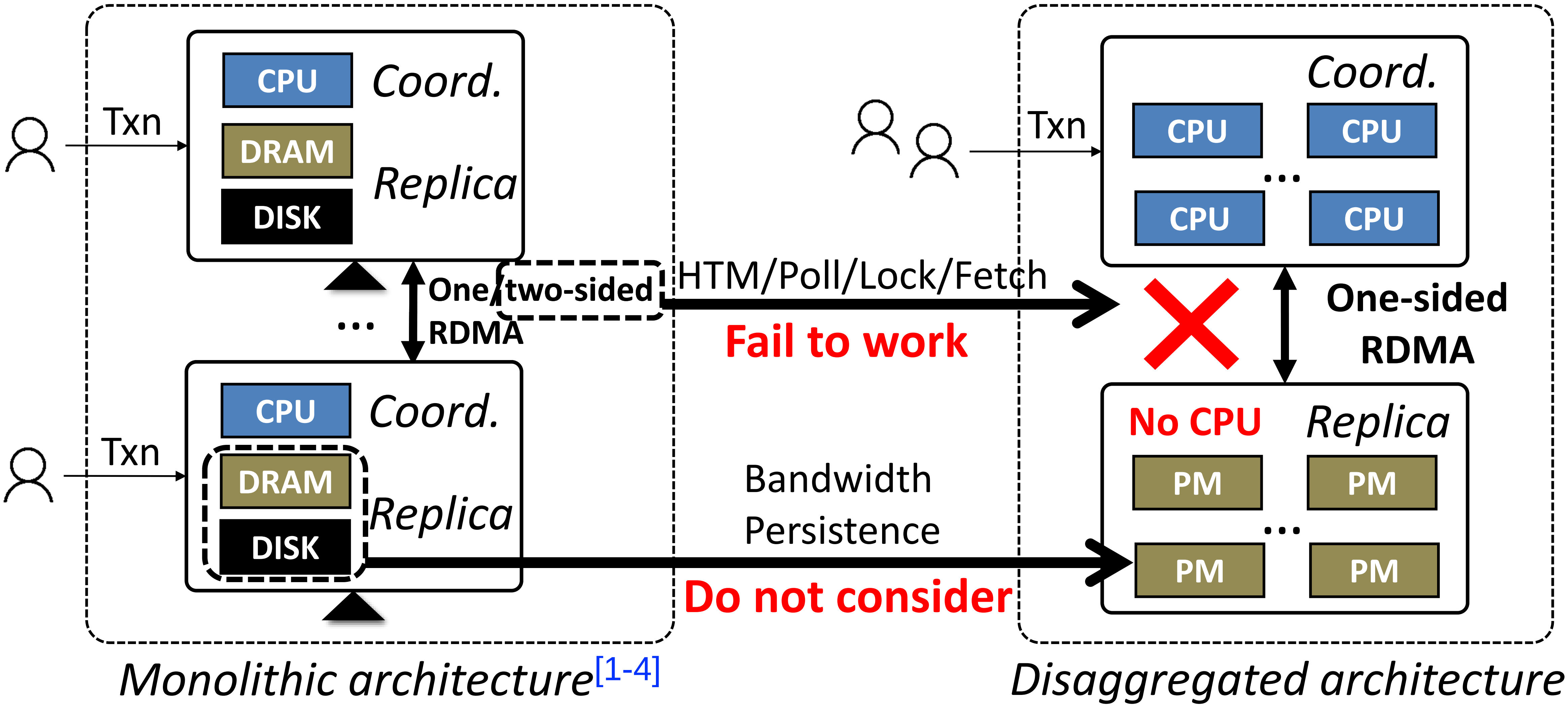

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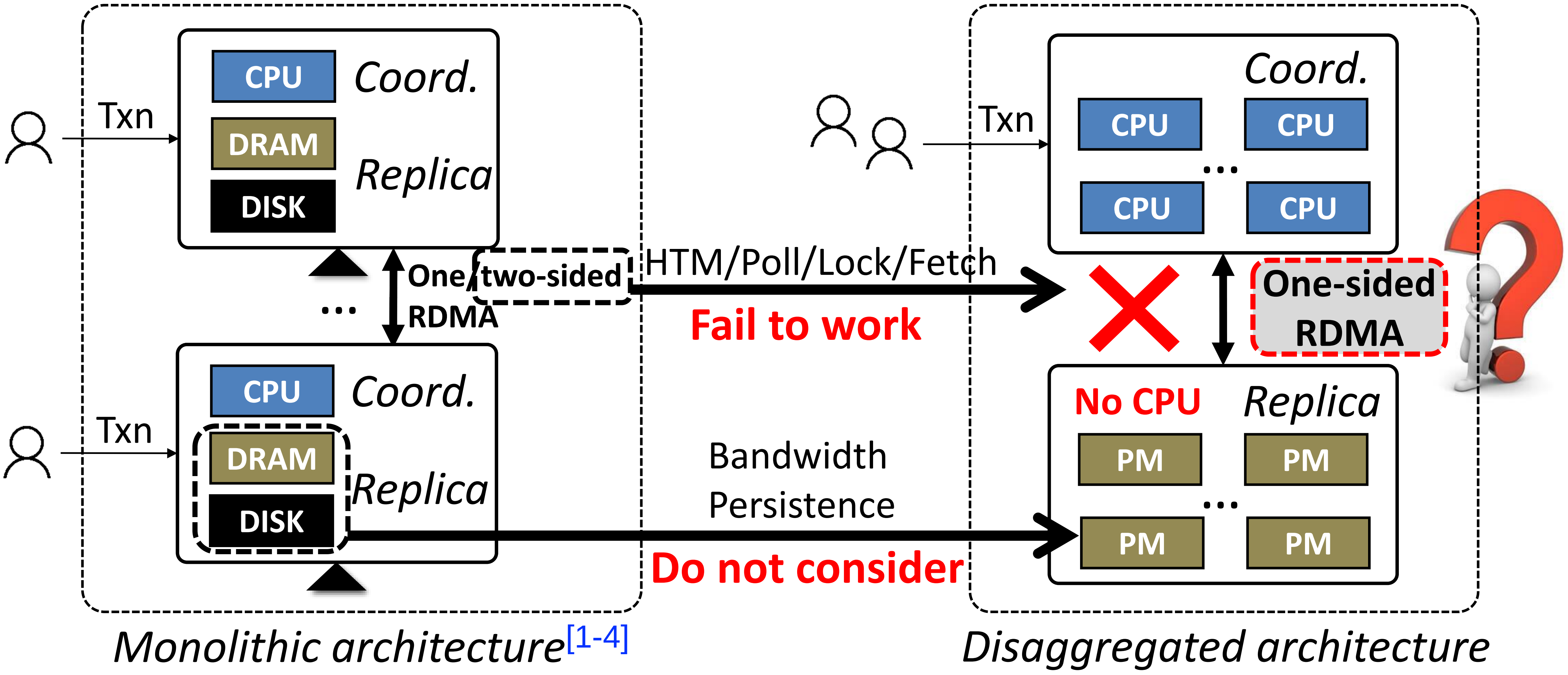

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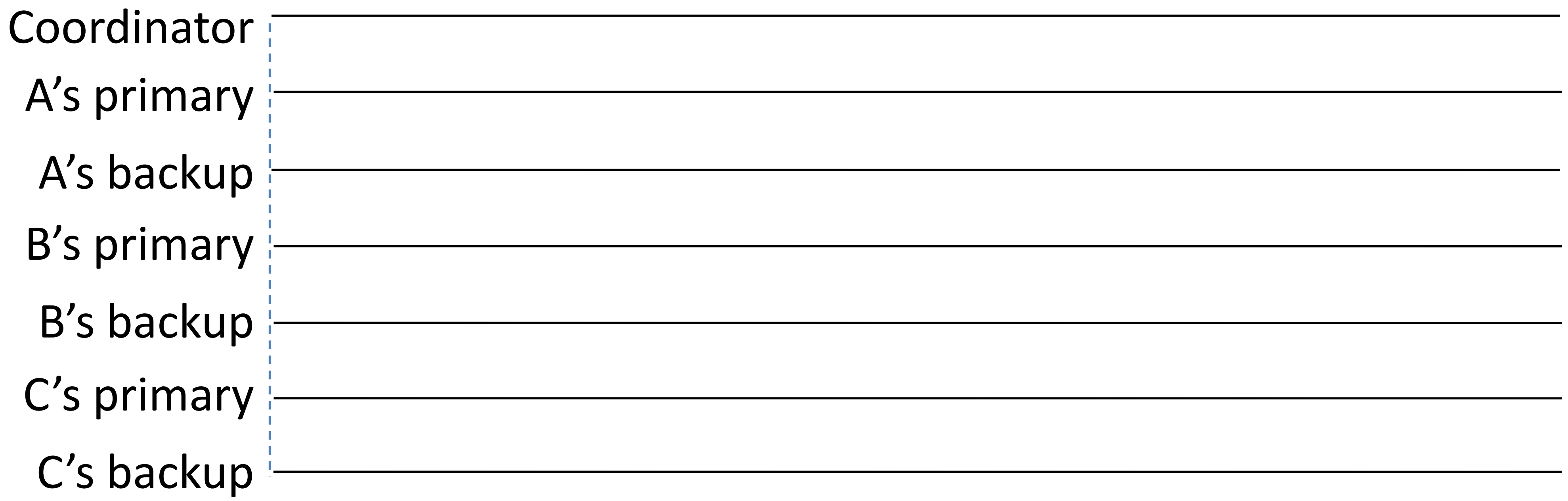

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Write A=A+C
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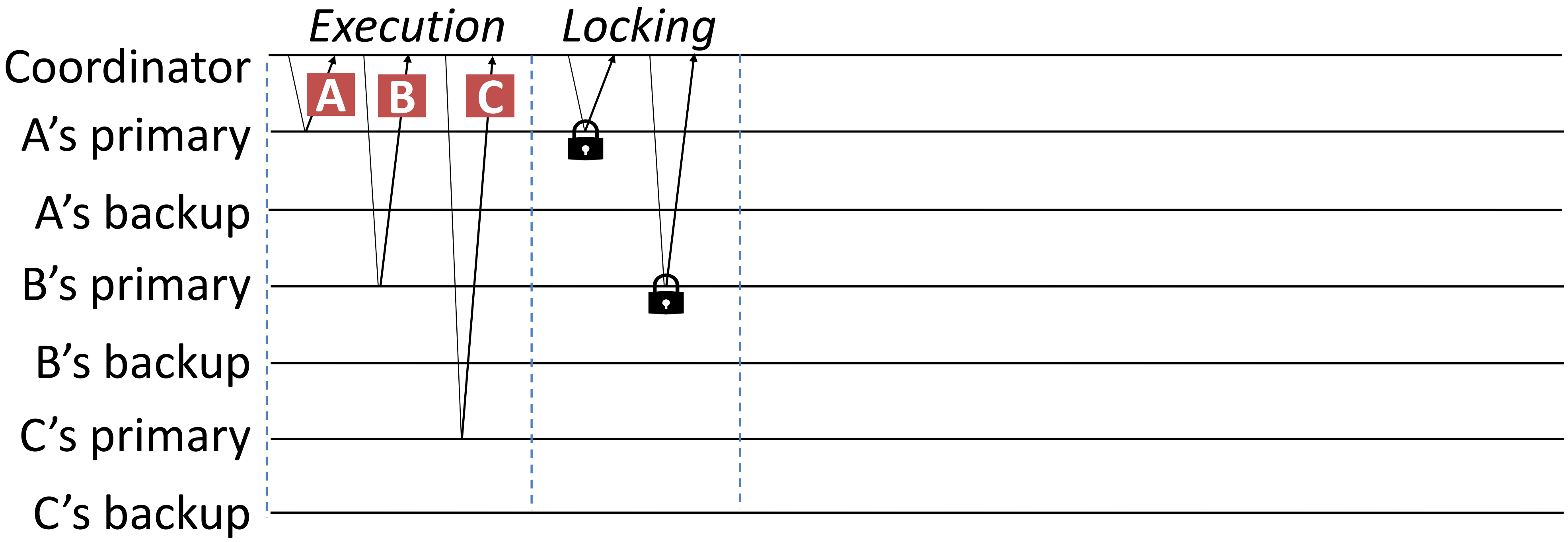

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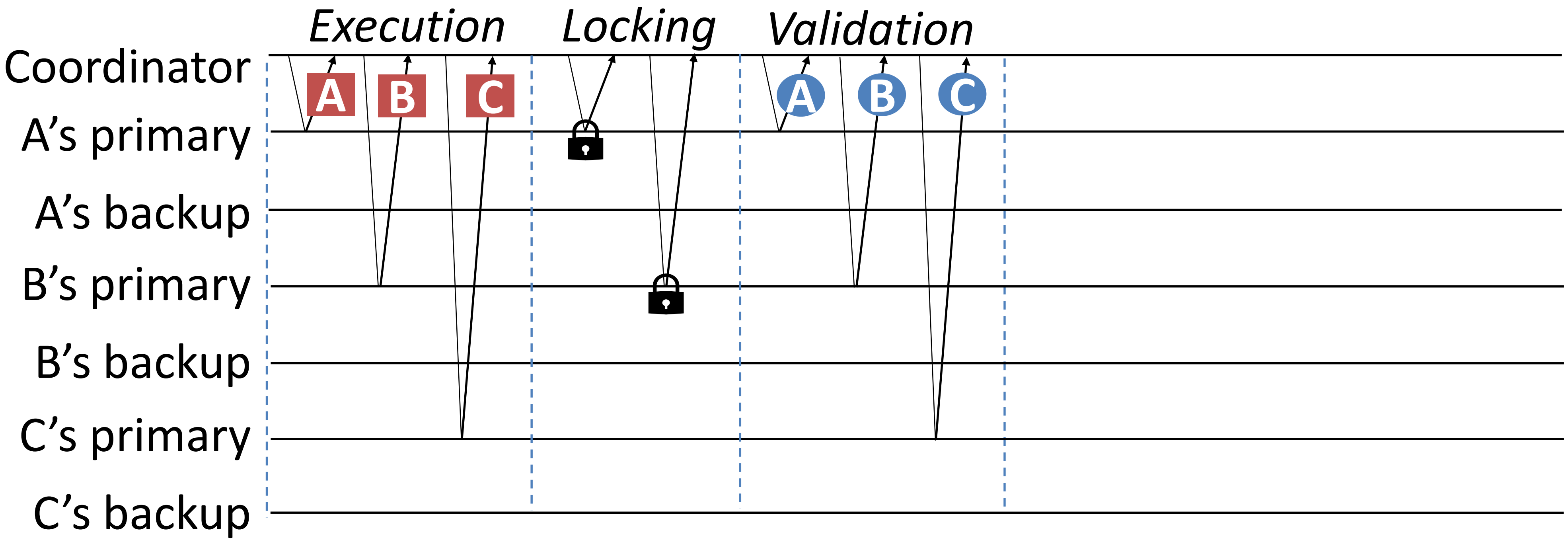

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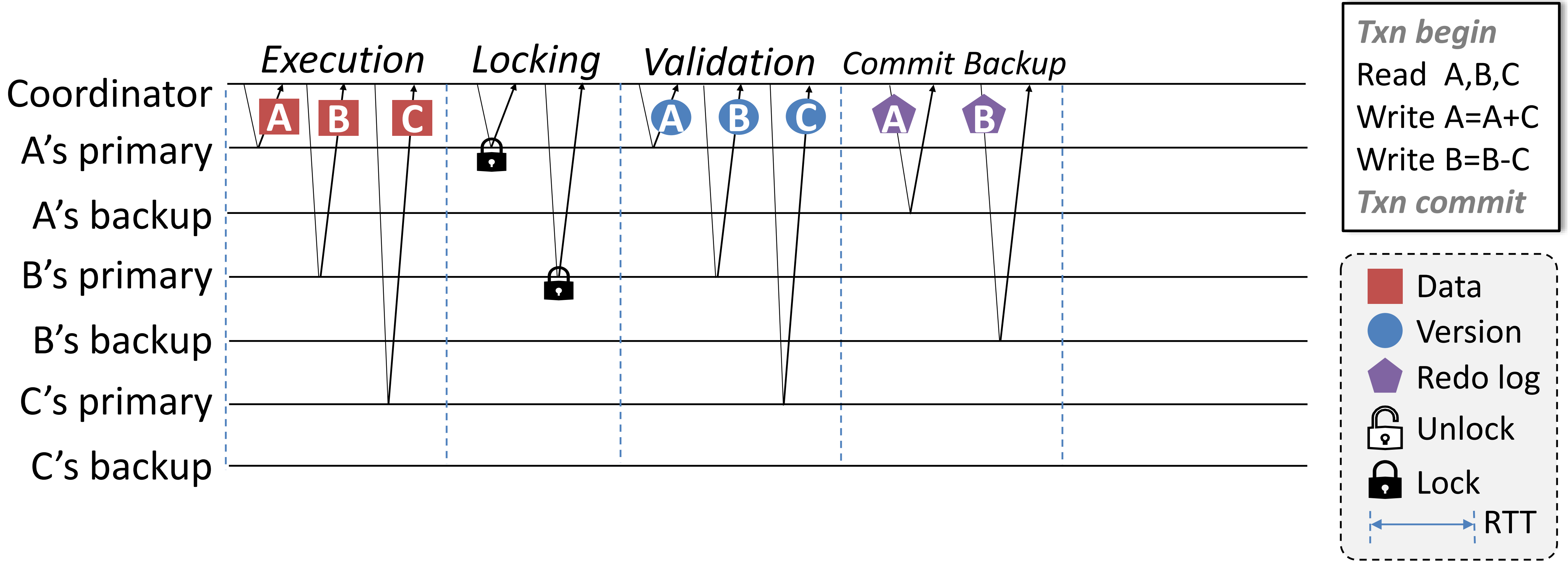

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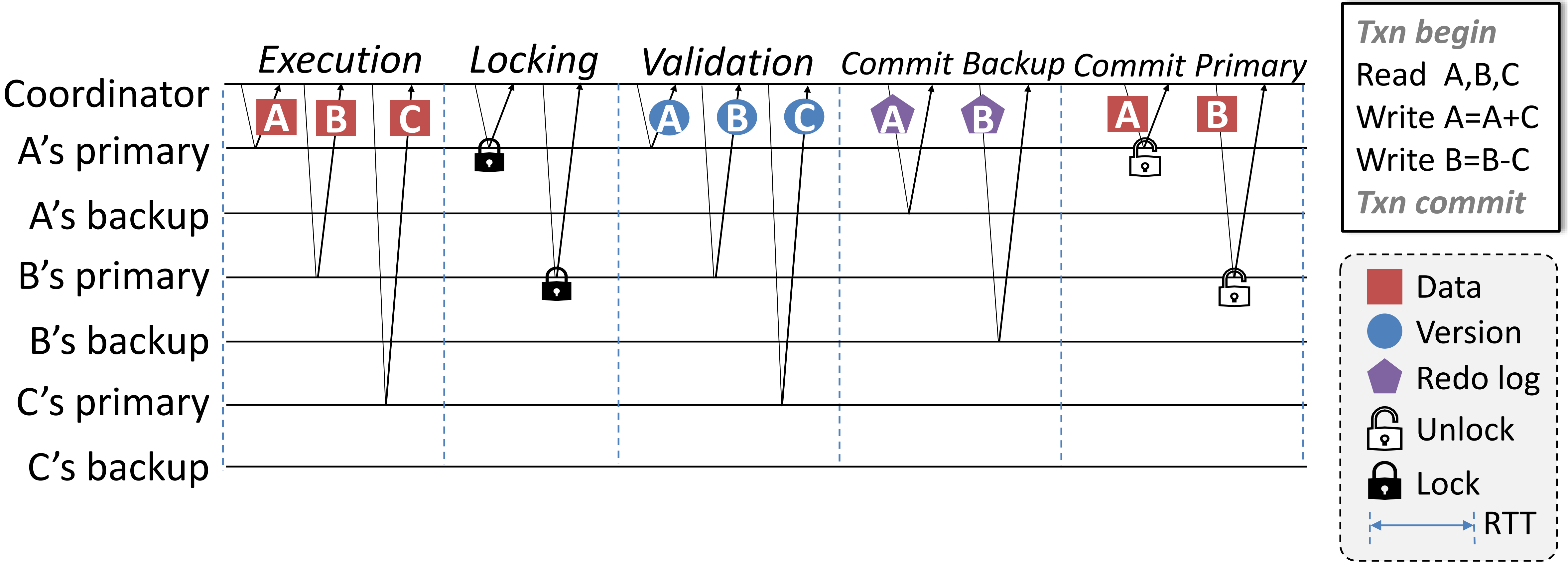

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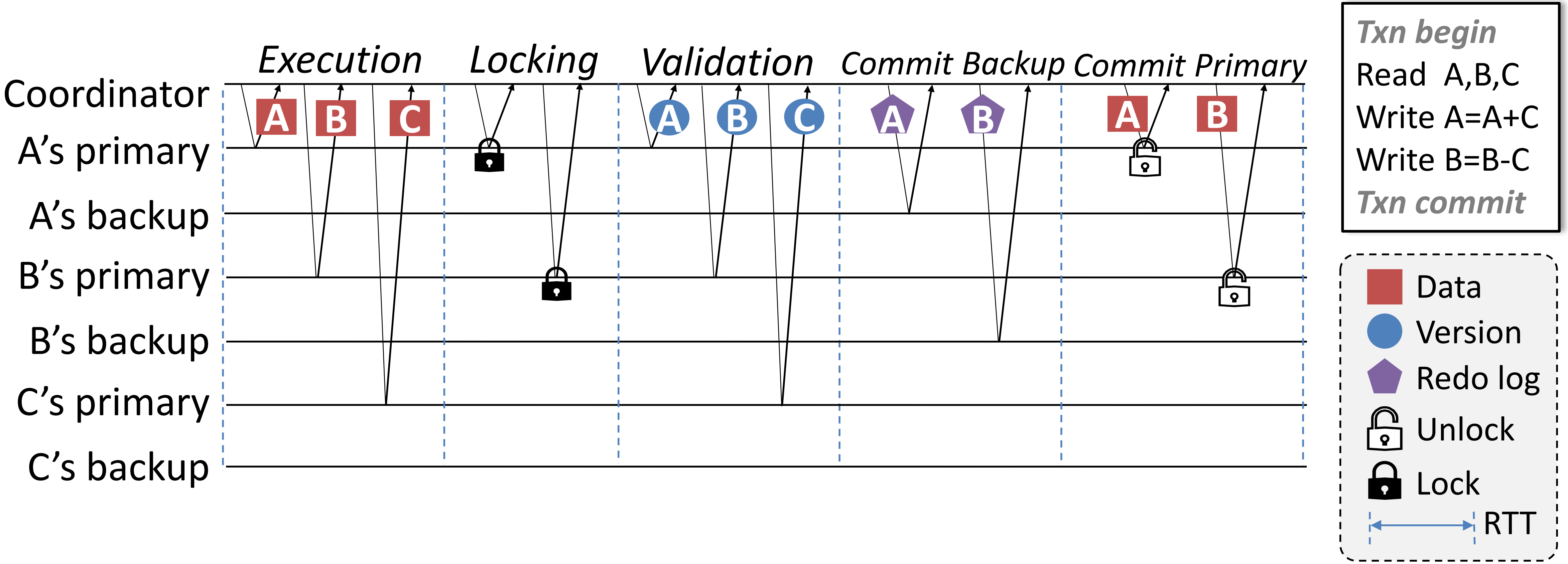

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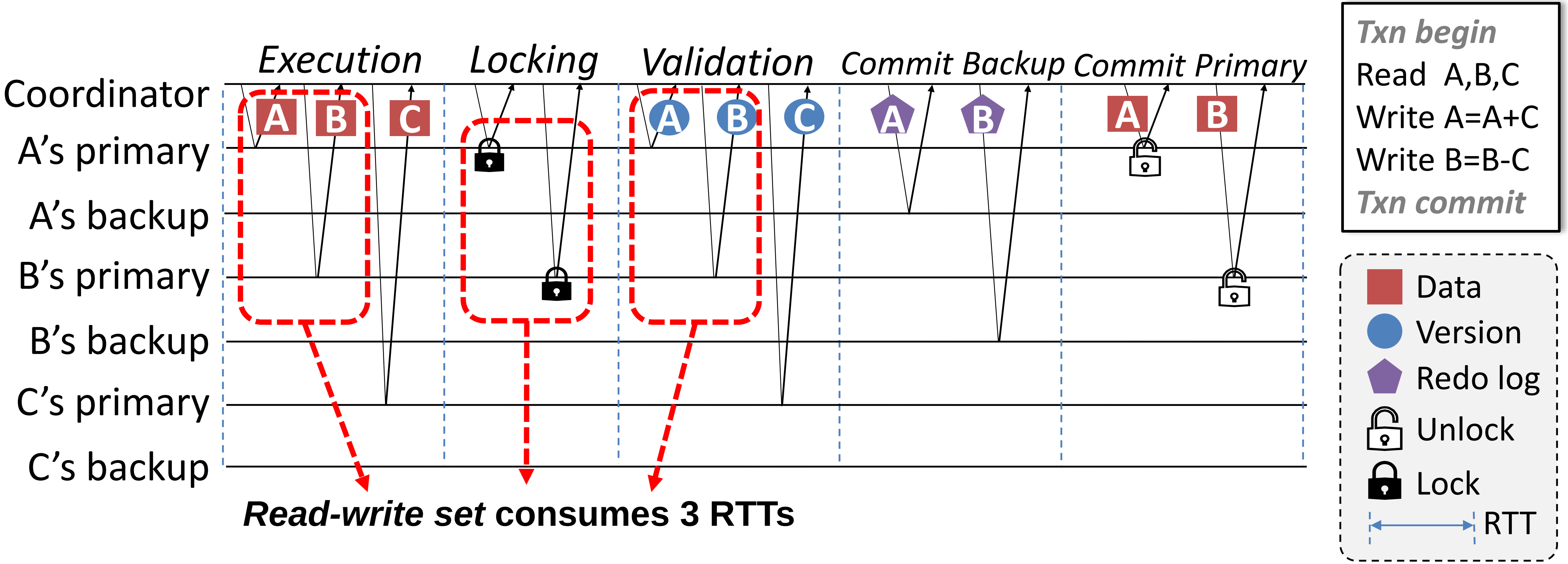

