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GeoGauss： Strongly Consistent and Light-Coordinated OLTP for Geo-Replicated SQL Database

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Replicated Databases

Benefits:

- Data locality
- High availability
- High read throughput

Huawei’s Global Data Centers

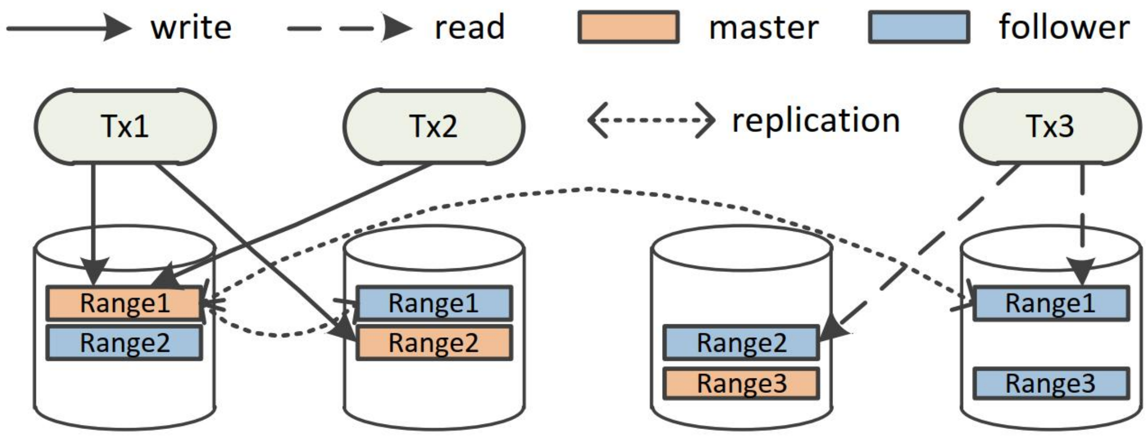
Sharded Master-Follower Replication

Method：

- Data sharding, e.g., Spanner and CockroachDB

Advantage：

- Scalability performance
- Balancing hotspots
- Reducing computing resource contention



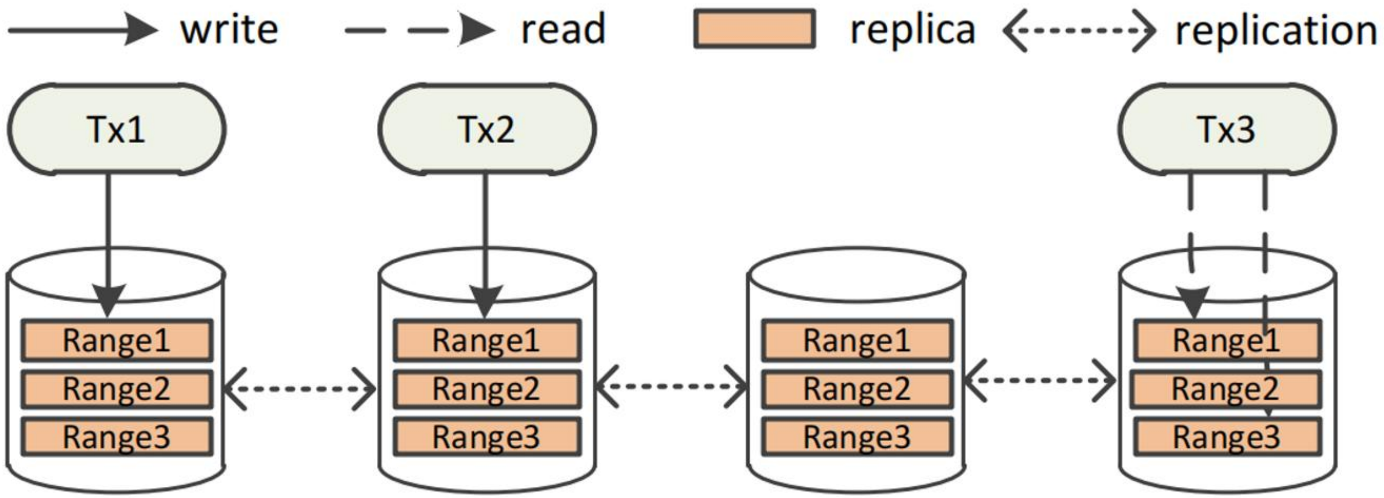
Disadvantage:

- Requests route to single master node
- Heavy coordination cost in cross-region scenarios

Multi-Master Architecture

Advantages:

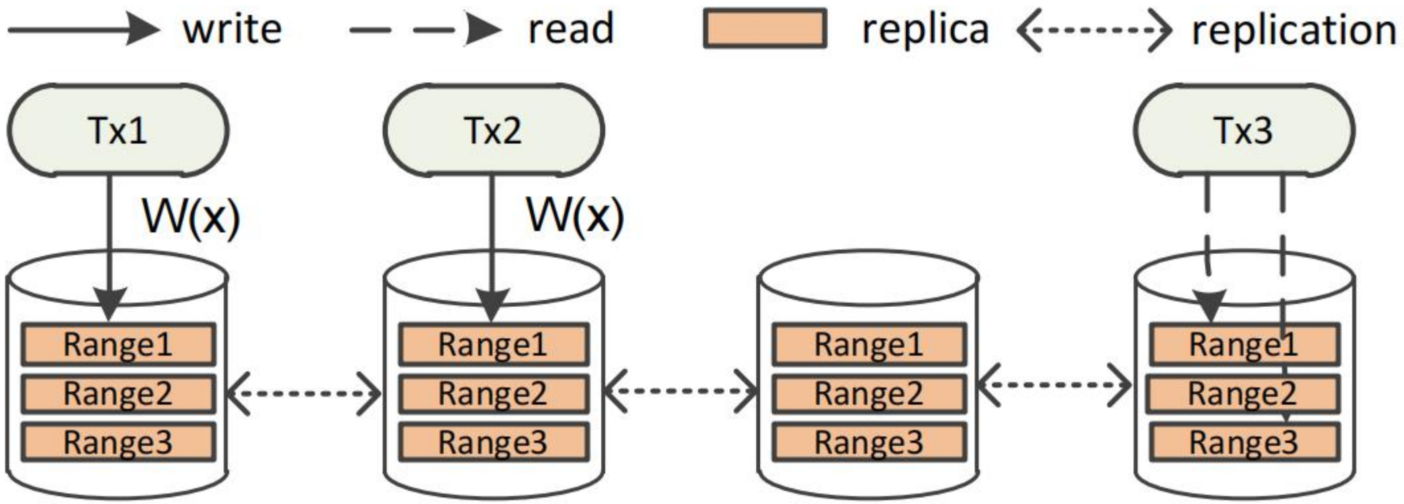
- All server nodes serve both read and write requests
- High availability
- Scalable read performance



Challenge 1 & Solution

Cross-Node Write-Write Conflicts

- Concurrent updates to multiple replicas of the same data
- Expensive coordination：
  - Heavy communication cost in geo-distributed databases



Challenge 1 & Solution

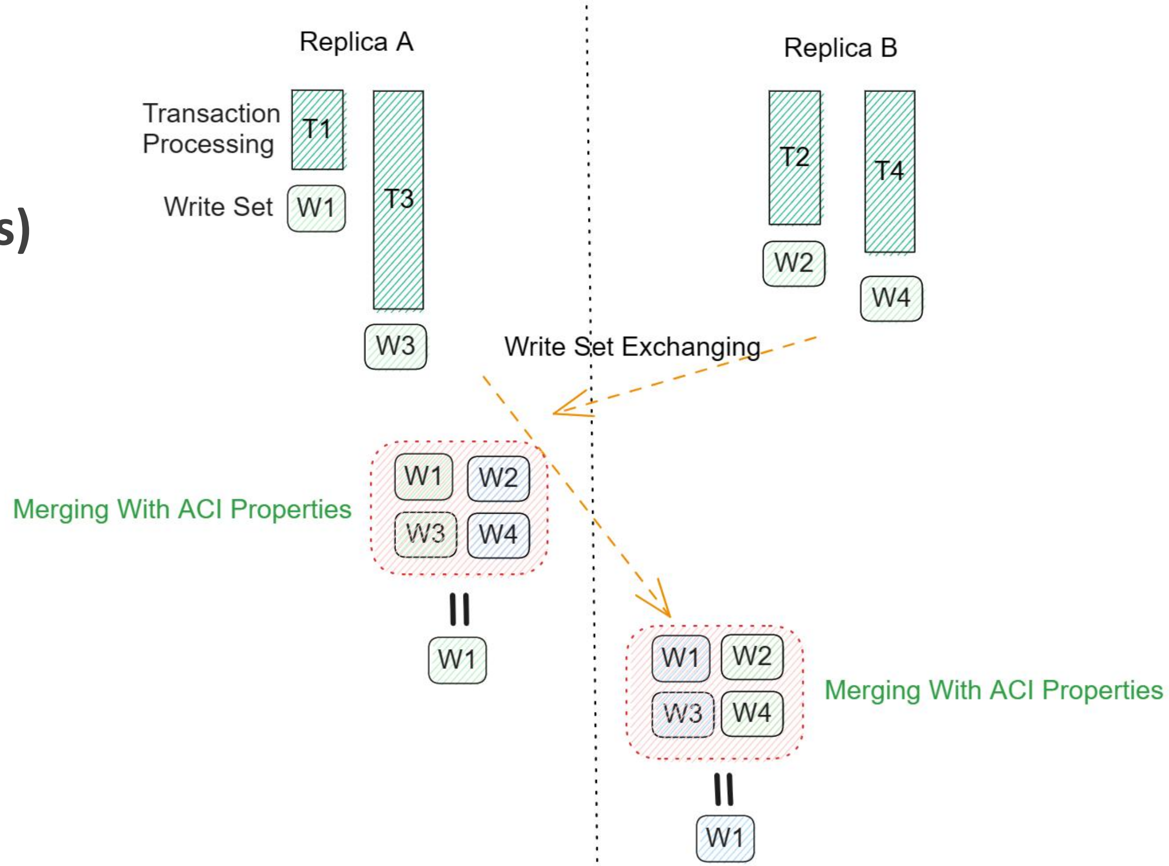
Cross-Node Write-Write Conflicts

Method： ***Conflict-Free Replicated Datatypes*** **(CRDTs)**

- Multi-Master architecture
- Exchange write sets
- Merge function with ACI properties :
  - (*associative, commutative, idempotent*)

Effect：

- Coordination-Free
- Eventual consistency