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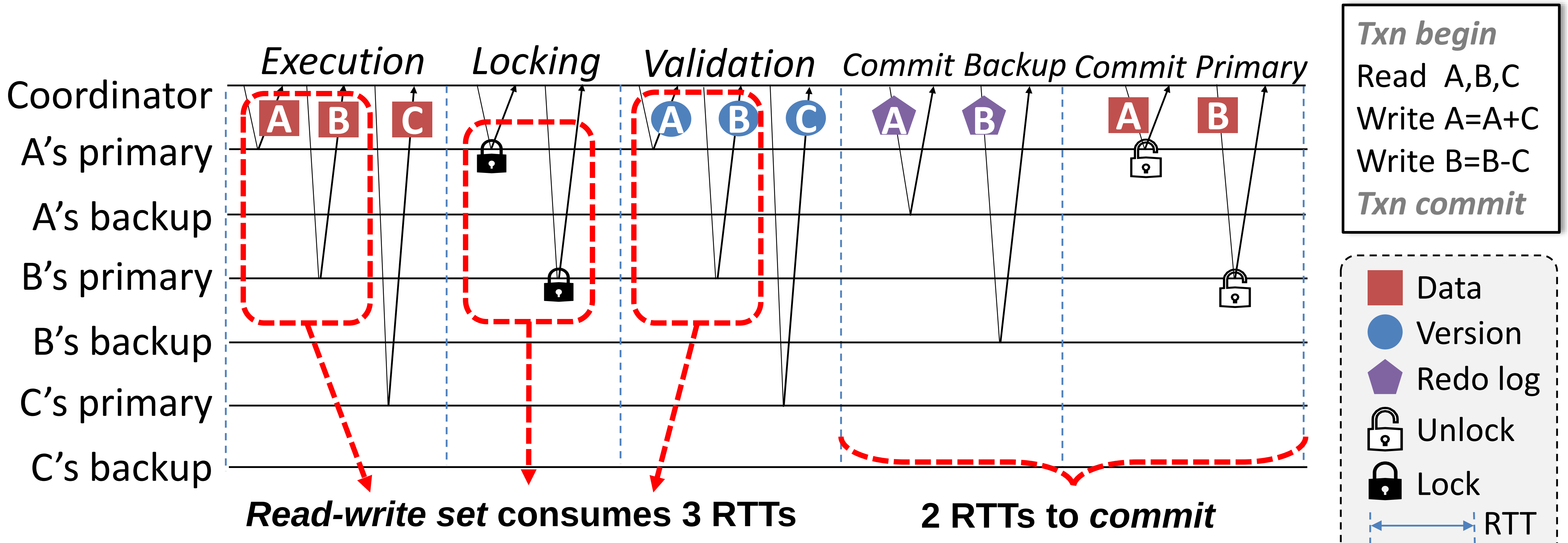

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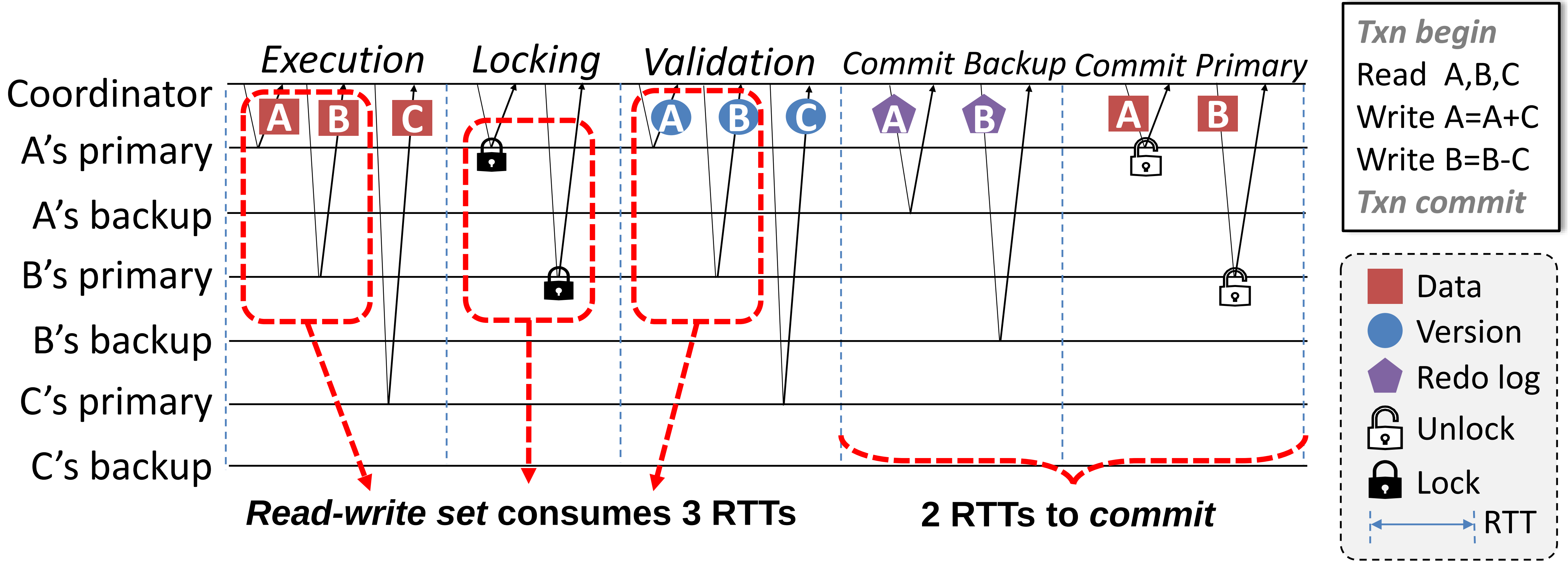

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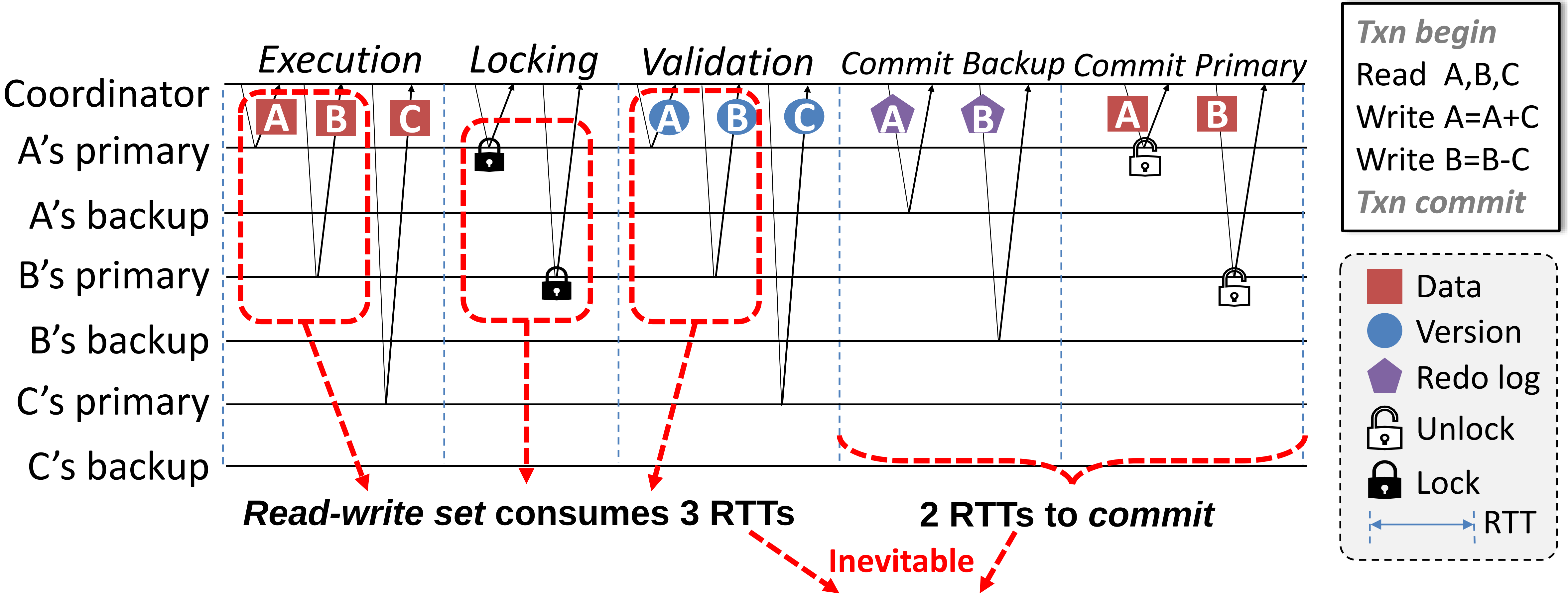

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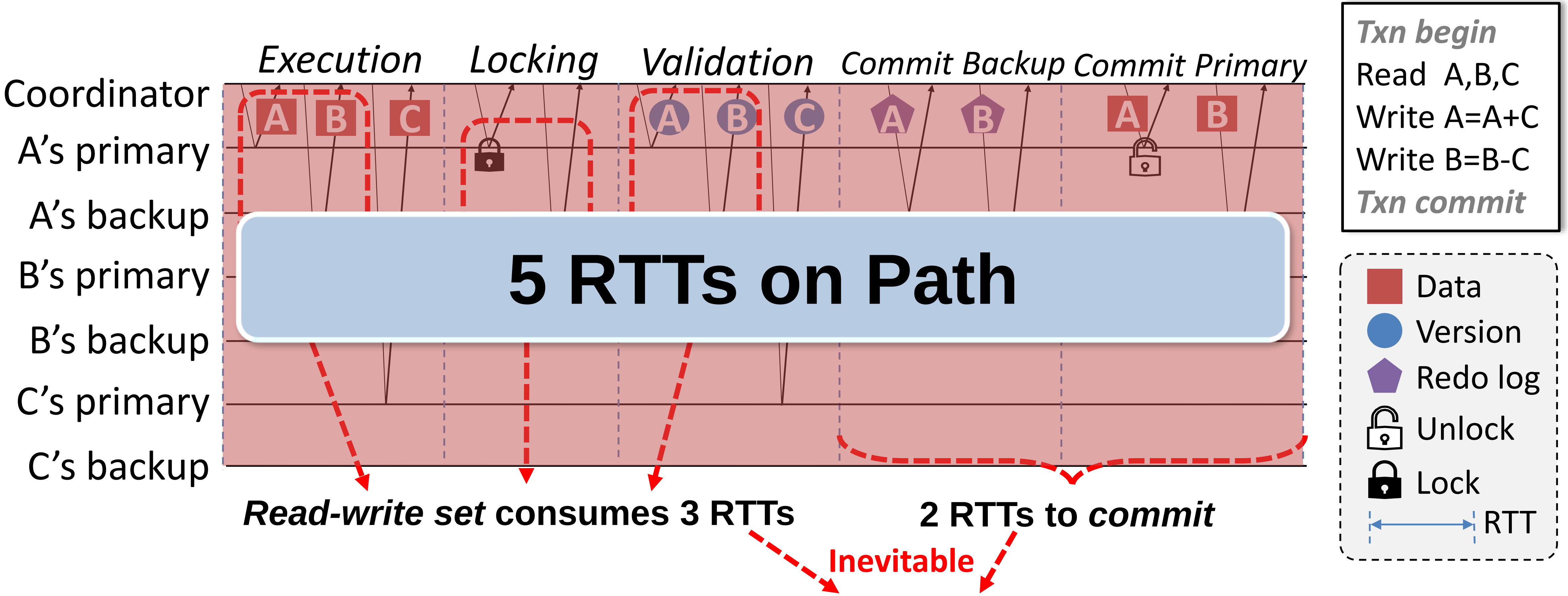

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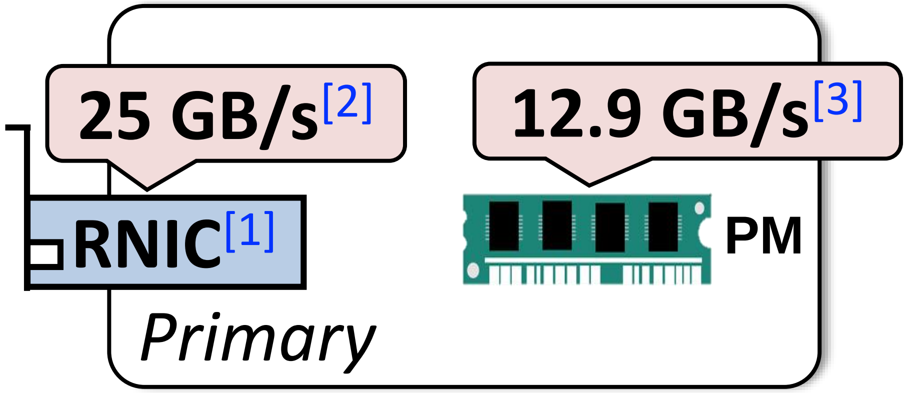

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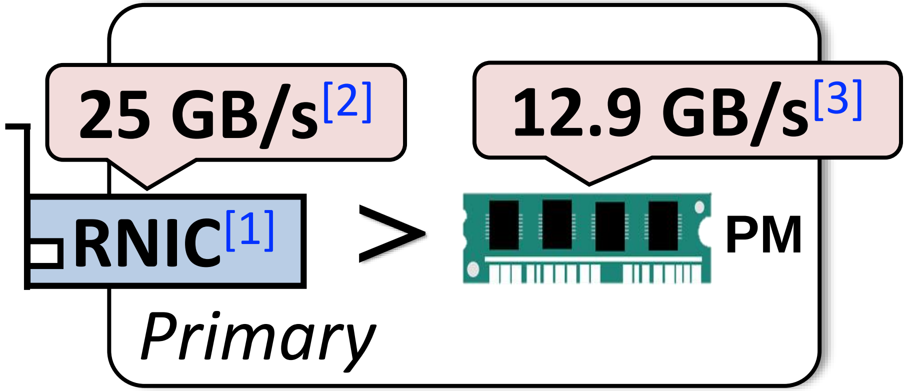

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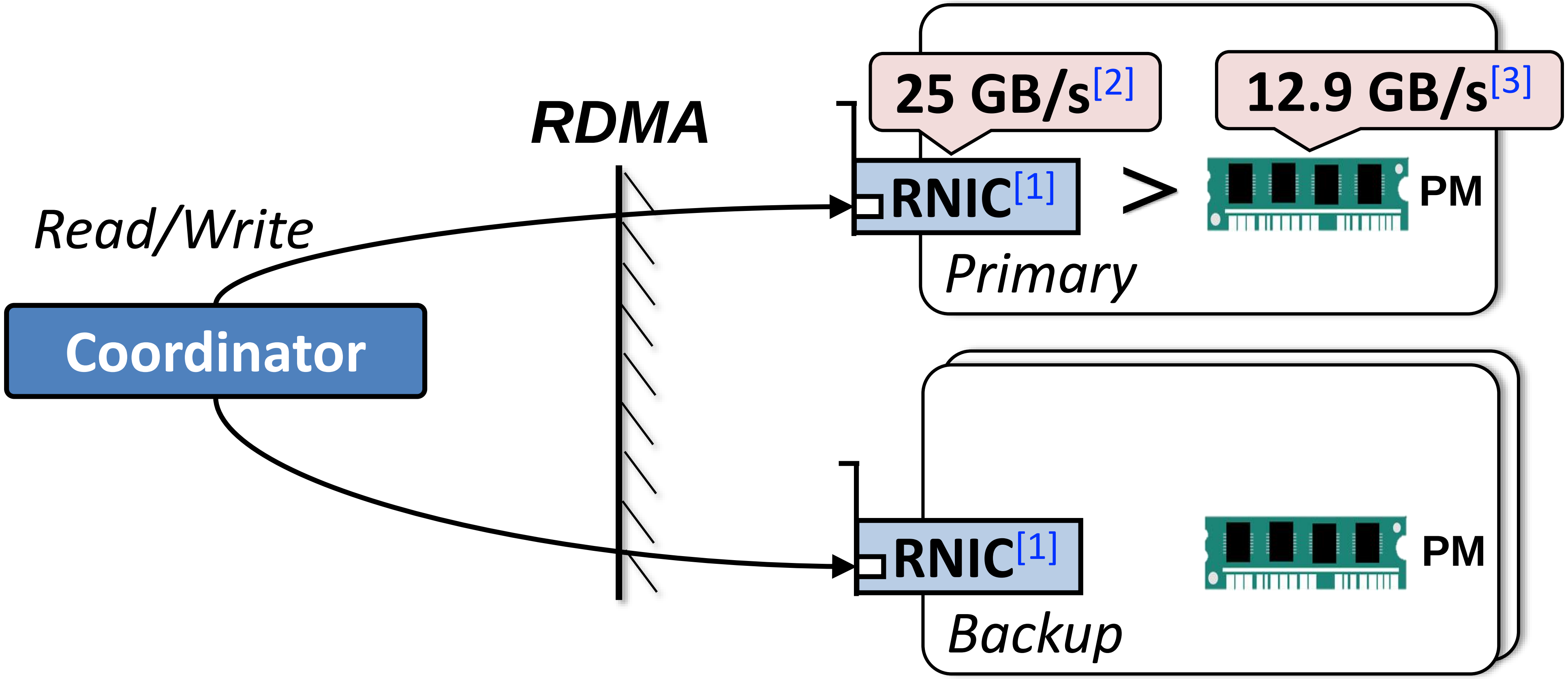

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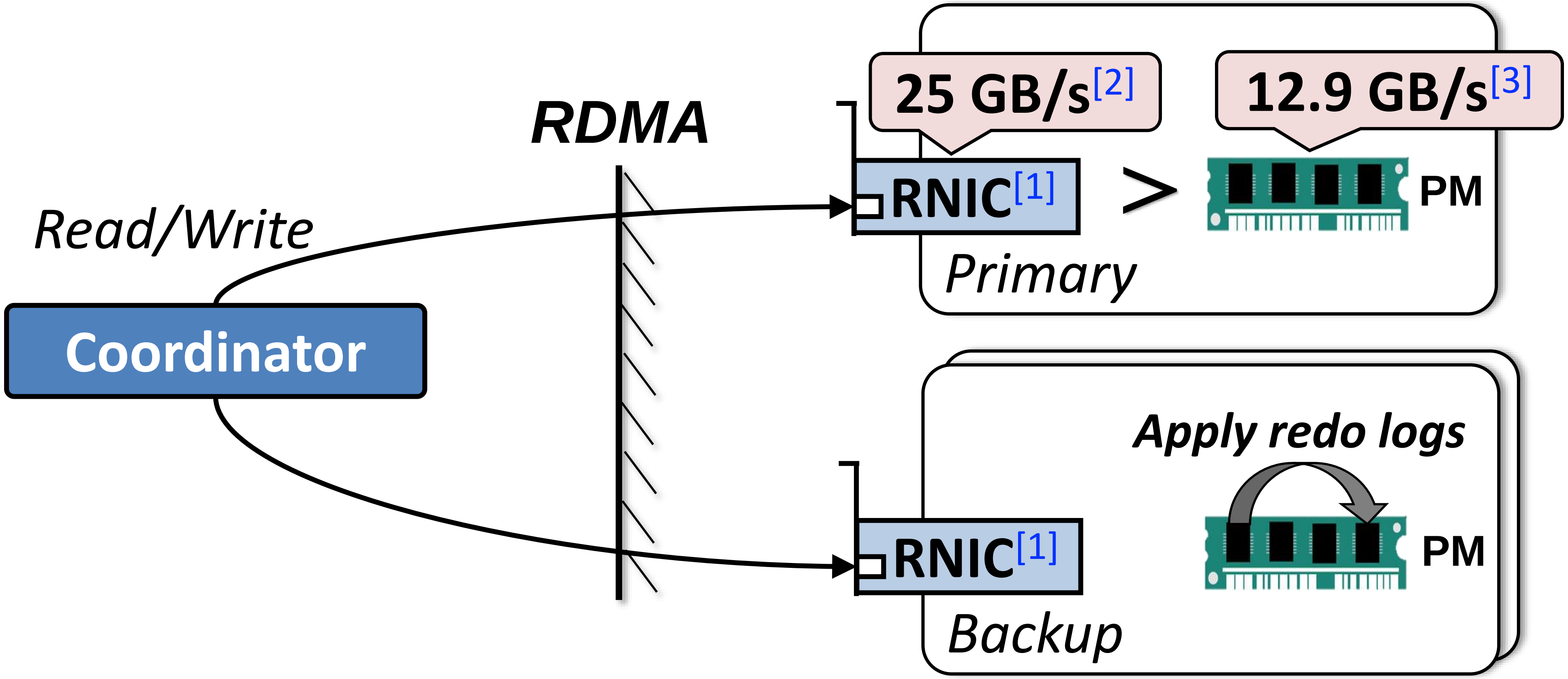

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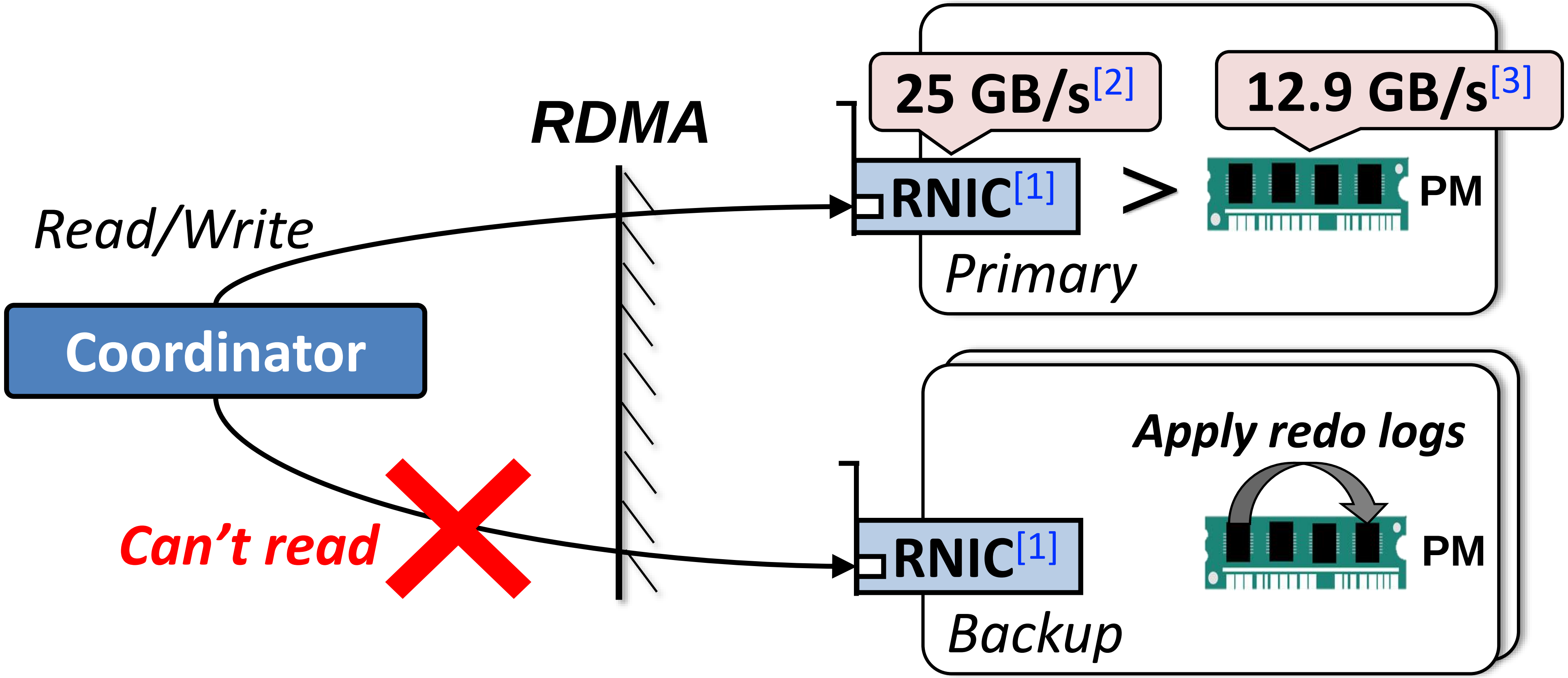

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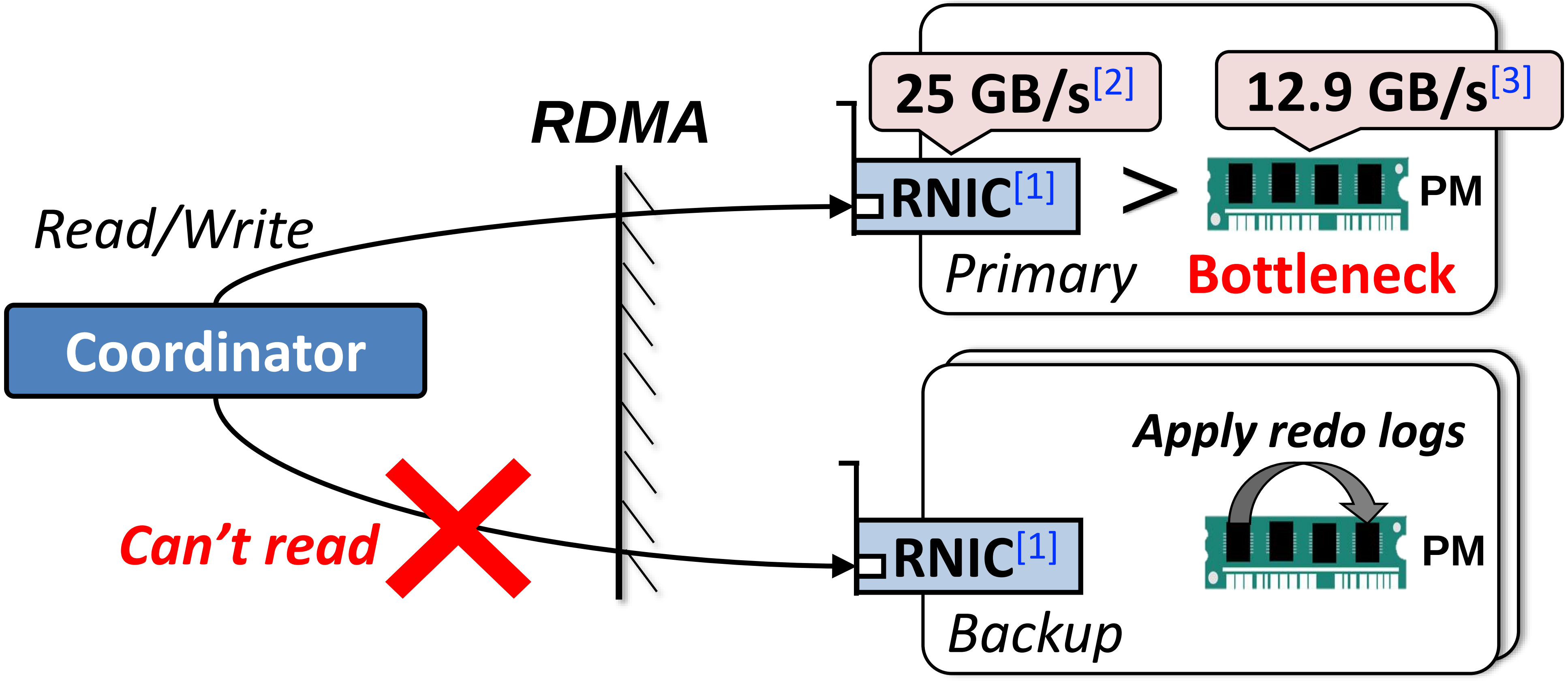

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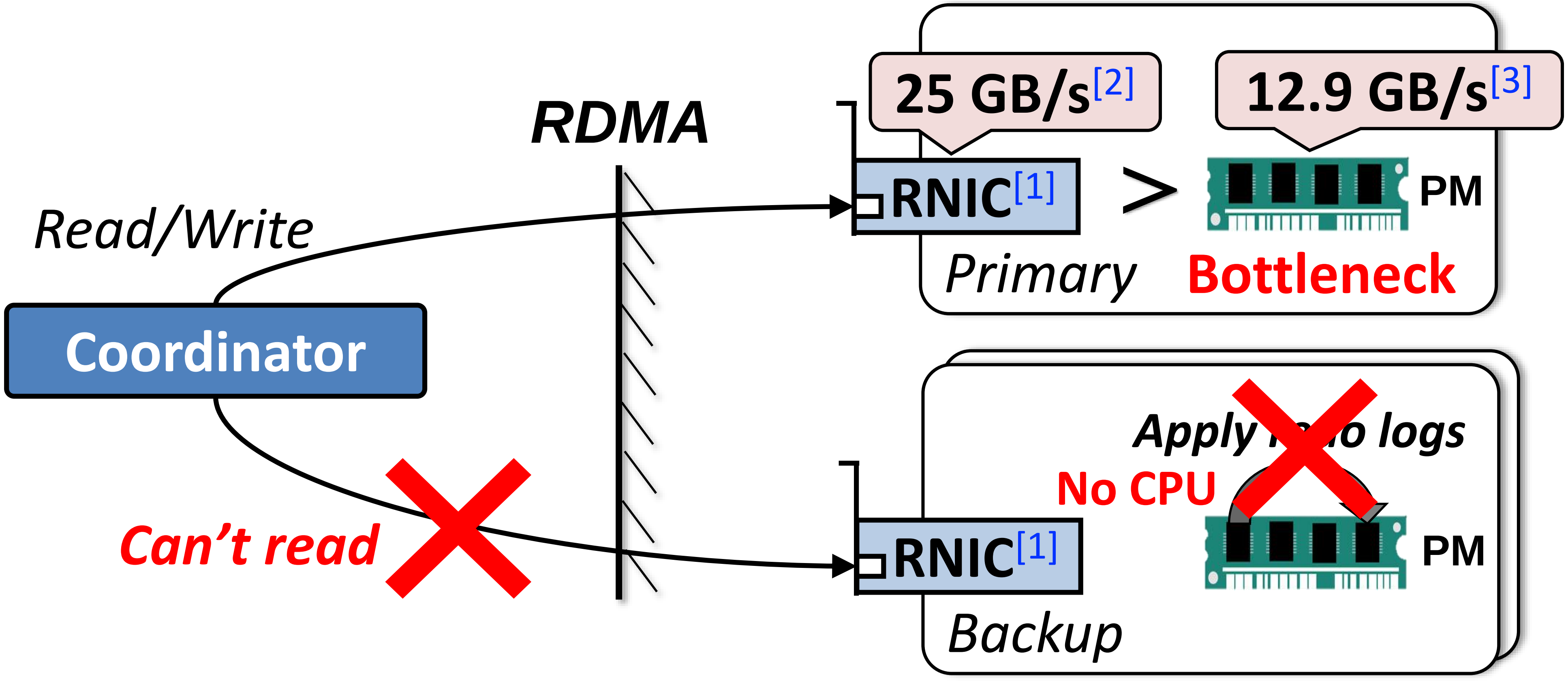

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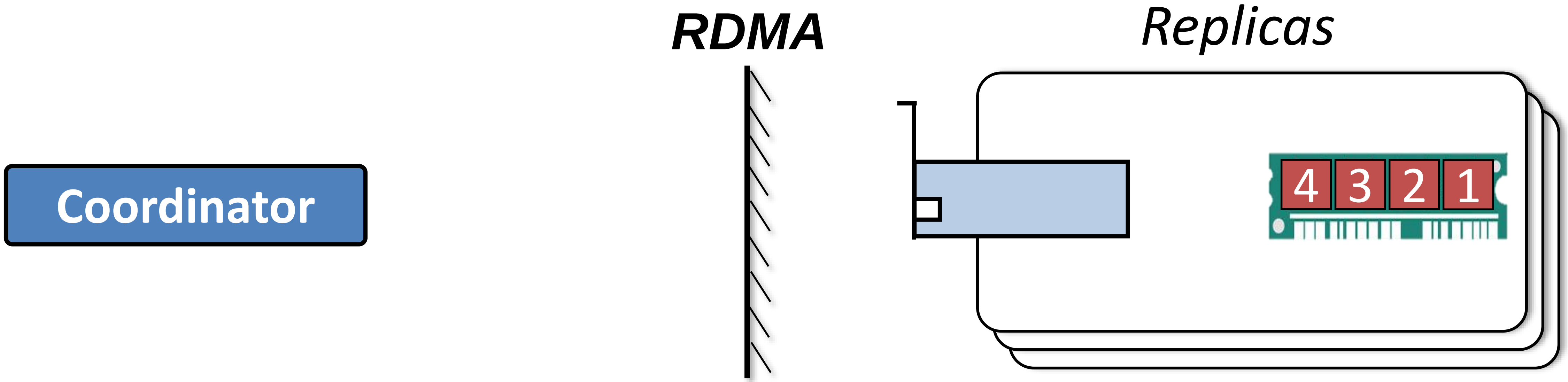

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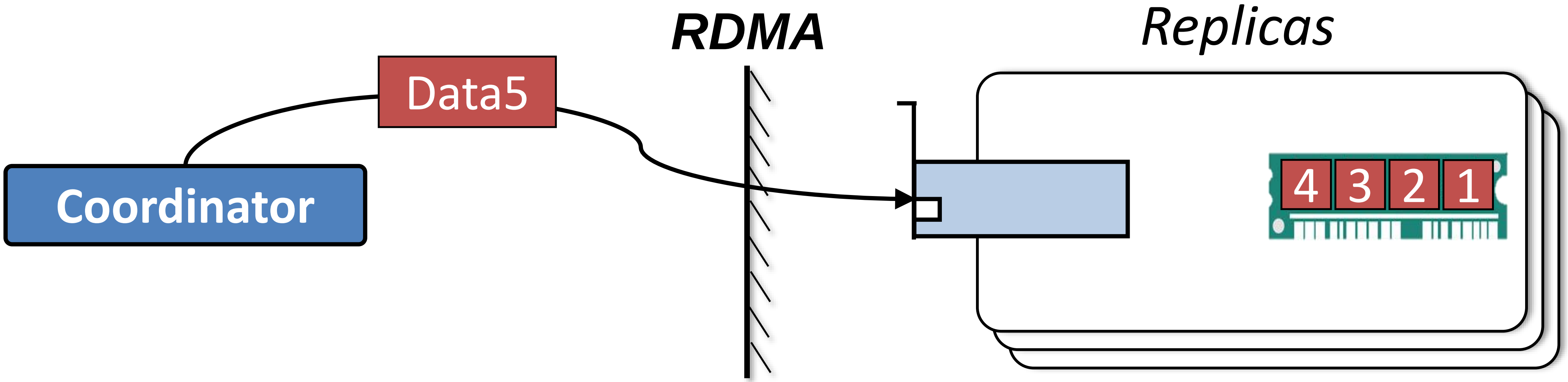

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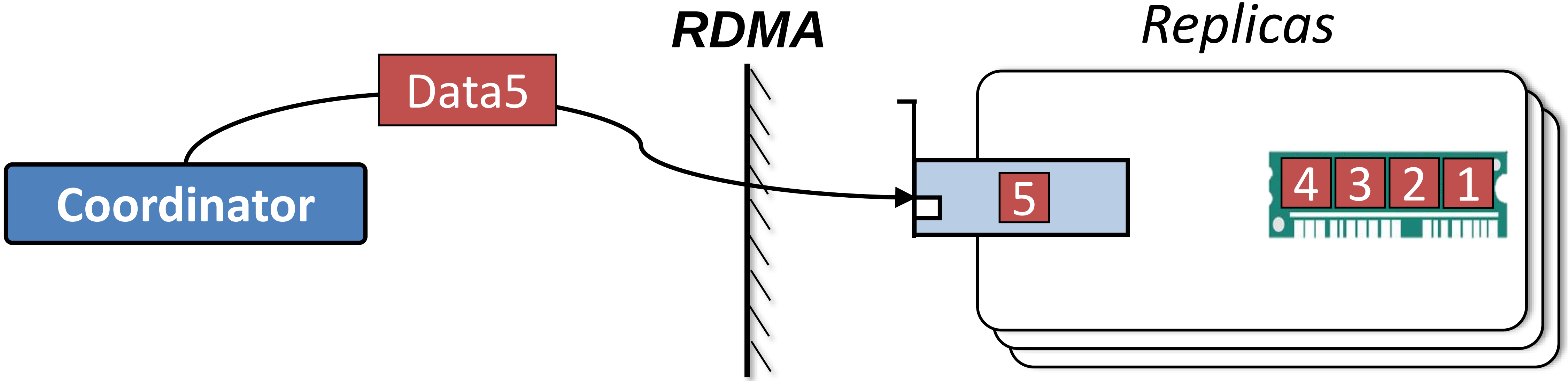

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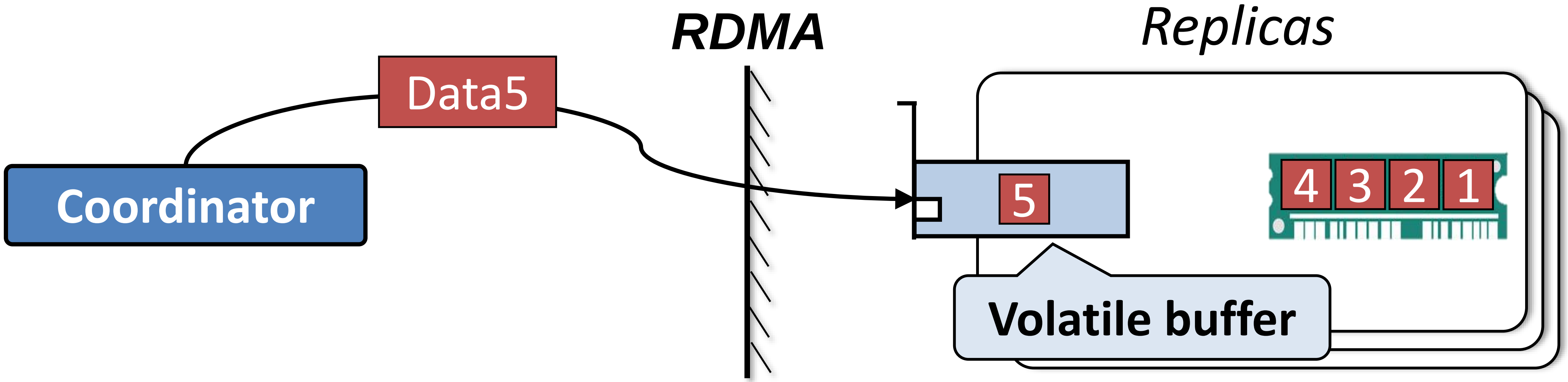

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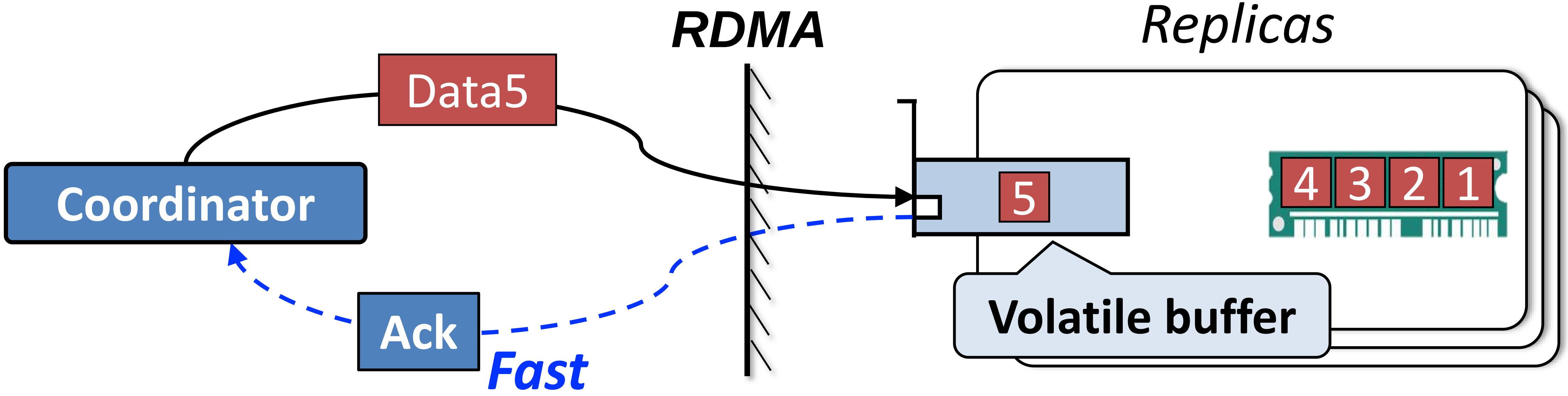

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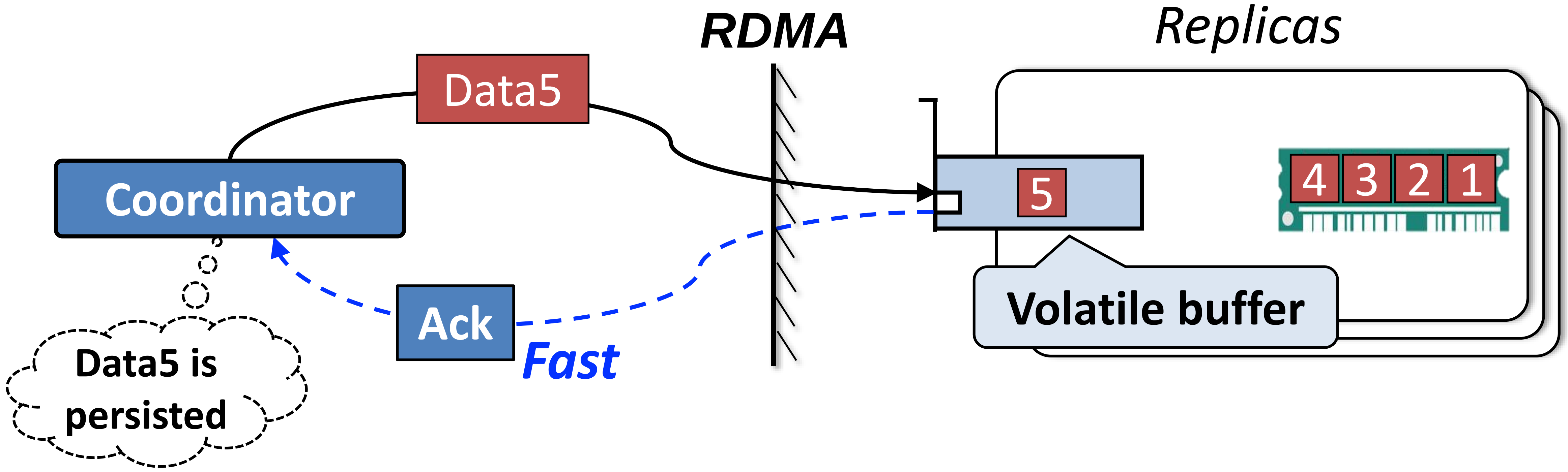

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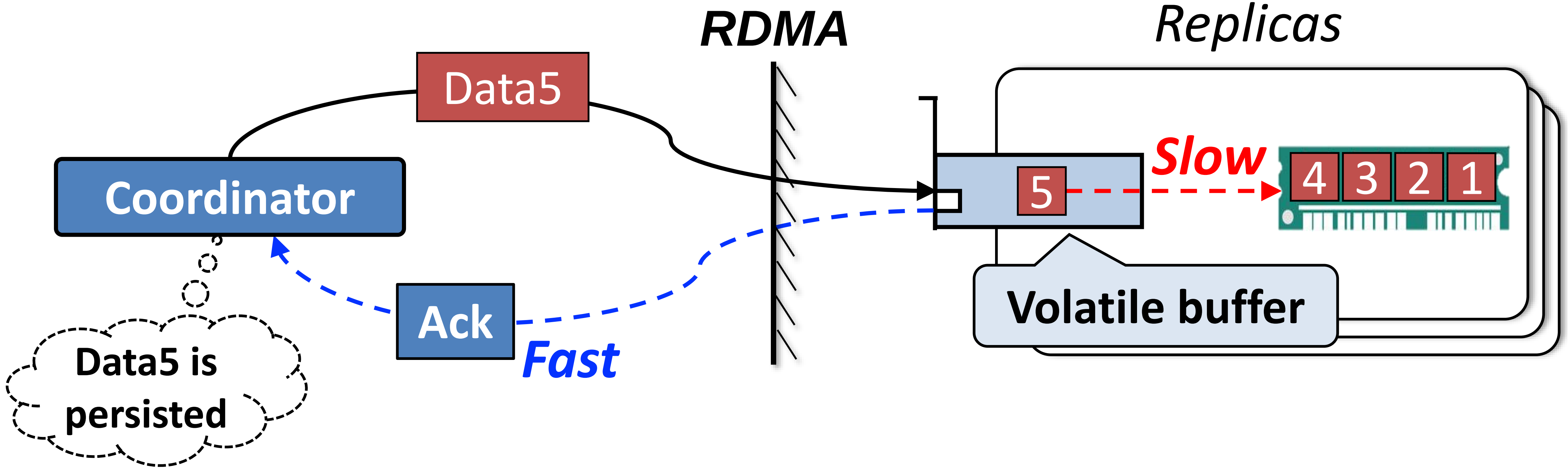

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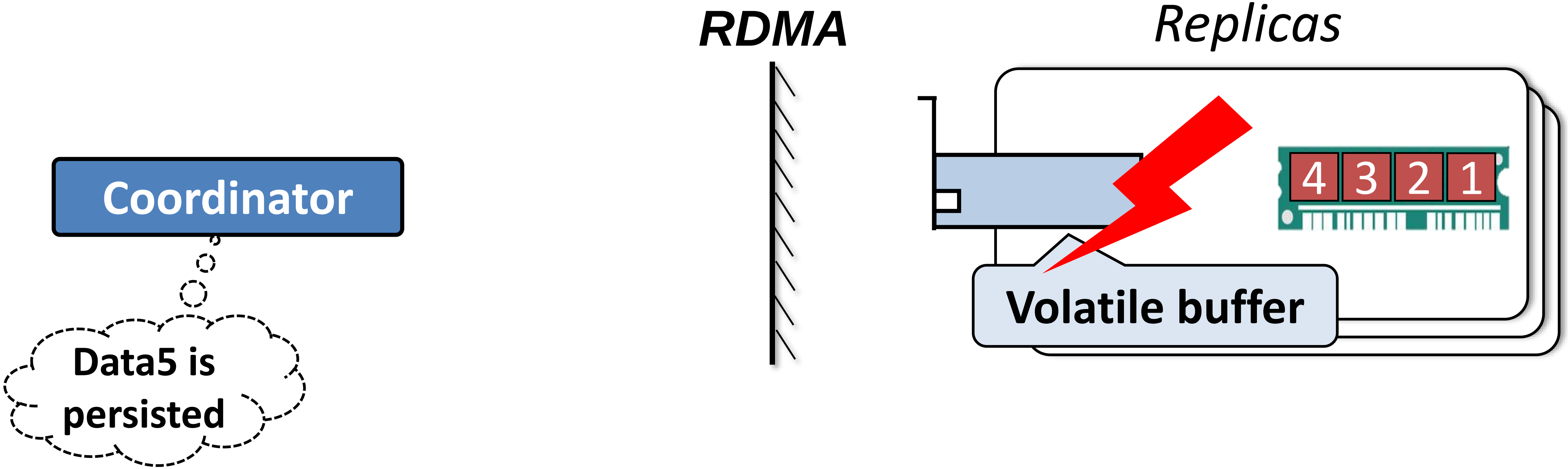

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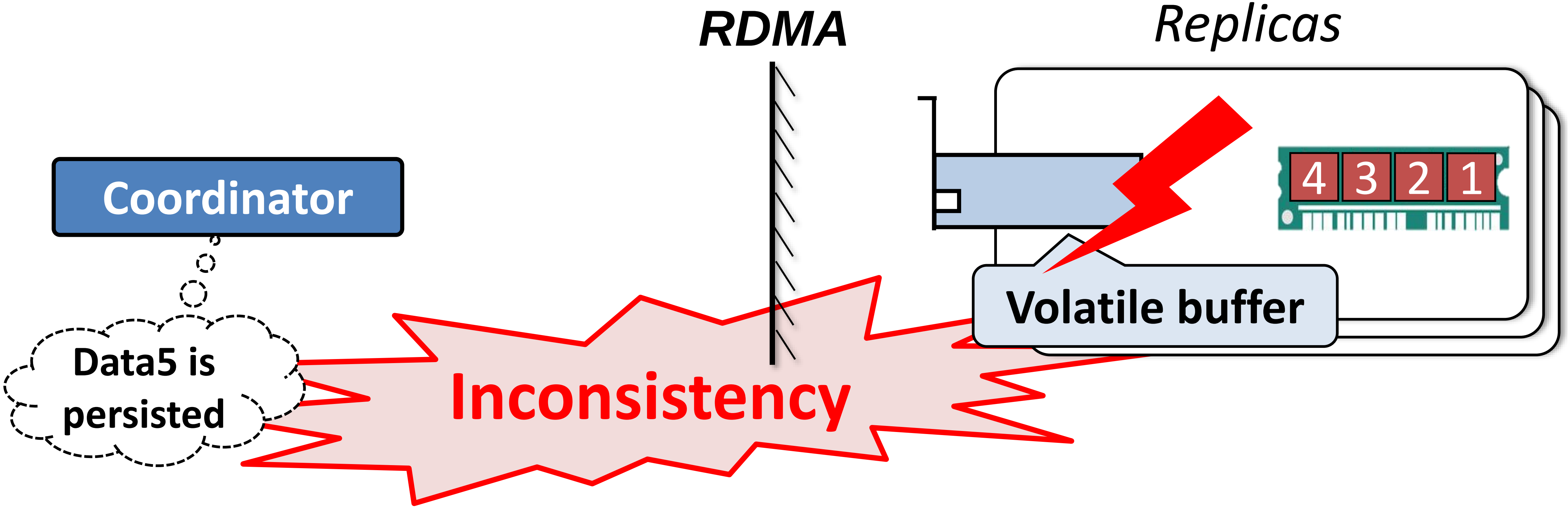

FORD: Solutions

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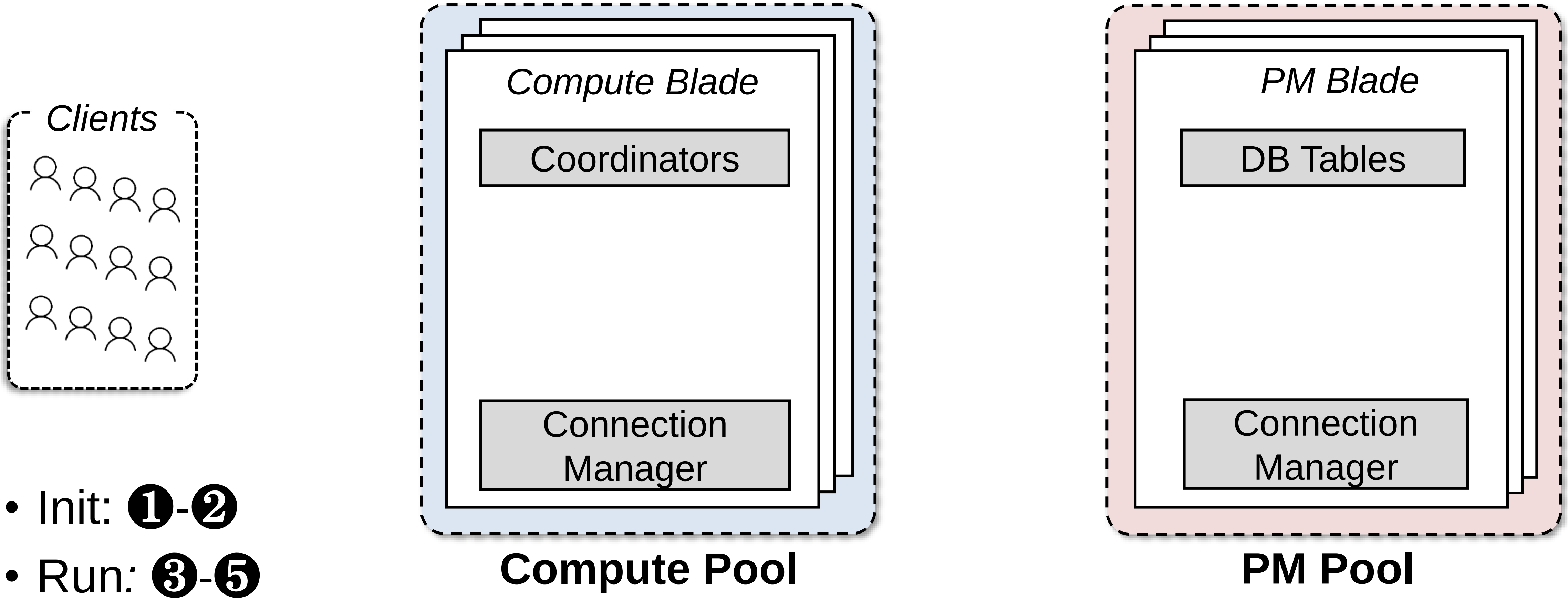
  - **Selective Remote Flush**

  ➔ Guarantee remote persistency with low overhead

Overview



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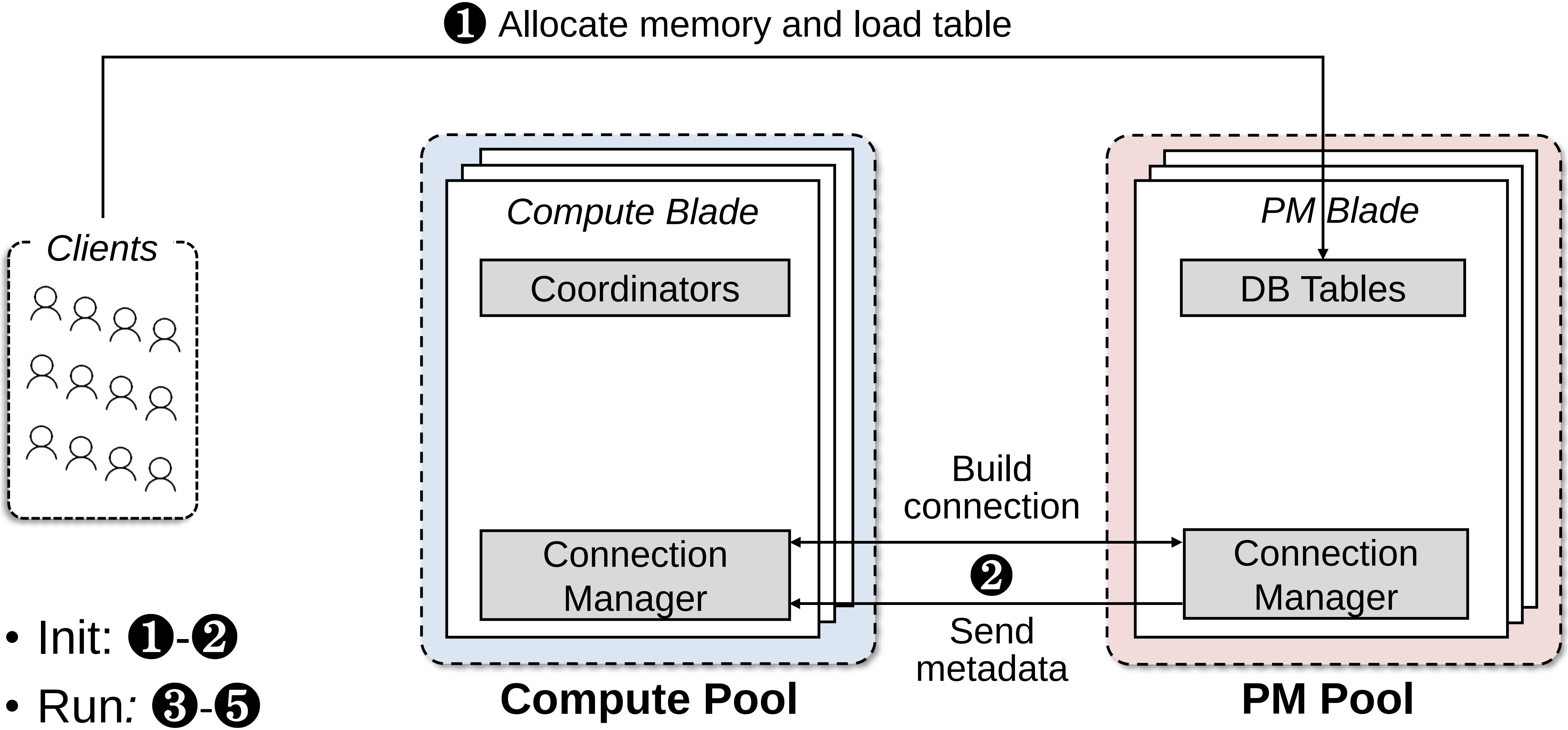

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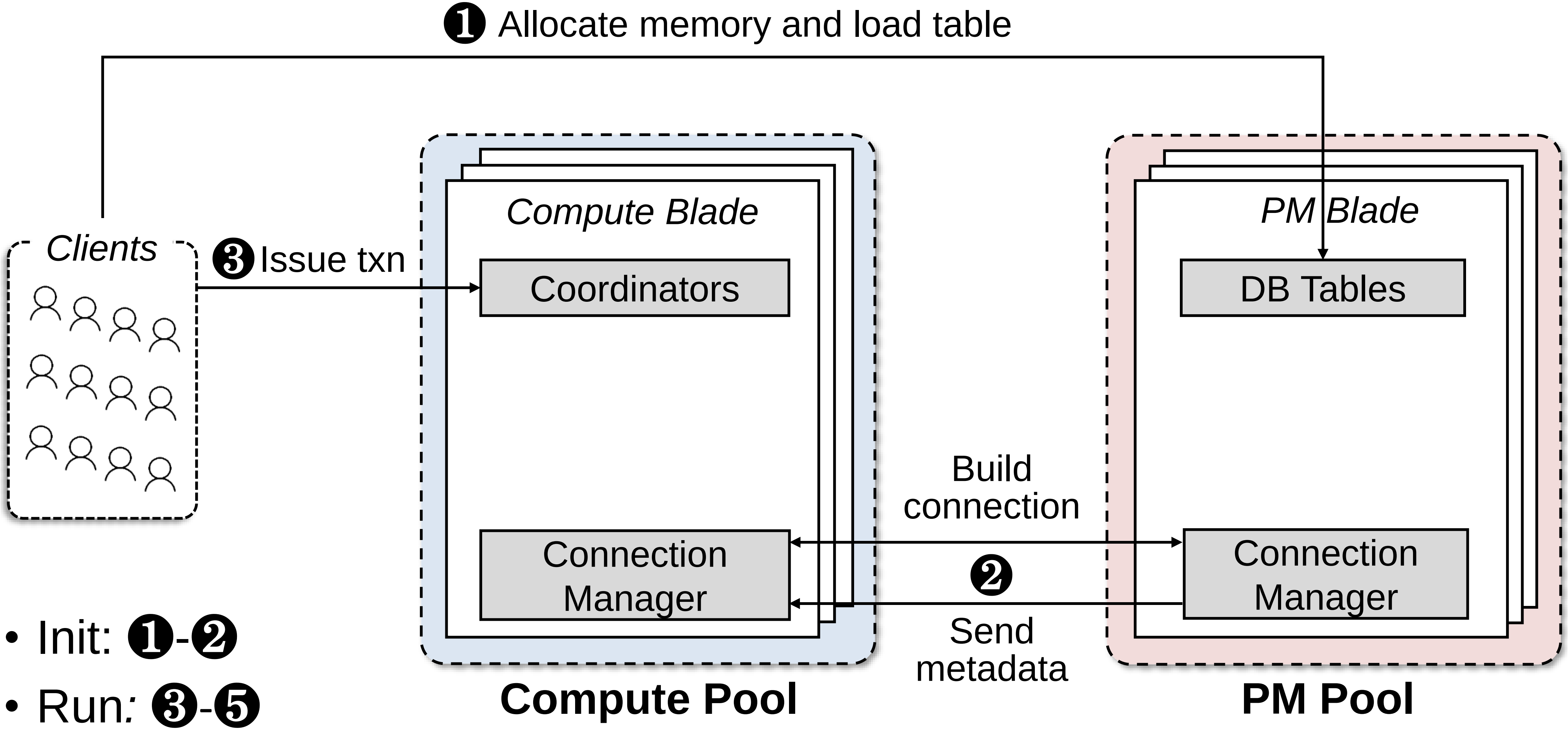

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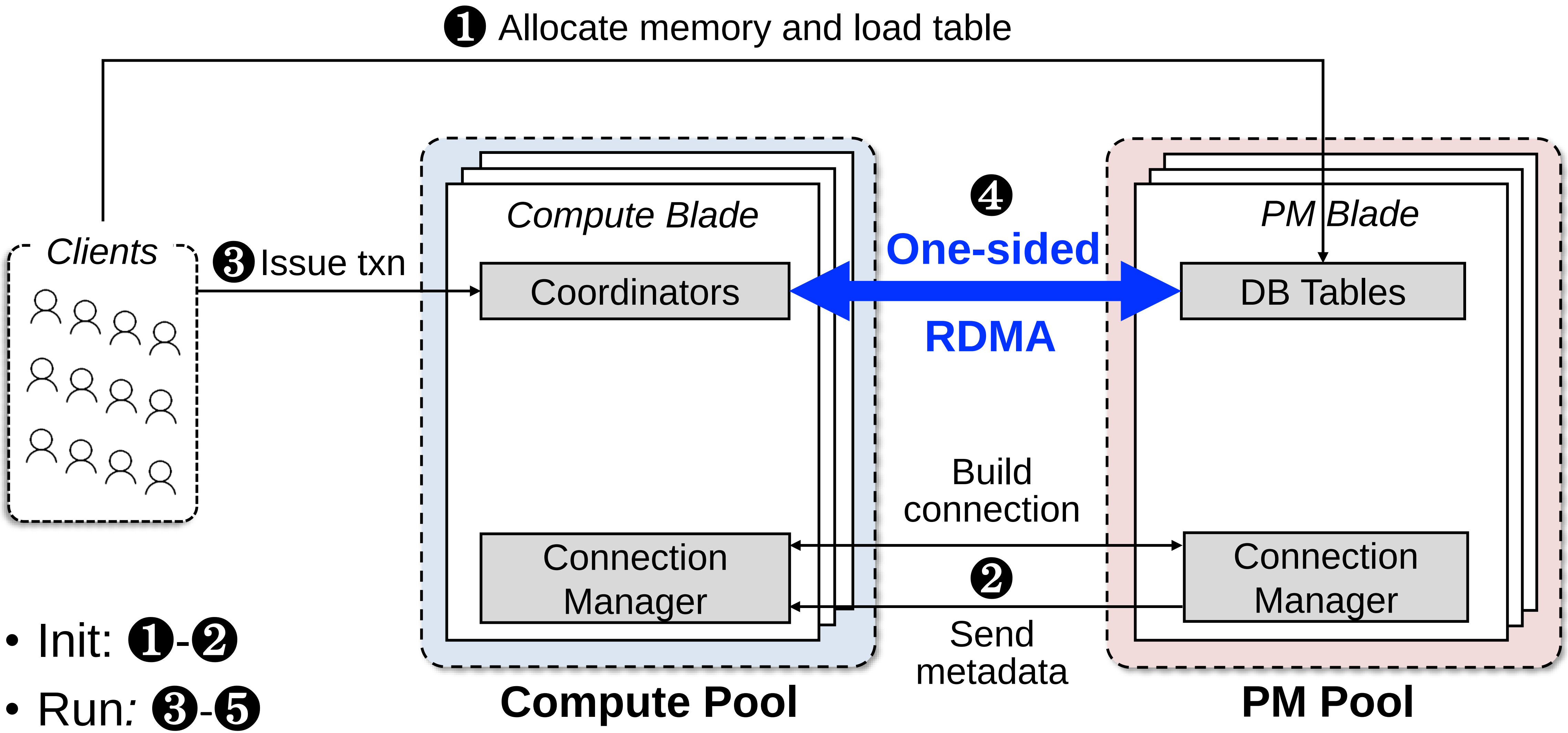
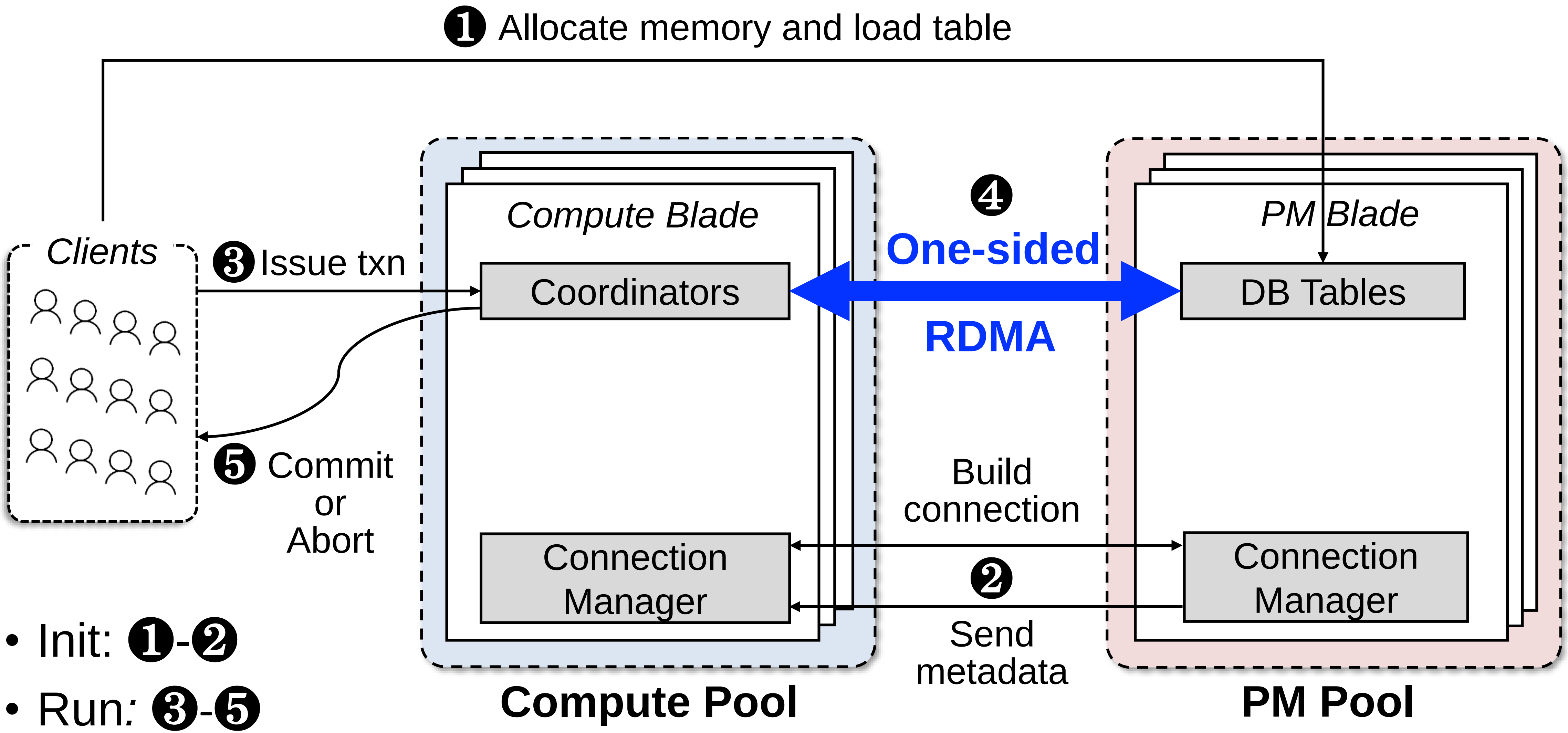
- Run: ❸-❺

Overview



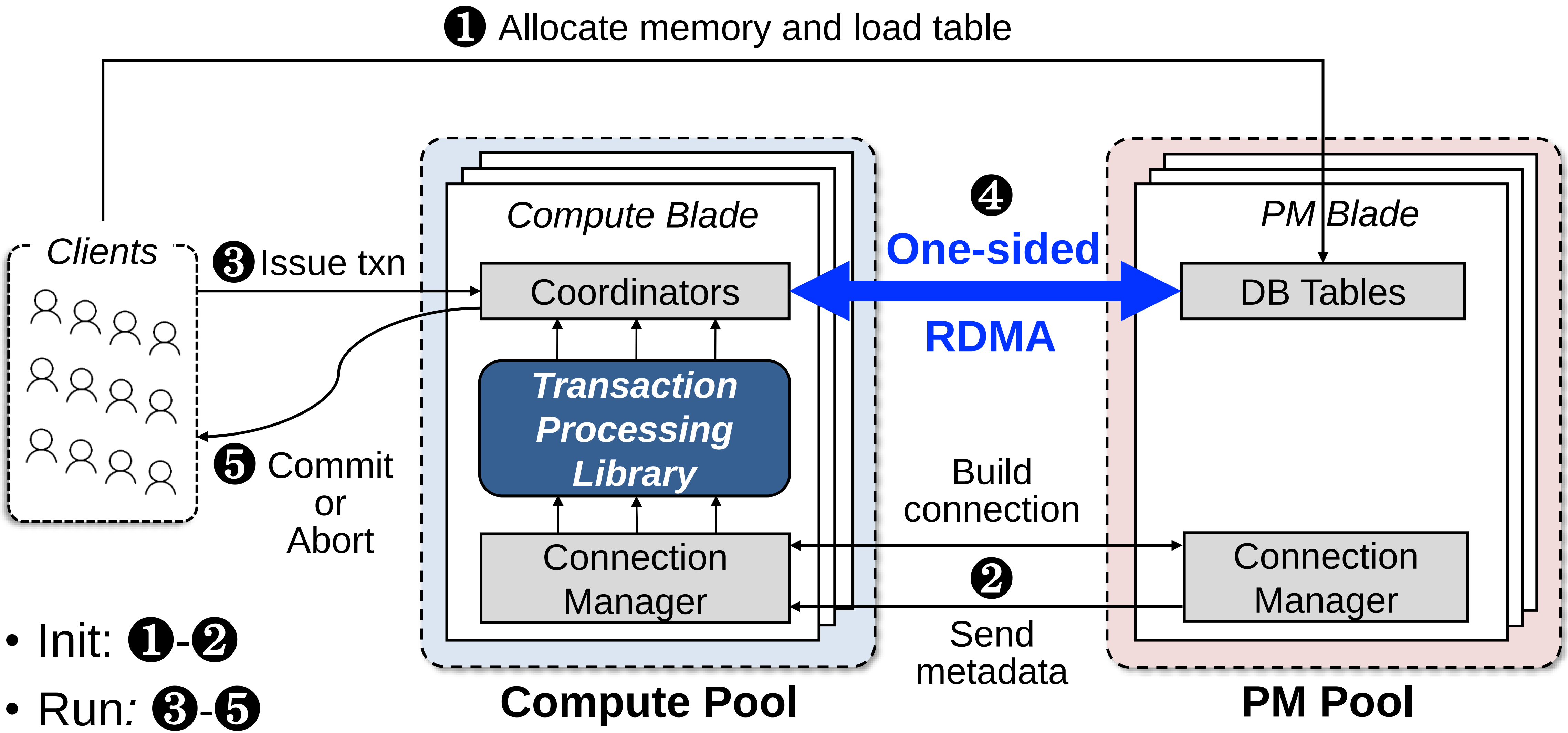
- Init: ❶-❷
- Run: ❸-❺

Overview



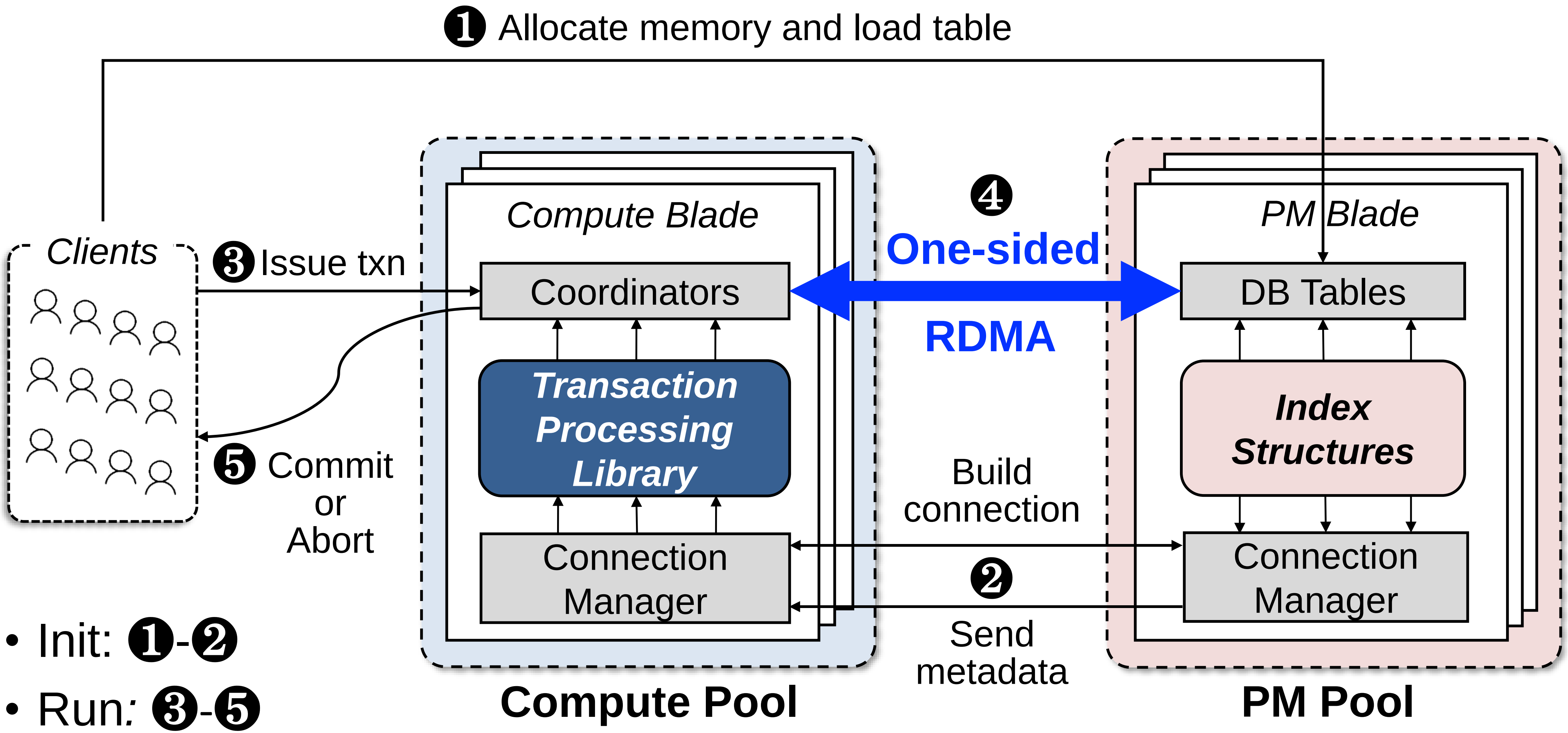
- Init: ❶-❷
- Run: ❸-❺

Overview



- Init: ❶-❷
- Run: ❸-❺

Overview



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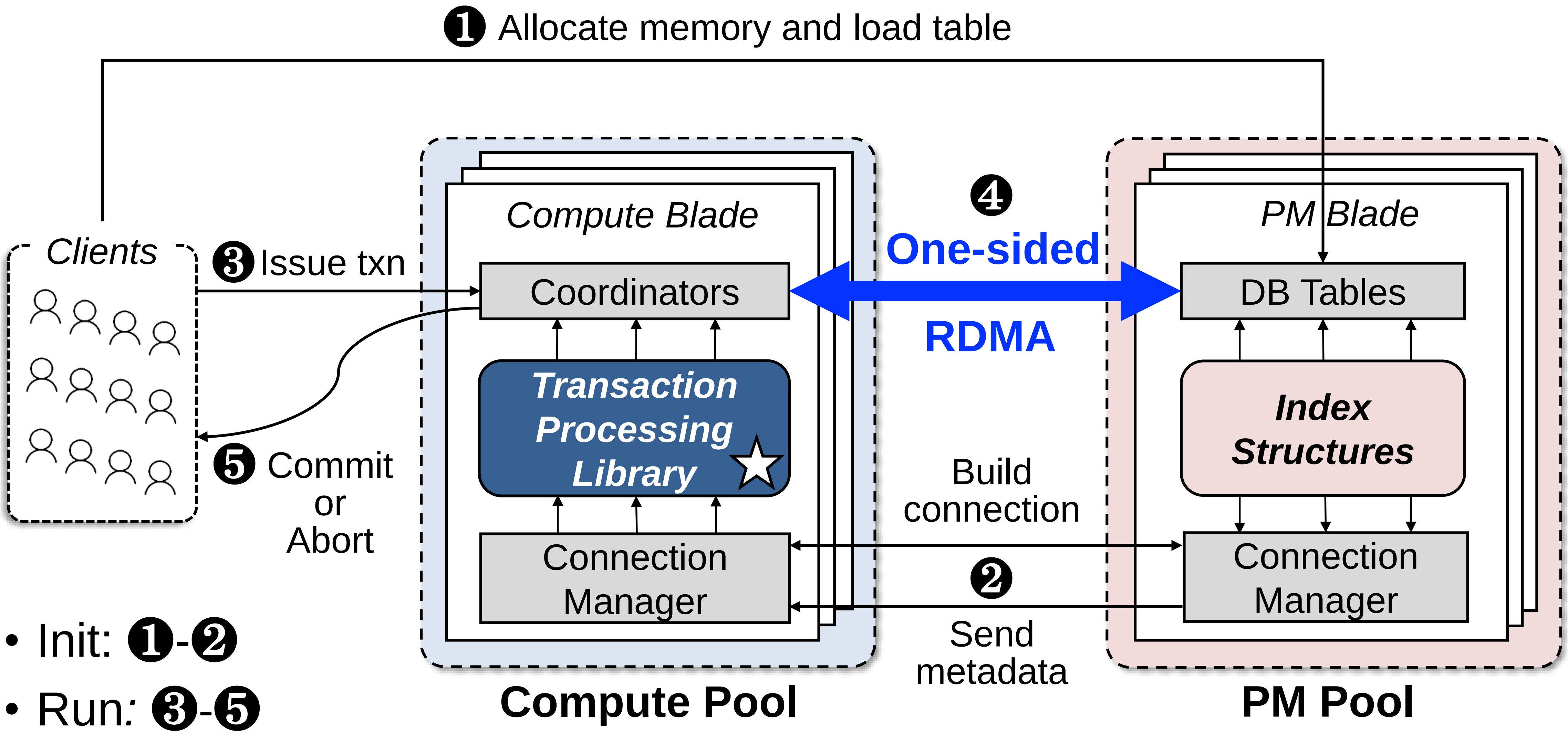
Overview



- Init: ❶-❷
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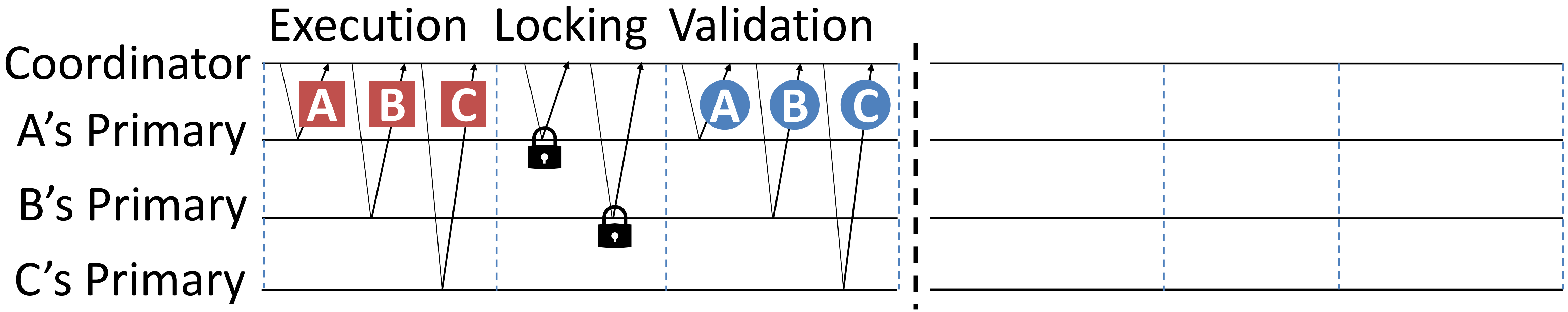
Hitchhiked Locking

- ➢ Read and lock the **read-write (RW) set** in execution
  - Avoid subsequent locking and validations
  - No lock on the read-only data



Txn begin
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Txn commit

RW set

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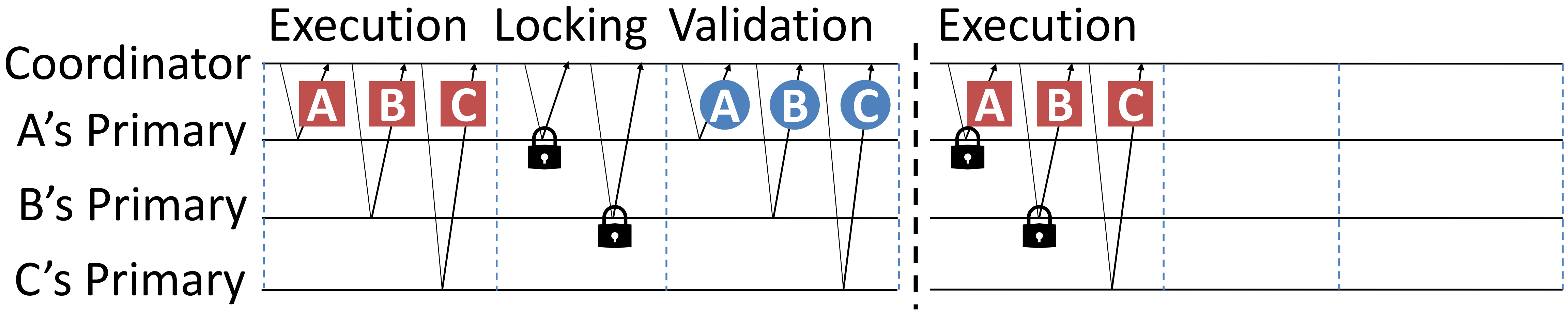

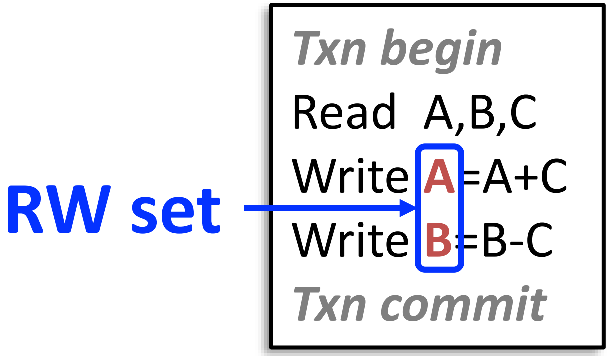

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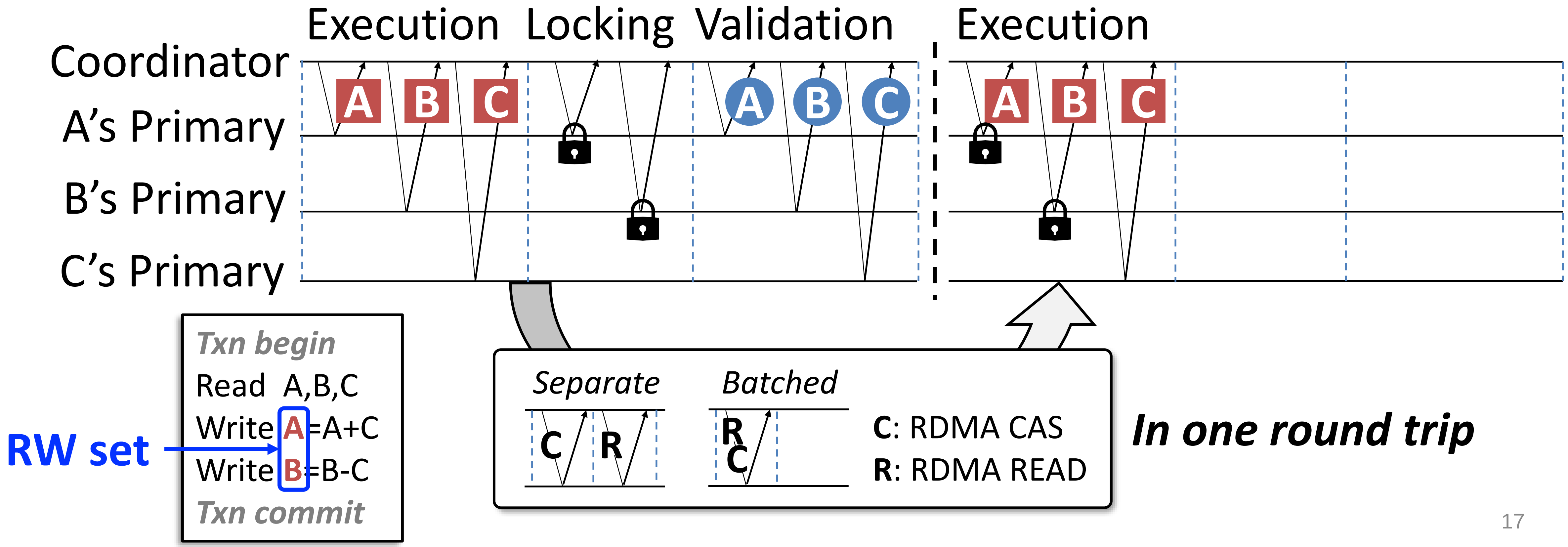

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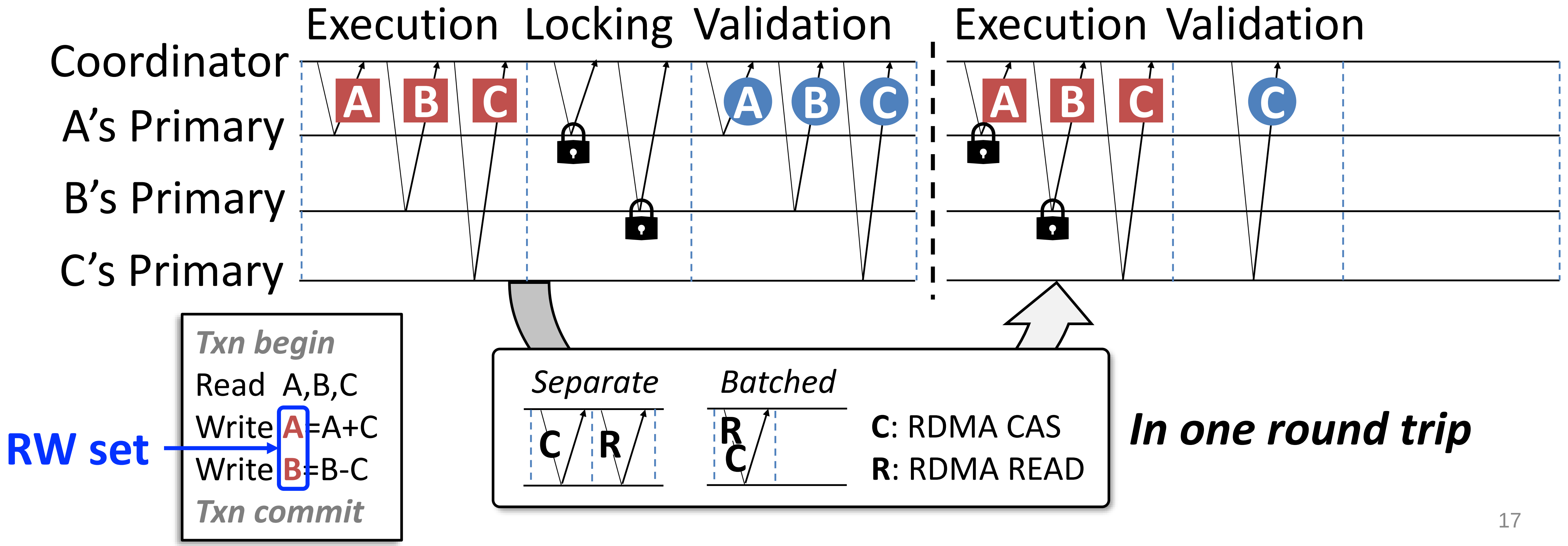

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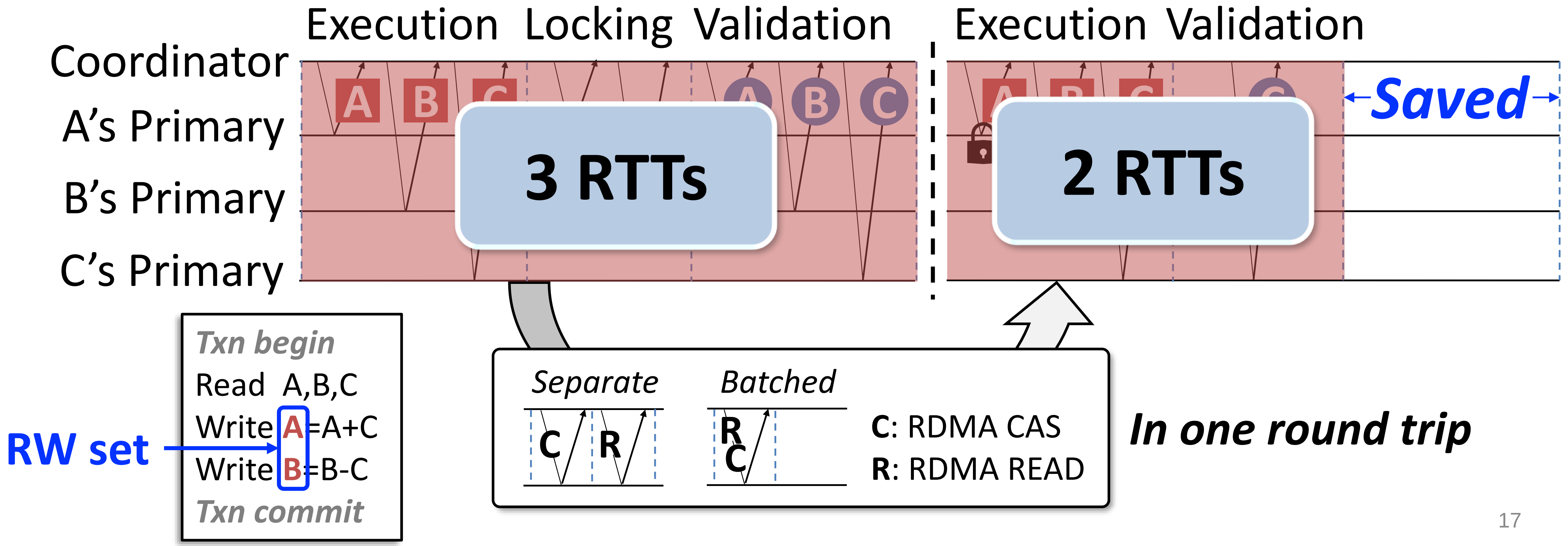
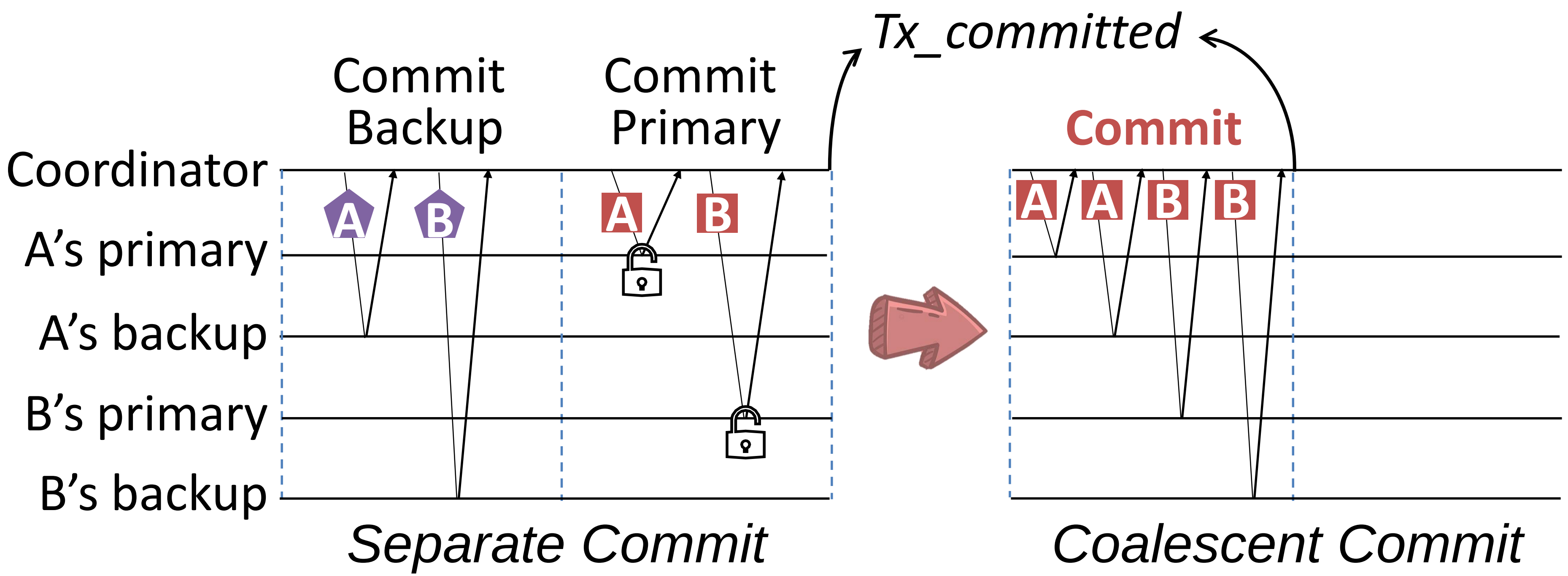


Coalescent Commit

➢ Commit all replicas **together** in one round trip

- In-place update: Parallel undo logging in execution phase
- Prevent reading partial updates: Control data visibility



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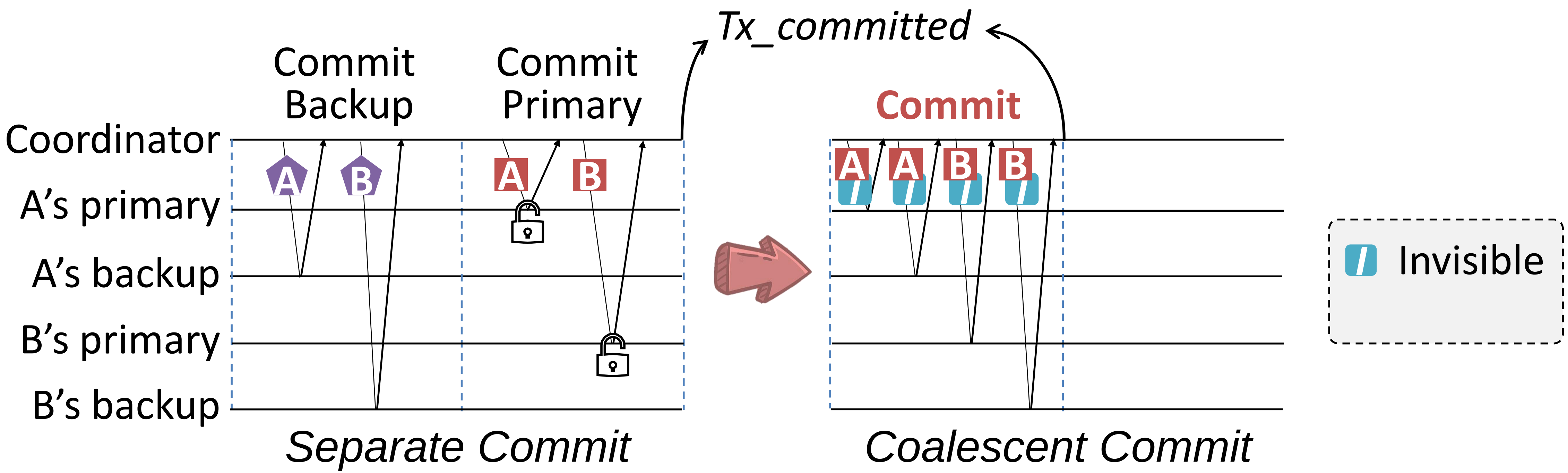

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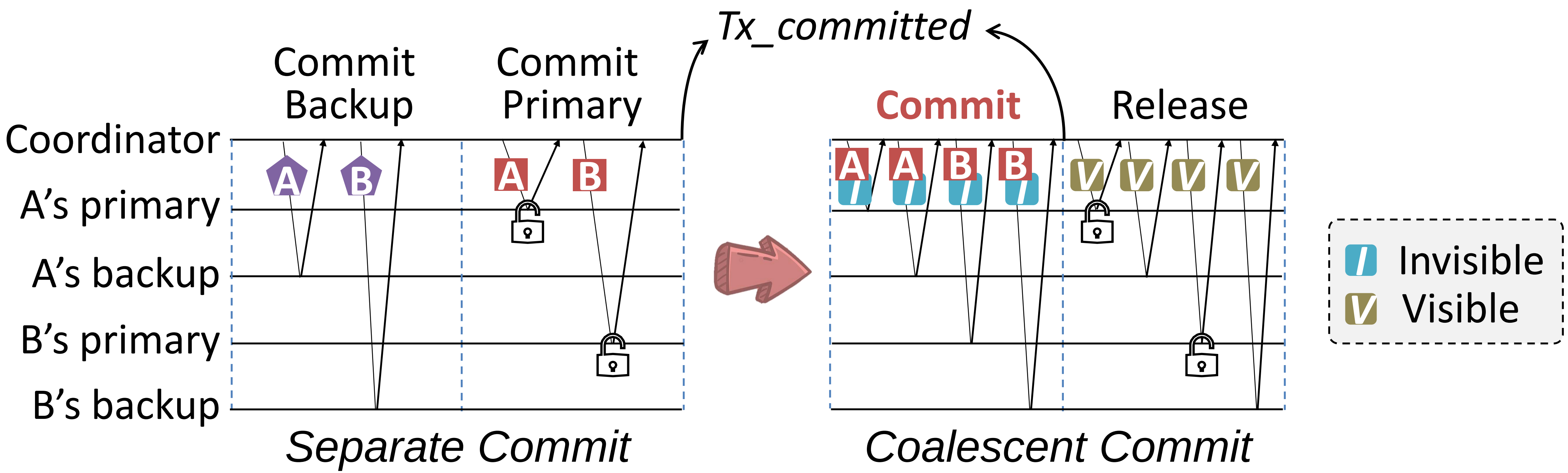

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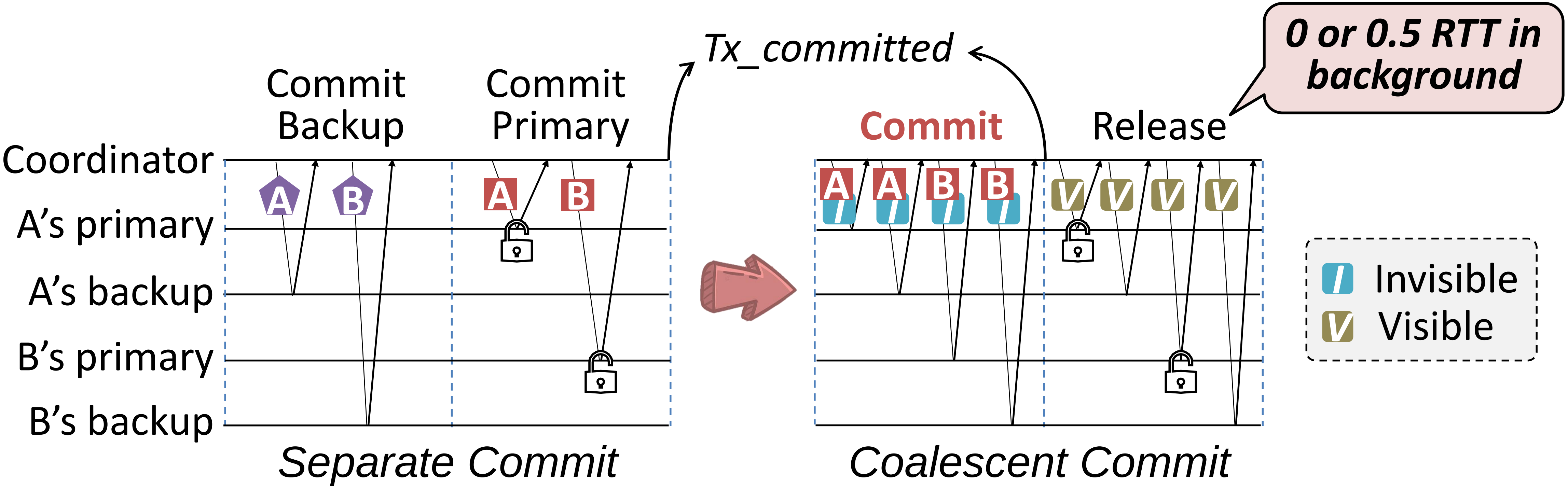

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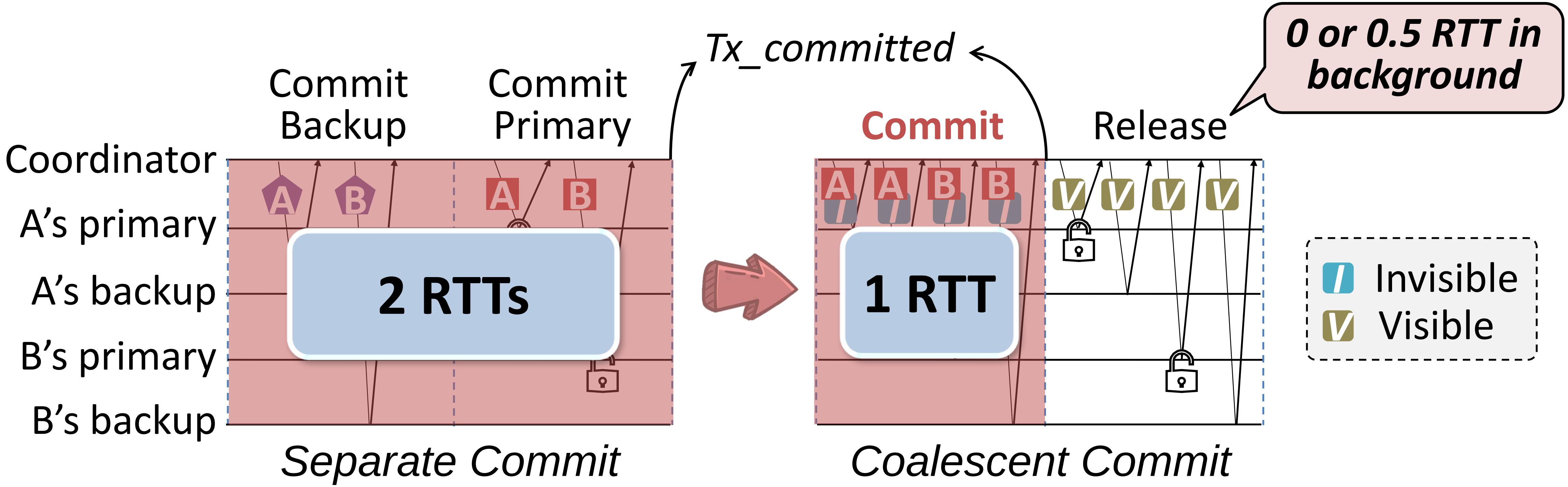
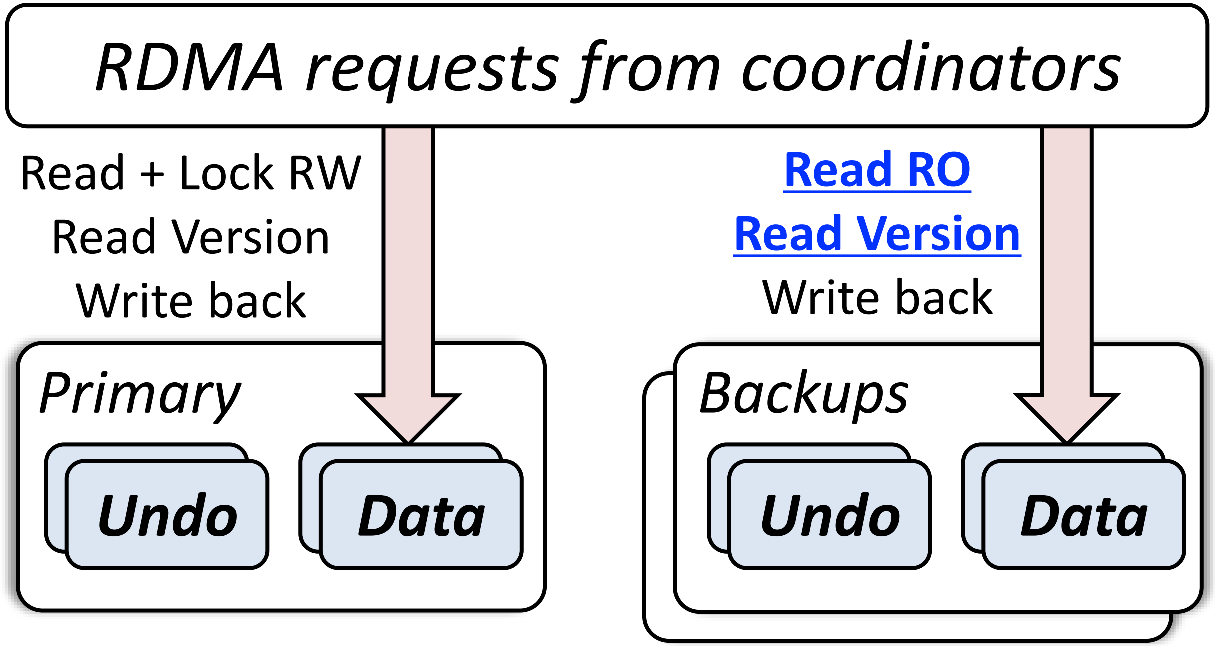


Backup-enabled Read

- Allows **backups** to serve **read-only (RO)** data
  - In-place update → No address redirection
  - Undo logging → No data migration → No CPU involvement in PM pool



Balance load → Improve throughput

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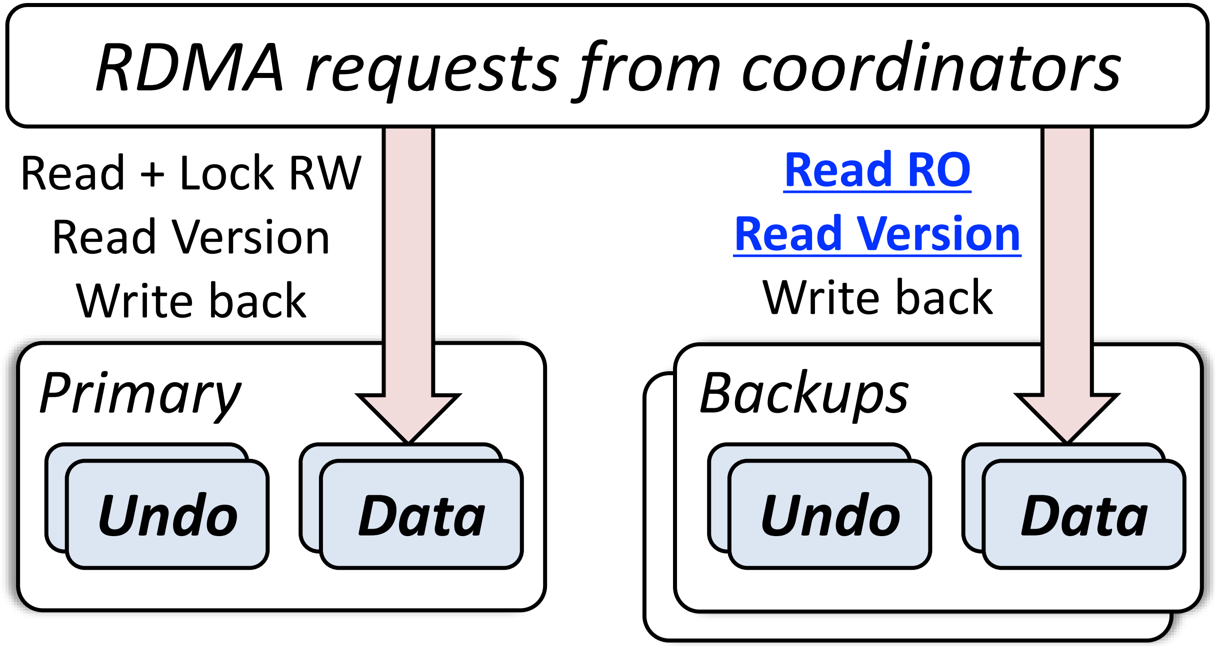

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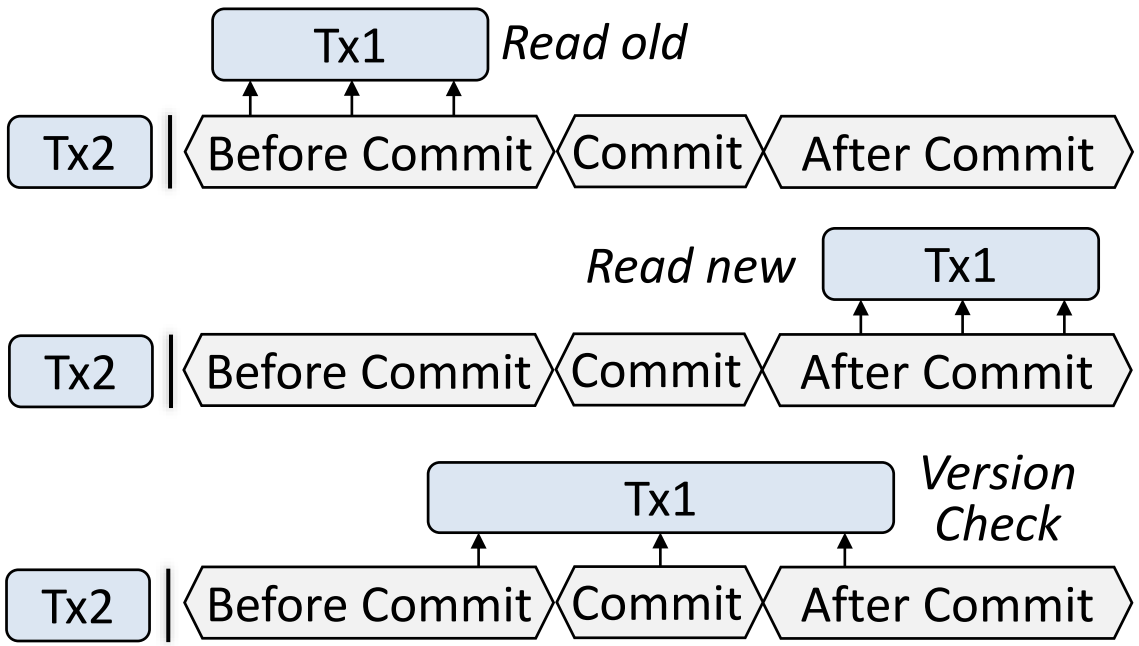

Correctness guarantee

Selective Remote Flush

- Only issue remote flushes to **<u>backups</u>** after the **<u>final</u>** write
  - Guarantee remote persistency
  - Ensure recoverability by backups
  - Reduce flushing round trips
  - Compatible with different flush primitives [1]

[1] One-sided RDMA **FLUSH** or **READ** (*READ-after-WRITE*)

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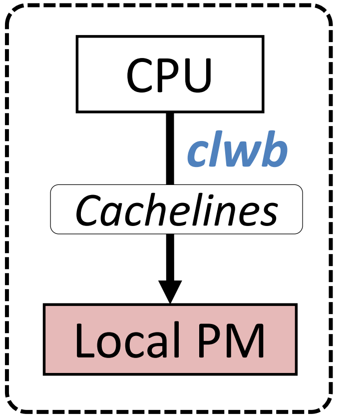

Single Node

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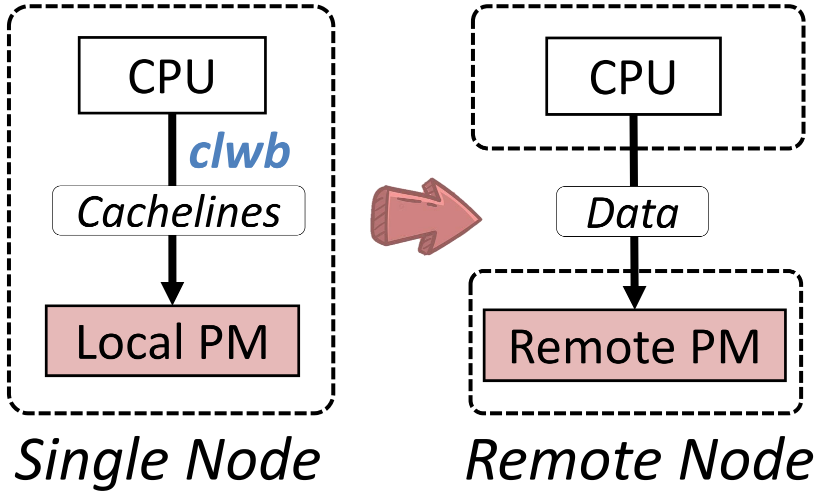

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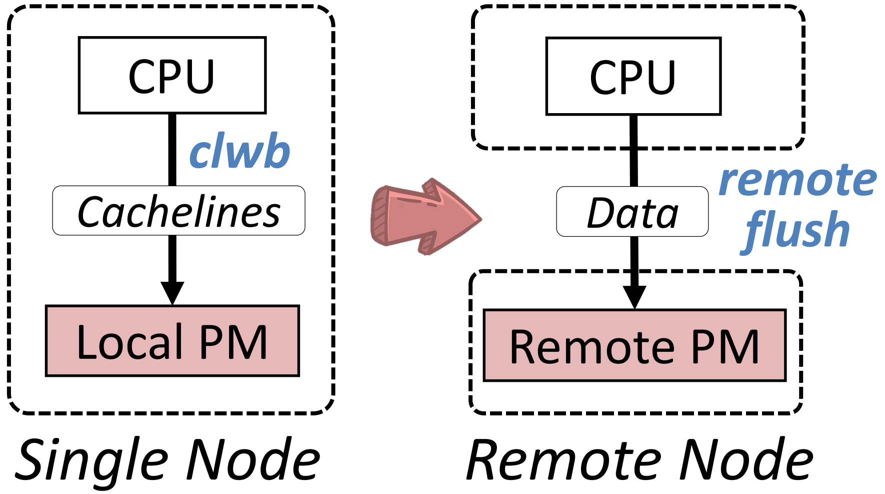

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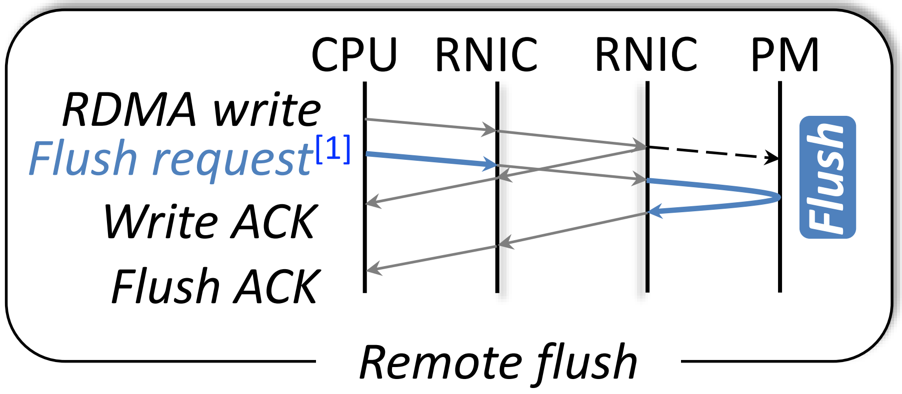

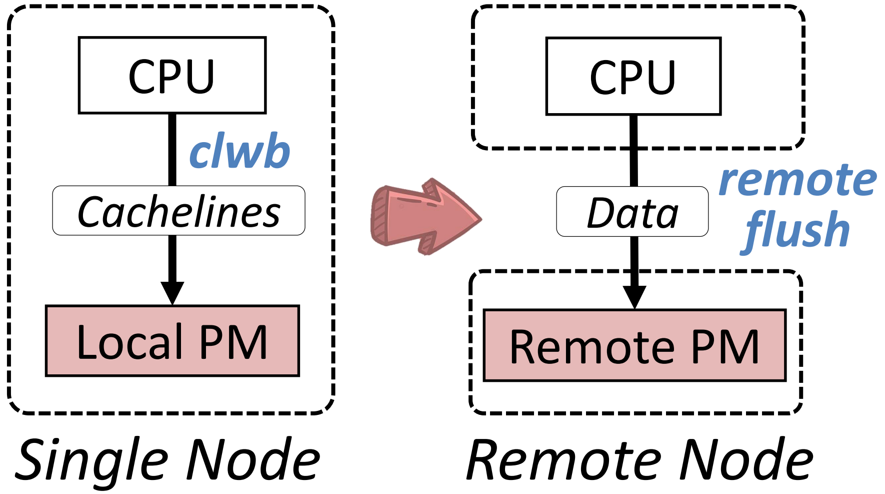

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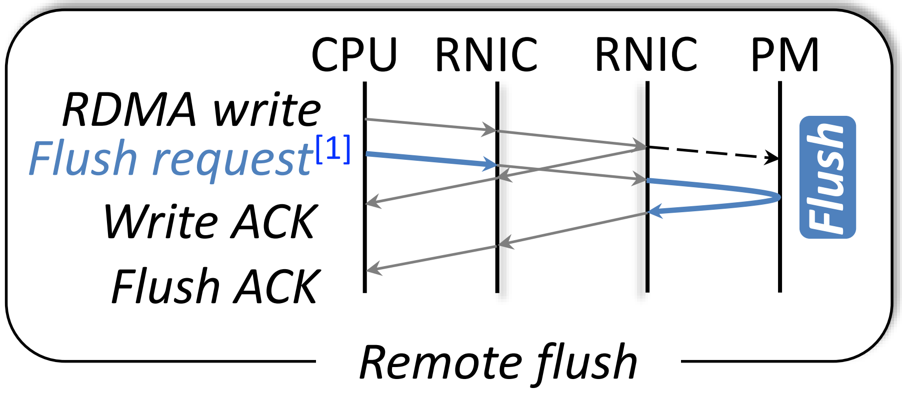

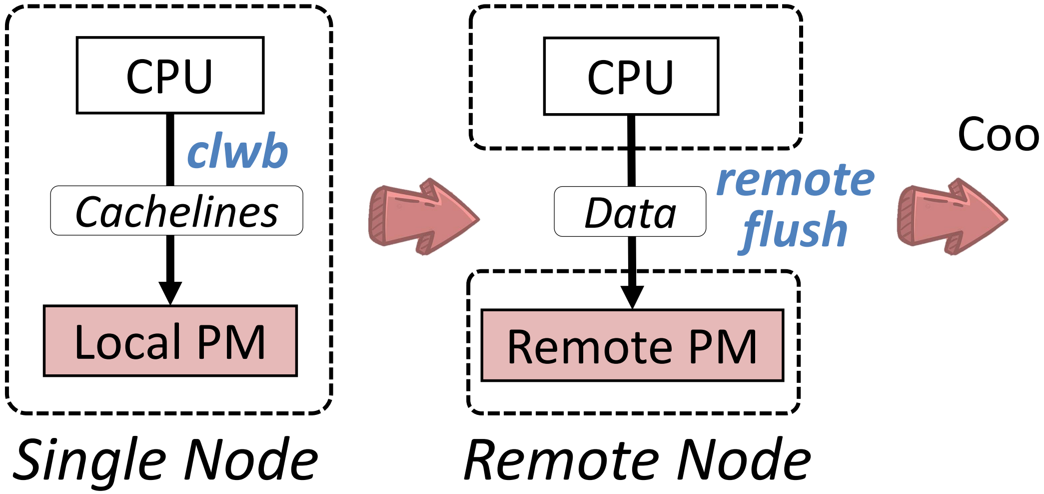

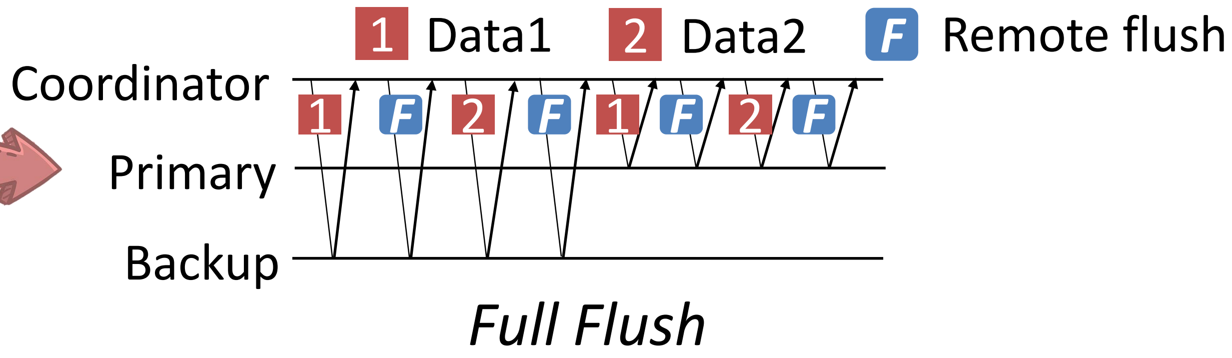

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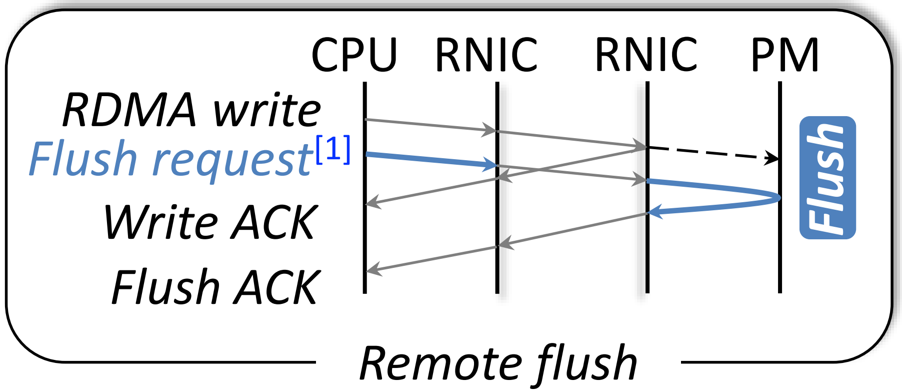

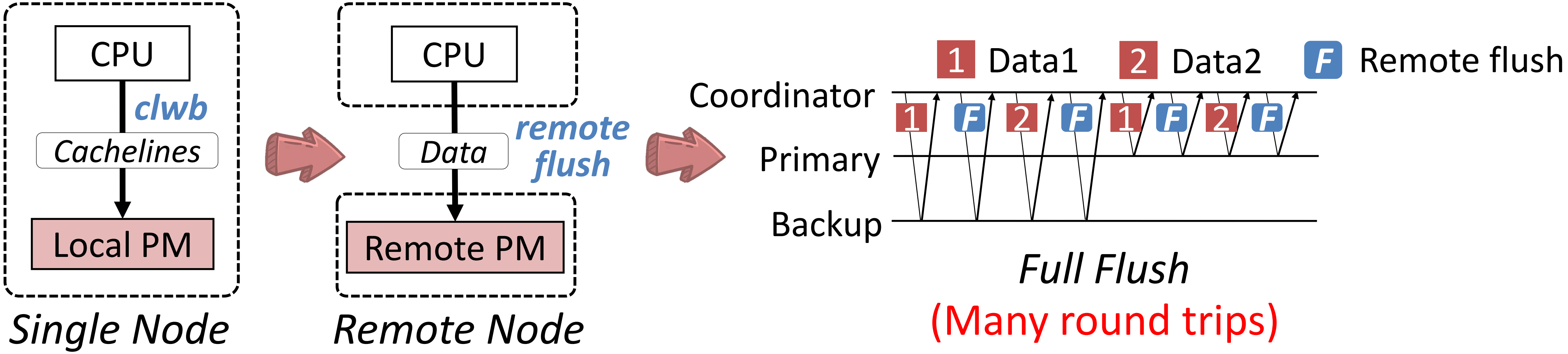

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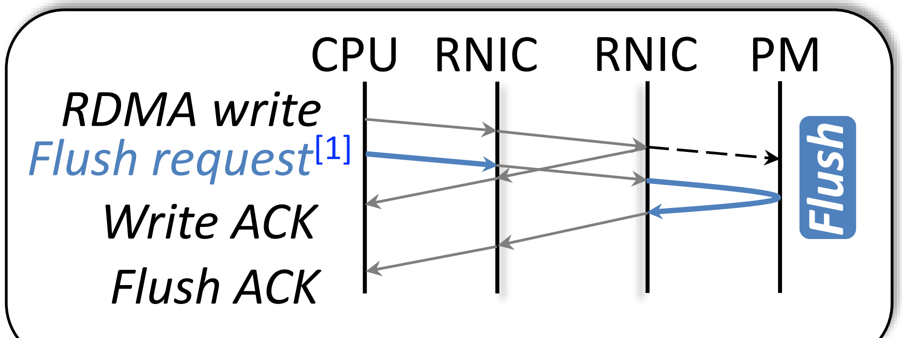
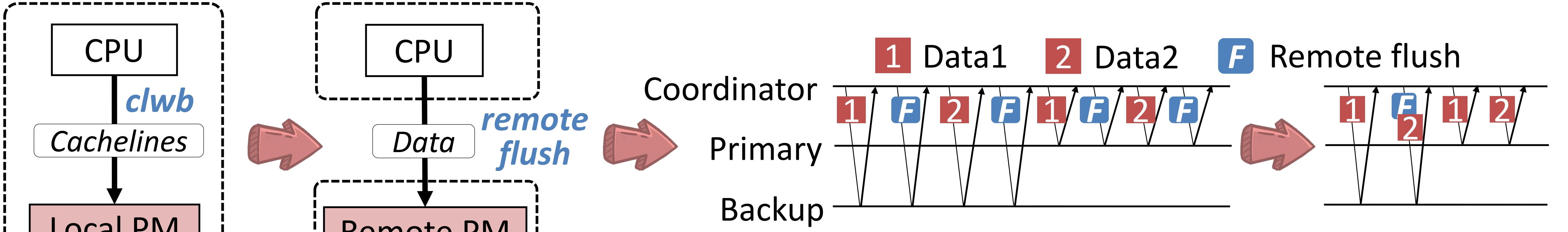


Remote flush



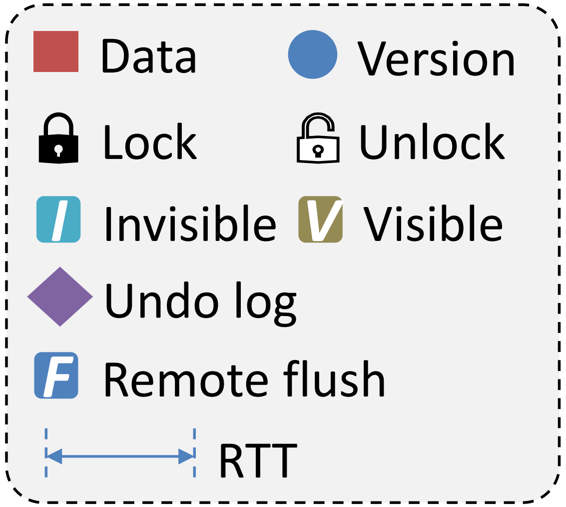
Single Node | Remote Node | Full Flush (Many round trips) | Selective Flush

[1] One-sided RDMA **FLUSH** or **READ** (*READ-after-WRITE*)

FORD Transaction

- **Put it all together:** One-sided RDMA and PM-conscious designs

Txn begin
Read A,B,C
Write A=A+C
Write B=B-C
Txn commit



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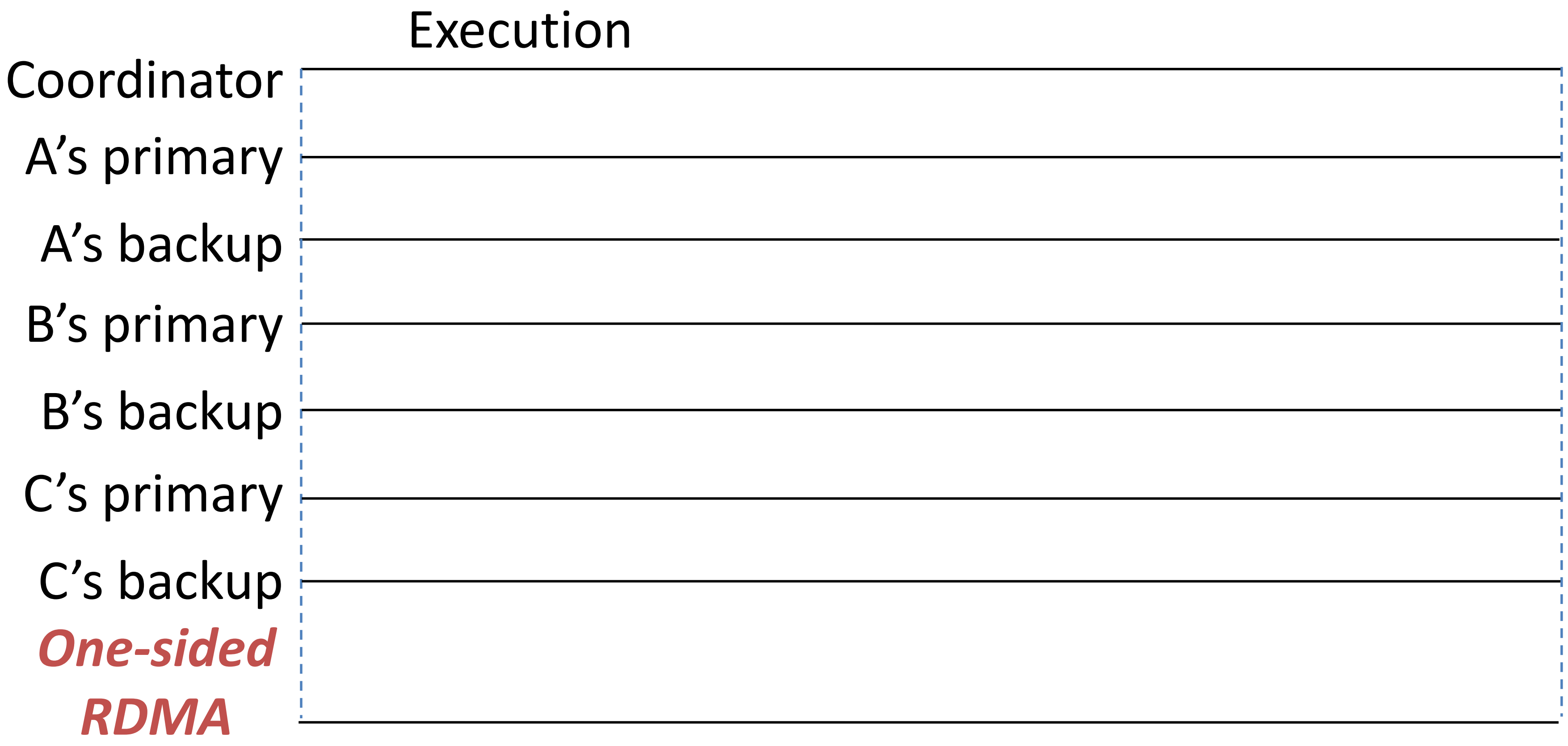

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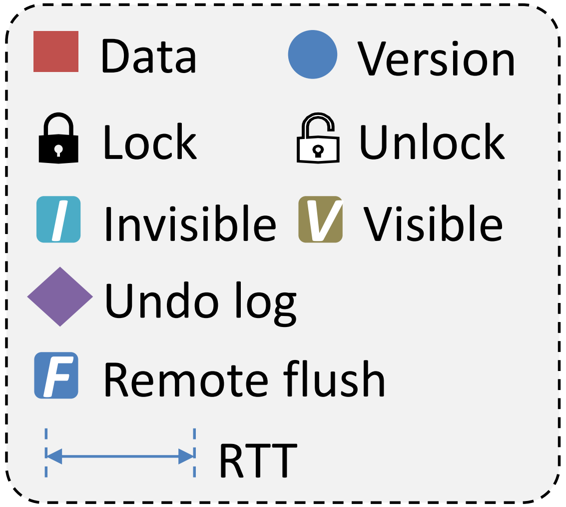

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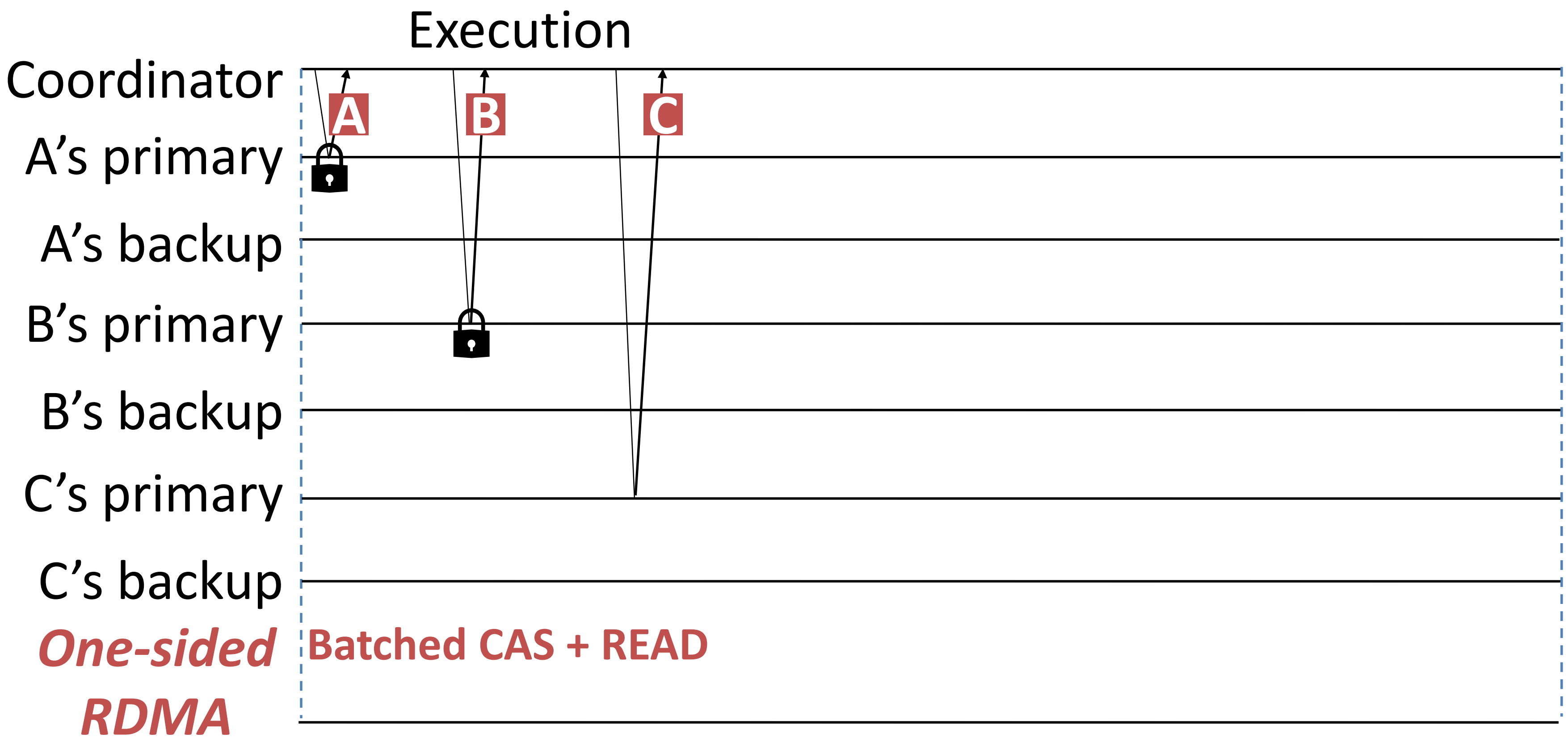

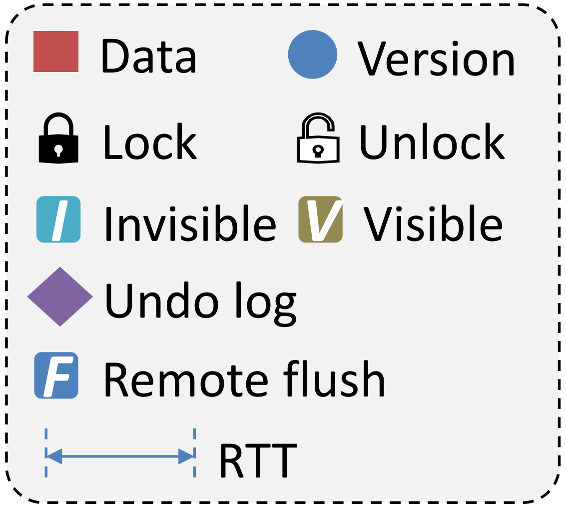

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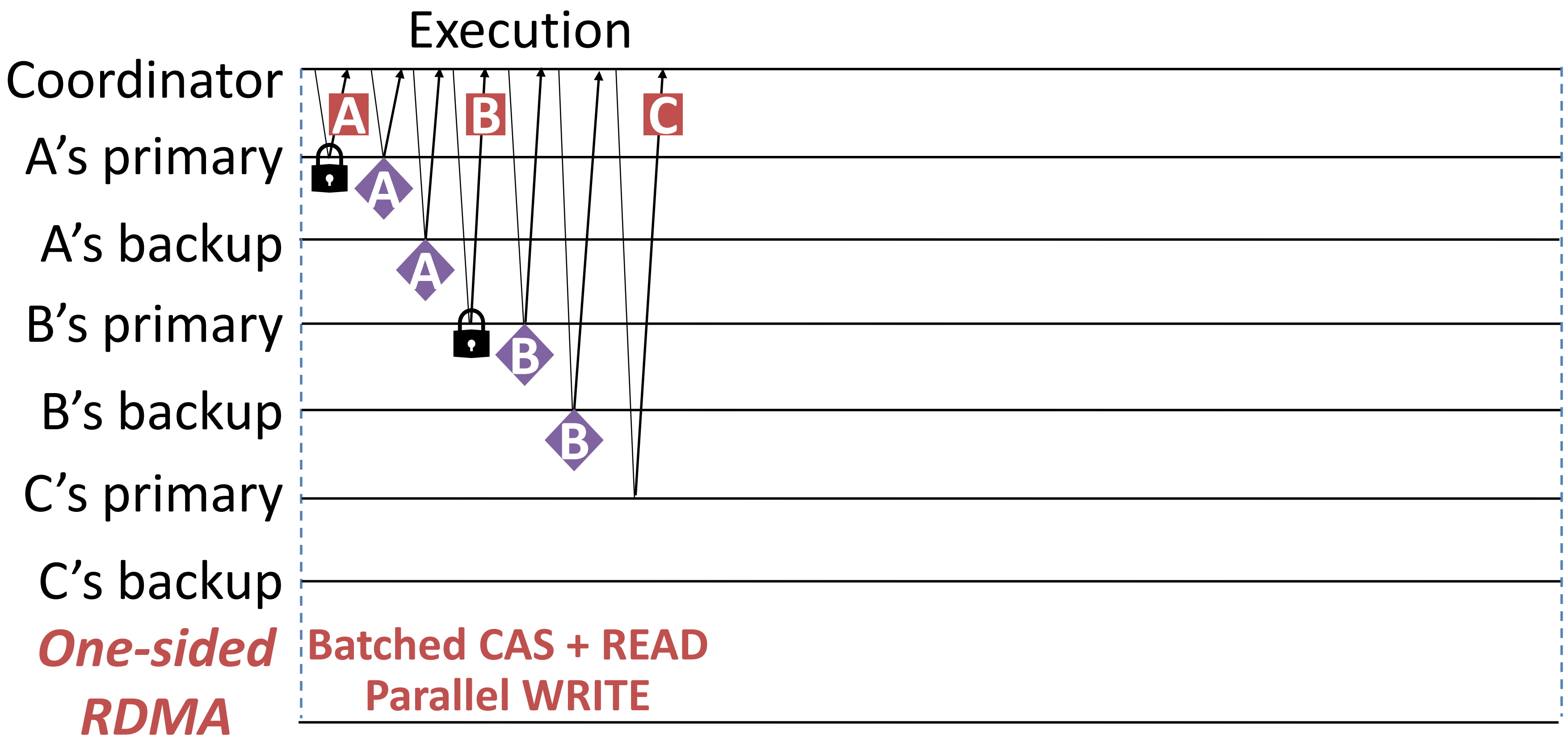

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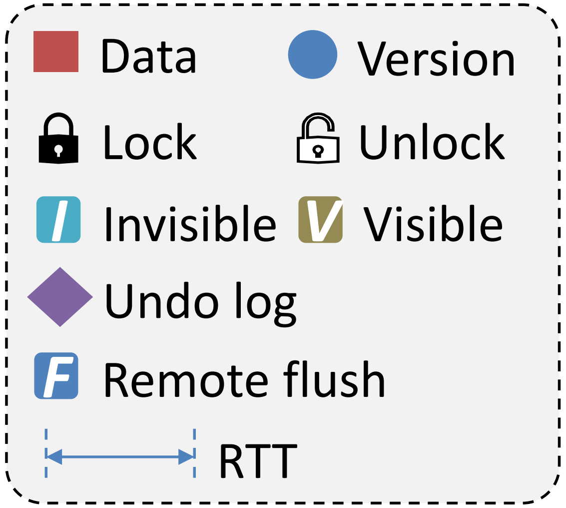

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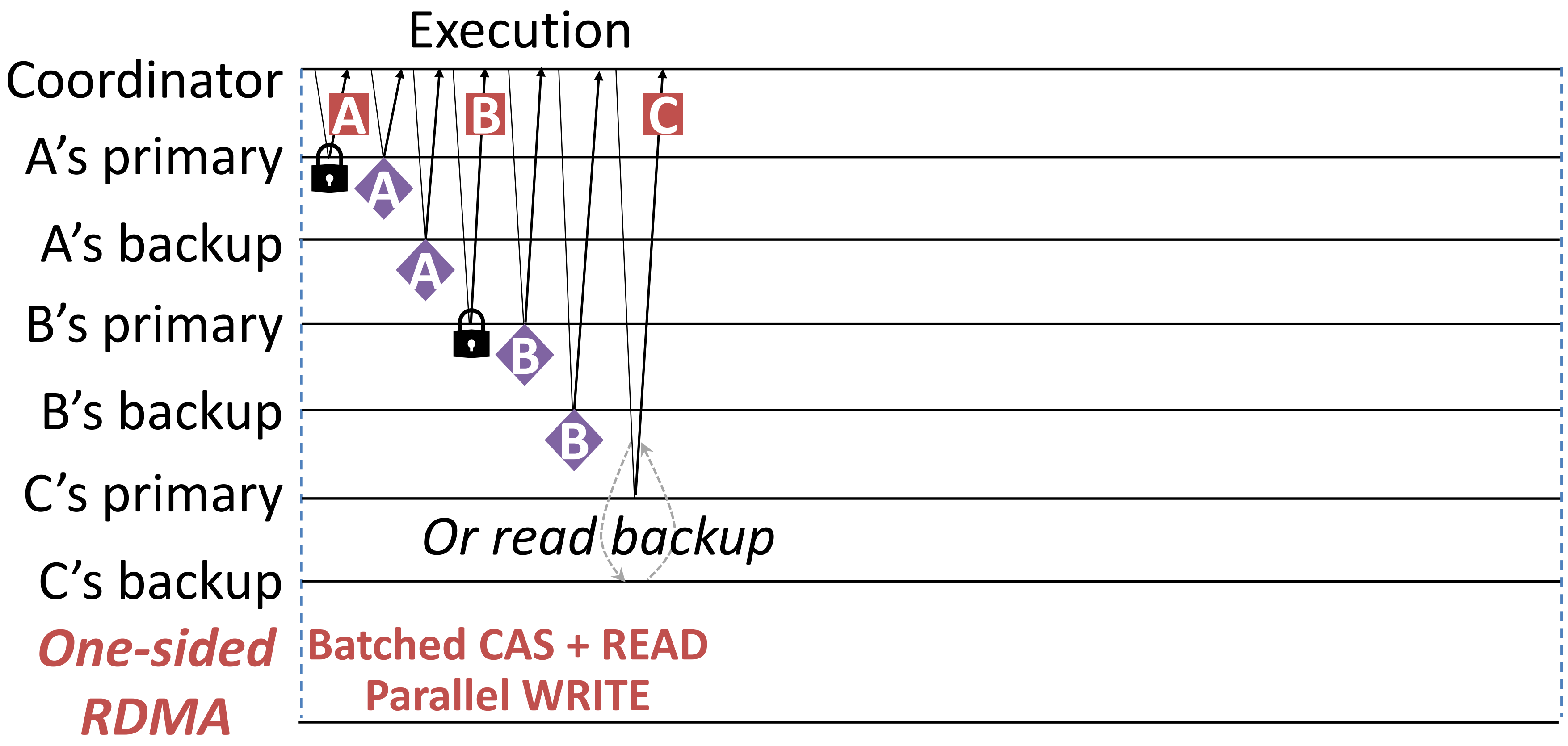

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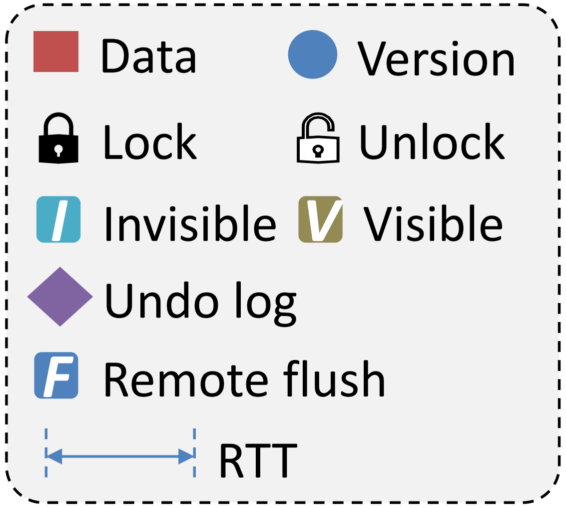

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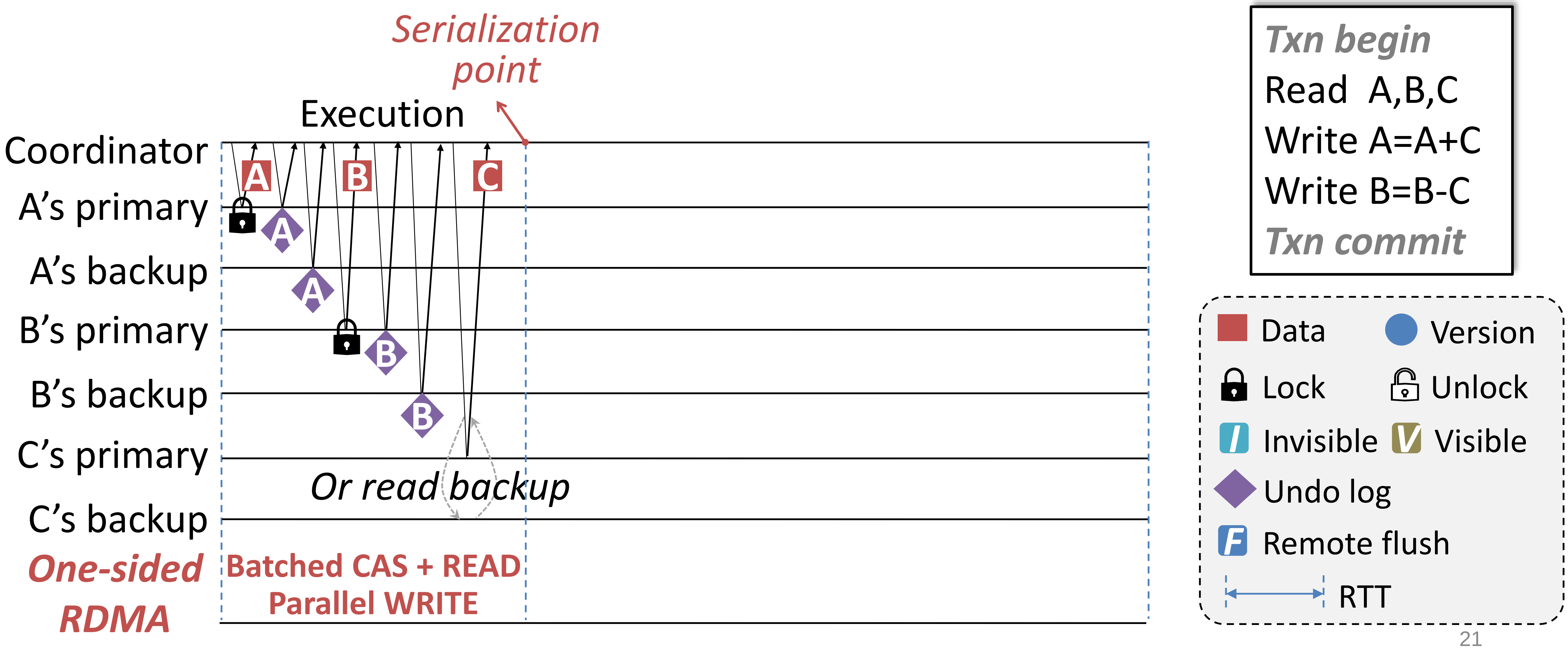

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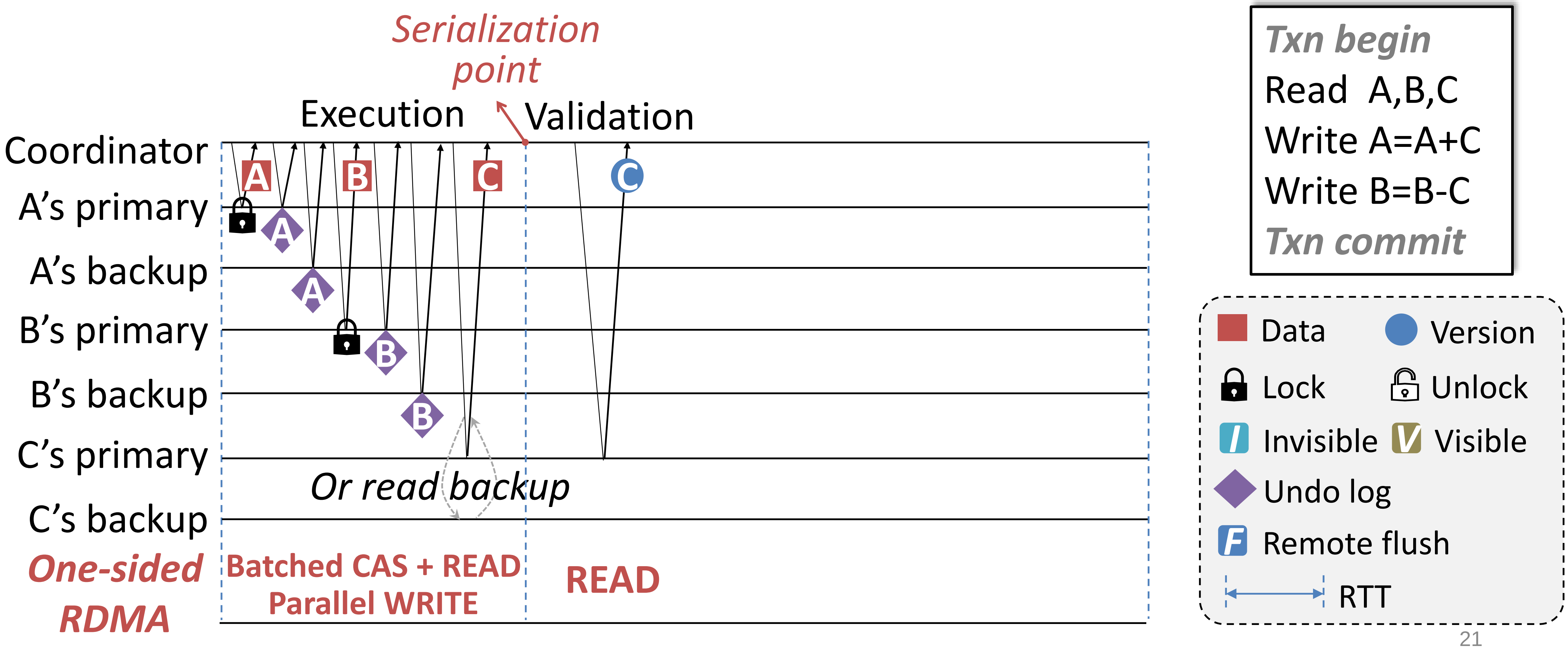

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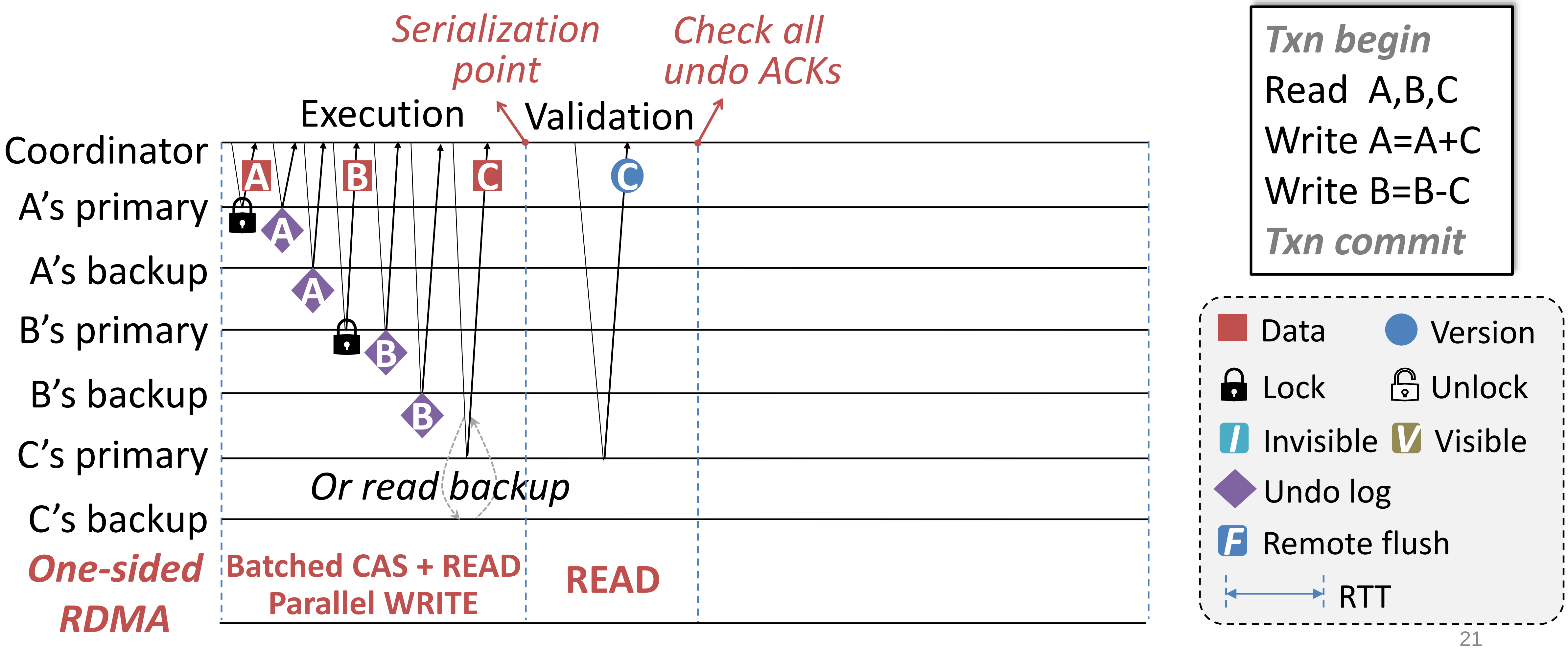

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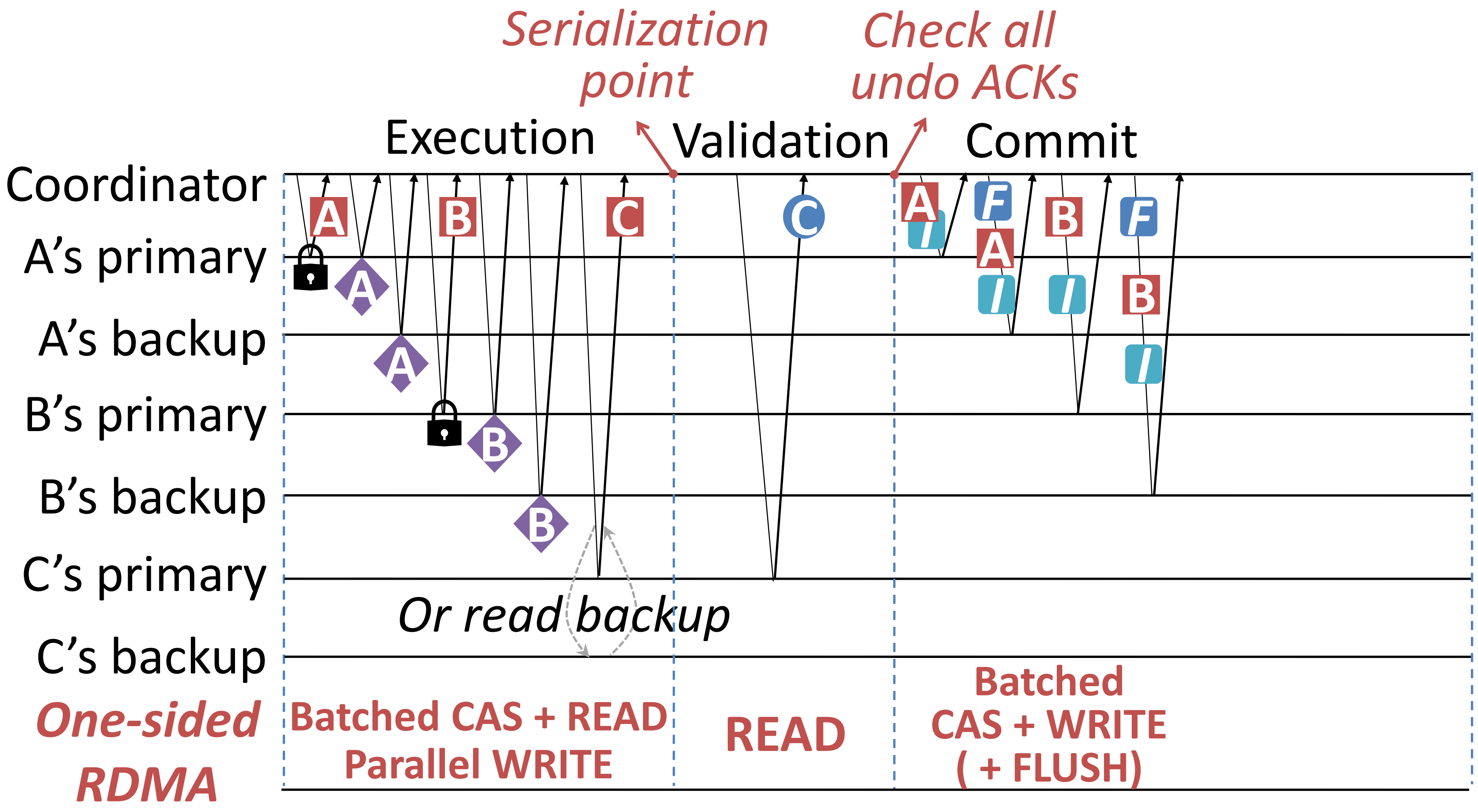

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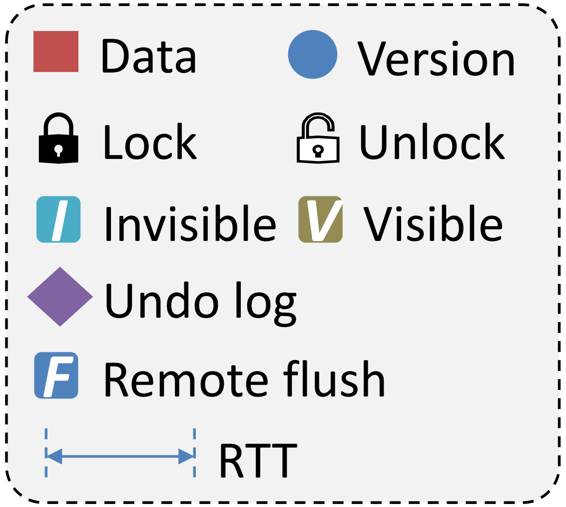

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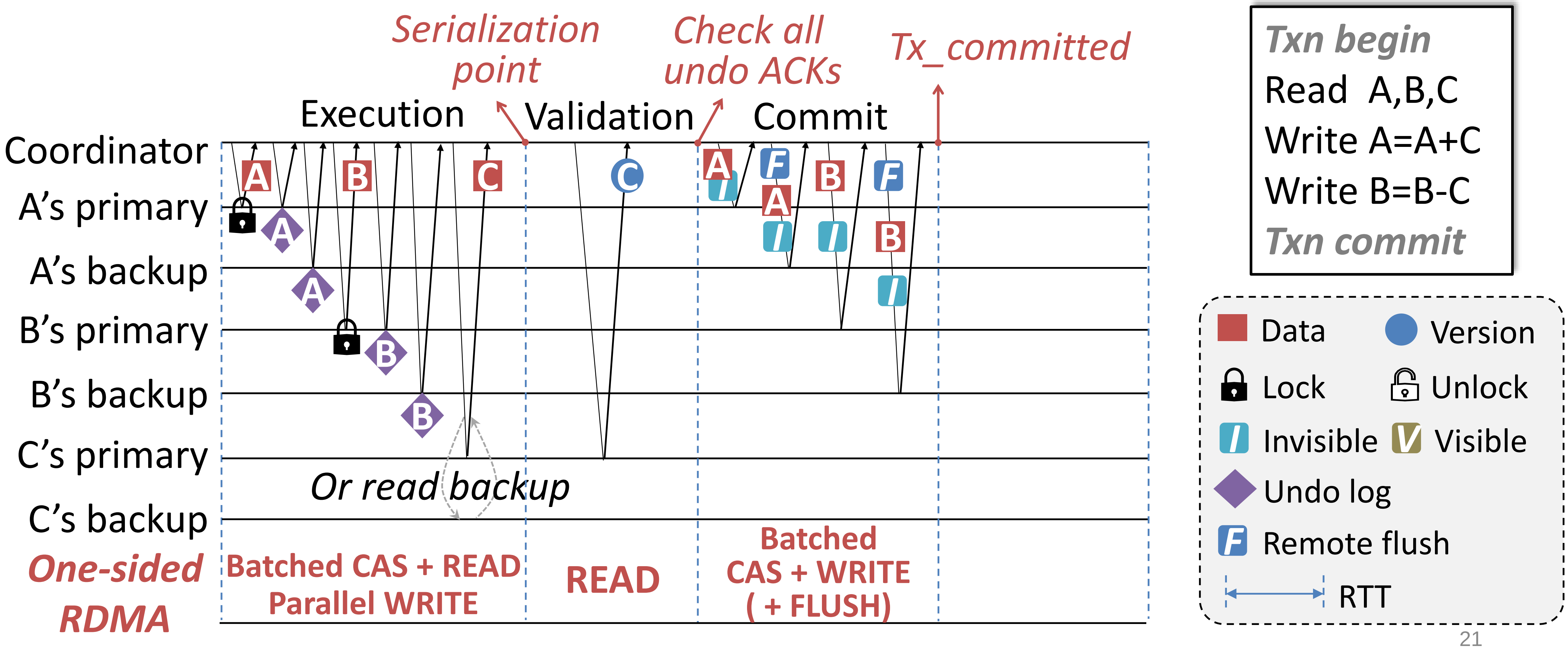

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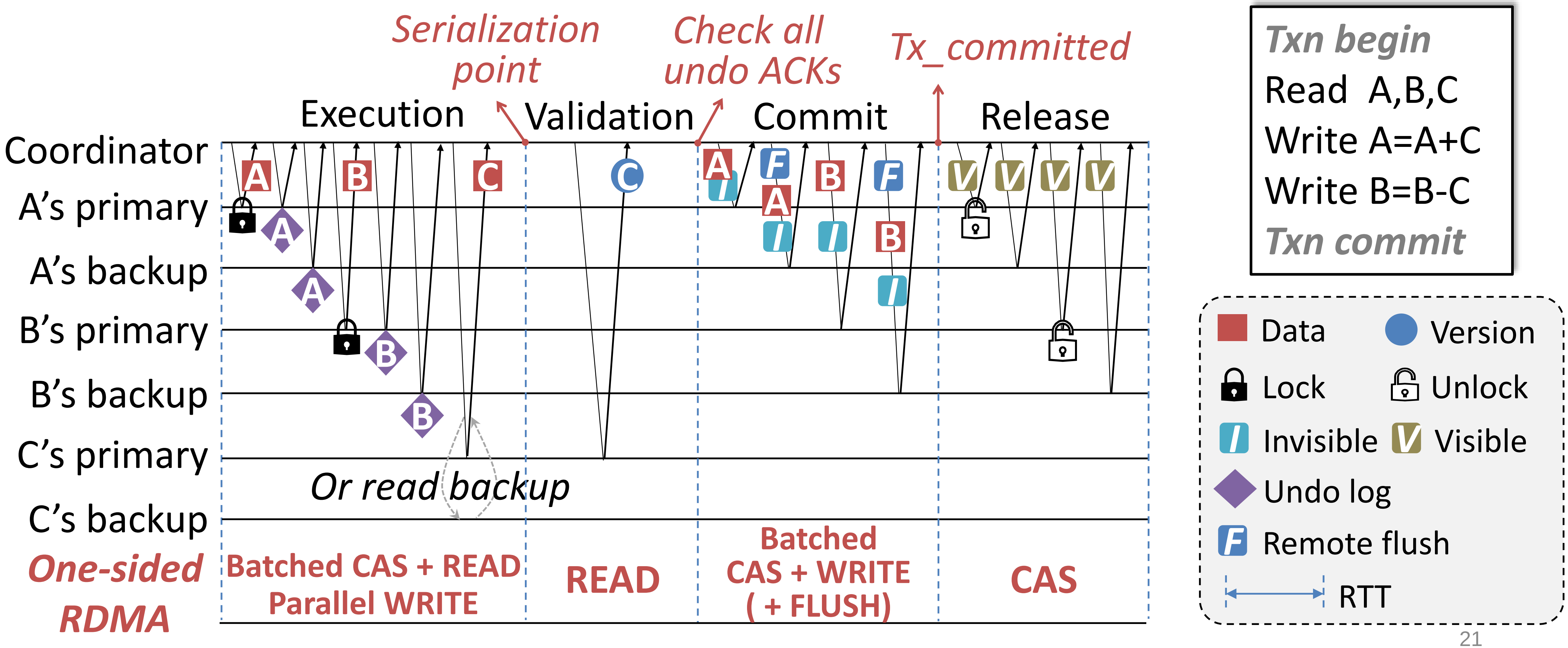

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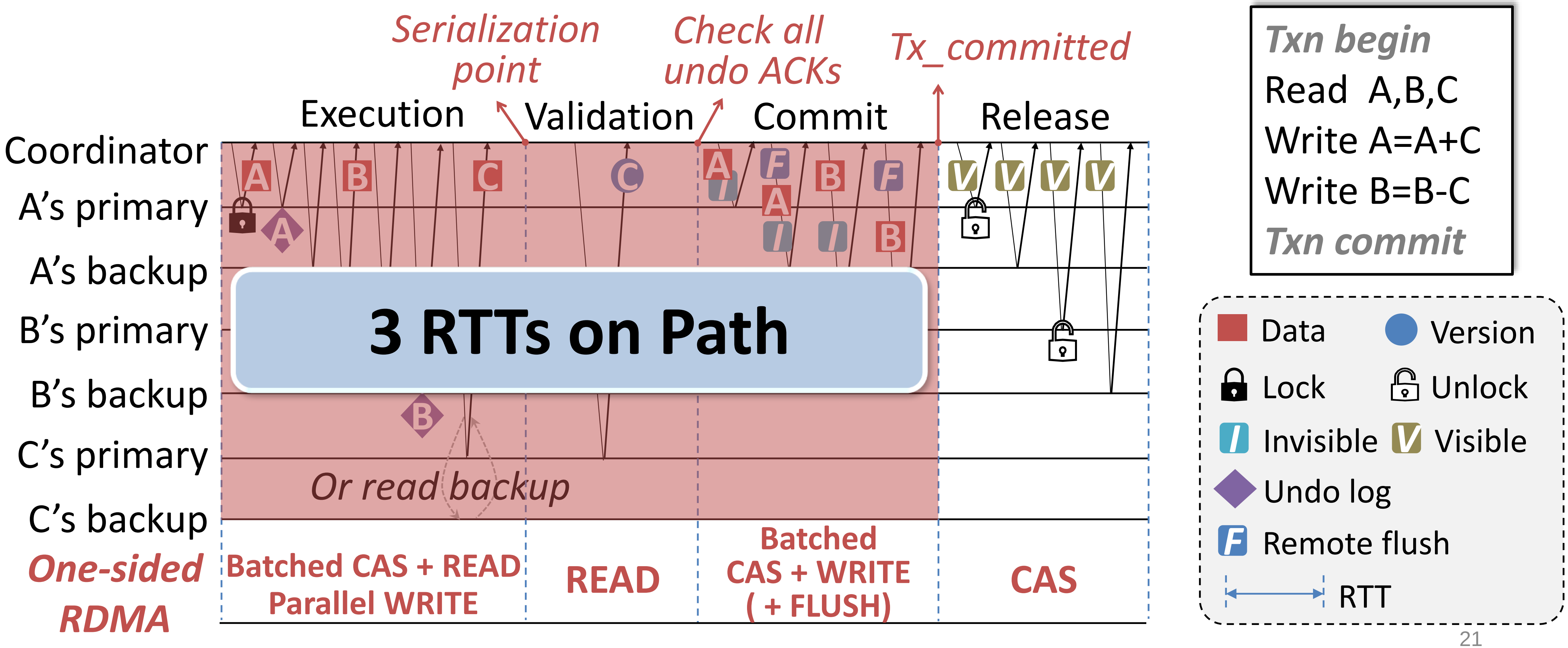


More Details

- ➢ Programming Interface
- ➢ Indexes in PM Pool
- ➢ Analysis on ACID and Serializability
- ➢ …

Figure 8: The hash table structure in FStore.

To enable coordinators to calculate remote addresses for one-sided RDMA in dtxn processing, the connection manager in PM pool sends the metadata (as listed below) of each hash table to the compute pool during network interconnections.

- `TableID` (8B): Global unique database table id.
- `Addr` (8B): Virtual start address of this hash table.
- `Off` (8B): Offset between `Addr` and MR's start address.
- `BucketNum` (8B): Bucket number of the hash table.
- `BucketSize` (4B): Size of a bucket (in bytes).
- `SlotNum` (4B): Number of slots per bucket.

Given the key (e.g., `K0`) of a record, if its remote address is buffered in the local cache, the coordinator directly reads the record using an RDMA `READ`. Otherwise, the coordinator reads a remote record as the following Steps:

S1: Calculate the bucket id:
`bucket_id = Hash(K0) mod BucketNum`
S2: Calculate the bucket offset in the remote MR:
`bucket_off = bucket_id × BucketSize + Off`
S3: Read the remote bucket (*bkt*) using `bucket_off`.
S4: Compare `K0` with the `SlotNum` keys in *bkt*. If a key = `K0`, the record is obtained. Then go to S7. Or else go to S5.
S5: If the `next` field of *bkt* is `NULL`, there is no such remote record. Then go to S8. Or else go to S6.
S6: Calculate the next bucket offset as below and go to S3.
`bucket_off = bkt.next − Addr + Off`
S7: Exit if the record is visible. Or else re-read it until visible.
S8: Exit with a `KEY_NOT_EXIST` hint.

Since the metadata size of a hash table is only 40B and each remote address is 8B, the local cache in compute pool can buffer all these metadata and addresses, as shown in Fig. 15b. Caching metadata is scalable, because the compute blades do not need to synchronize their metadata with each other: 1) The metadata of index does not change. 2) If the cached addresses are stale, FORD enables the coordinator to detect this and update its own cached addresses, as discussed in § 3.2.

4.2 Transaction Interfaces

FORD provides a runtime library, called *FLib*, for applications to process dtxns. Flib exposes the following interfaces:

- `TxBegin`: Start to execute a dtxn and record its id.
- `AddRO`: Add an initialized FObj to the read-only set.
- `AddRW`: Add an initialized FObj to the read-write set.
- `TxExecute`: The coordinator reads the remote data specified in read-only and read-write sets, and then executes the dtxn logic. Our hitchhiked locking and backup-enabled read schemes are leveraged.
- `TxCommit`: After execution, the coordinator commits the updated data to remote primaries and backups using our coalescent commit and selective remote flush schemes.

```
bool WriteCheck(uint64_t dtxn_id, DTXN* dtxn) {
  // The `dtxn` invokes FLib interfaces
  dtxn->TxBegin(dtxn_id);
  // Use a random account as the key
  uint64_t acct_id = RandomAccount();
  FObj* sav_obj = new FObj(SavingsTableID, acct_id);
  FObj* chk_obj = new FObj(CheckingTableID, acct_id);
  dtxn->AddRO(sav_obj);
  dtxn->AddRW(chk_obj);
  if (!dtxn->TxExecute()) return false;
  // Get record values and run transaction logic
  sav_val_t* sav = (sav_val_t*) sav_obj->value;
  chk_val_t* chk = (chk_val_t*) chk_obj->value;
  if (sav->balance + chk->balance < PredefinedAmount)
    chk->balance -= (PredefinedAmount + 1);
  else chk->balance -= PredefinedAmount;
  bool status = dtxn->TxCommit();
  delete sav_obj; delete chk_obj;
  // Report commit (true) or abort (false) to client
  return status;
}
```

Figure 9: The example of C++ code using FLib interfaces.

Figure 10: The comparisons between (a) sequential processing, and (b) interleaved processing, in one thread.

Our transaction interfaces support general transaction processing. Specifically, the developers are not required to know all the read/write sets at the beginning of each transaction. Instead, developers call `AddRO`, `AddRW`, and `TxExecute` multiple times when reading/writing data occurs during a transaction. Fig. 9 illustrates an example of using our interfaces in the `Write Check` transaction of the SmallBank benchmark [50]. This transaction reads the balances from the `Savings` and `Checking` tables, and updates the balance in the `Checking` table. It shows that our interfaces are easy-to-use.

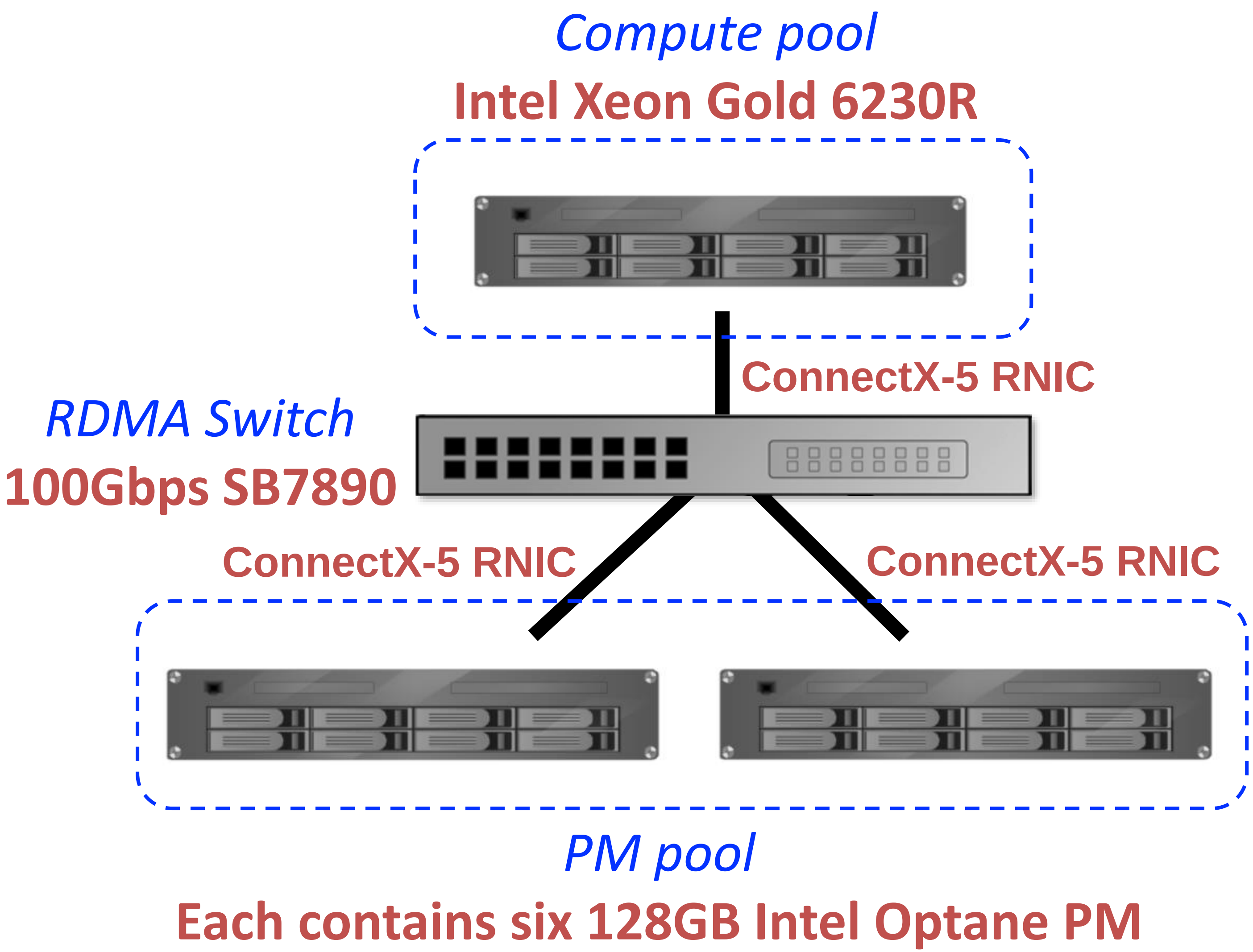
4.3 Interleaved Transaction Processing

As shown in Fig. 10a, sequentially processing dtxns in a thread wastes the CPU cycles due to waiting for RDMA ACKs, which significantly decreases the throughput. To avoid CPU idling in the compute pool, FORD leverages an interleaved processing scheme that enables multiple coordinators in one thread to process different dtxns in pipeline, as presented in Fig. 10b. In this way, the network RTTs are efficiently hided and the CPU cores in the compute pool are fulled utilized to improve the throughput.

We use coroutines [29, 60] to implement the interleaved processing. Each CPU thread generates several coroutines and each coroutine acts as a coordinator to execute dtxns. After issuing the RDMA requests, a coroutine yields its CPU core to another coroutine to process the next dtxn. A dedicated coroutine in each thread polls RDMA ACKs. If all ACKs of a coroutine arrived, FORD schedules this coroutine to occupy the CPU core to resume execution. The results in Fig. 16 show that using a proper number of coroutines improves the throughput without heavily increasing the latency.

Evaluation

- **Benchmarks**
  - KV store
    - 8B key + 40B value
    - Skewed (θ = 0.99) + Uniform
  - TATP
    - RO/RW: 80%/20%, 48B
  - SmallBank
    - RO/RW: 15%/85%, 16B
  - TPCC
    - RO/RW: 8%/92%, 672B
- **Comparisons**[1]
  - FaRM@SOSP’15
  - DrTM+H@OSDI’18

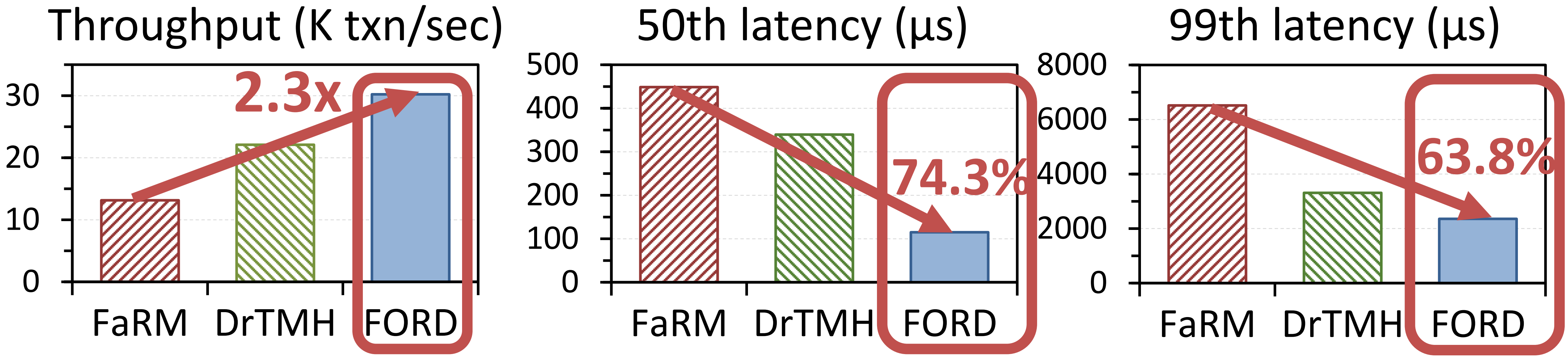


Testbed

[1] Protocols are re-implemented using one-sided RDMA

End-to-End Performance

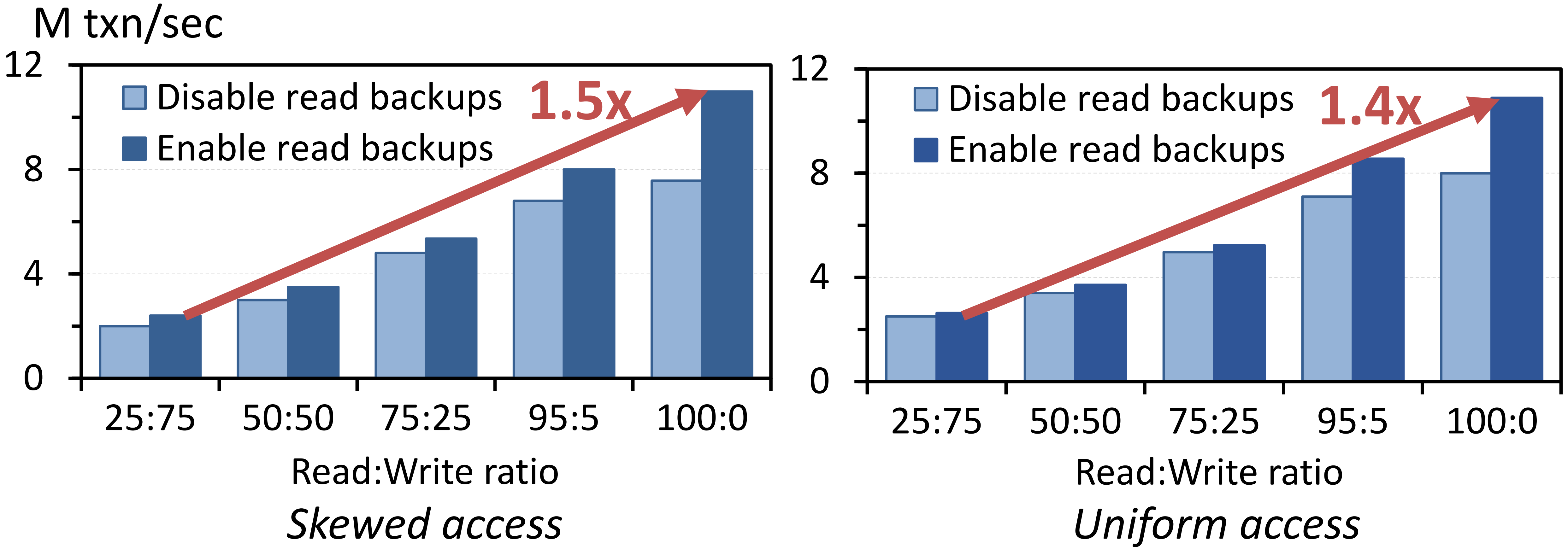
- 112 coordinators
- **Efficient round trip reduction and backup utilization**



TPCC results

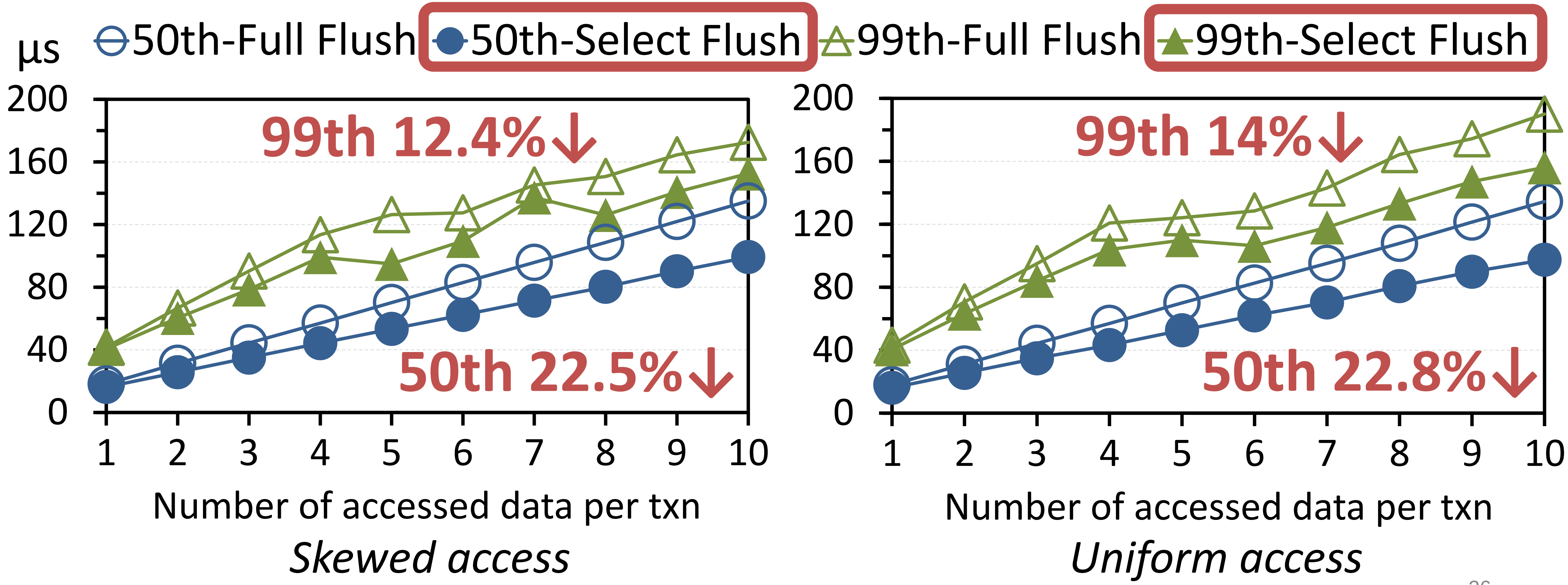
Read backup

- KV store, 1 backup

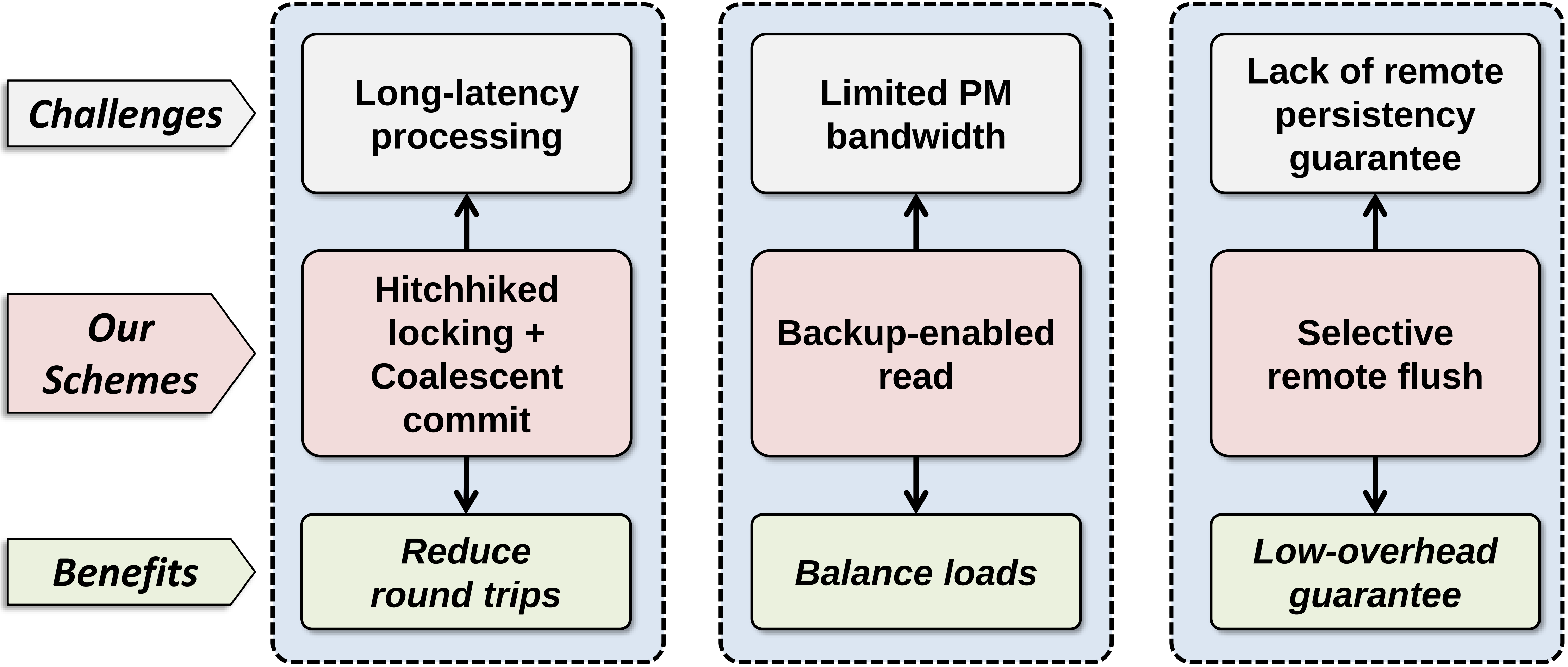


Remote flush

- KV store, 1 coordinator



Conclusion



https://github.com/minghust/ford

Thank you! Q&A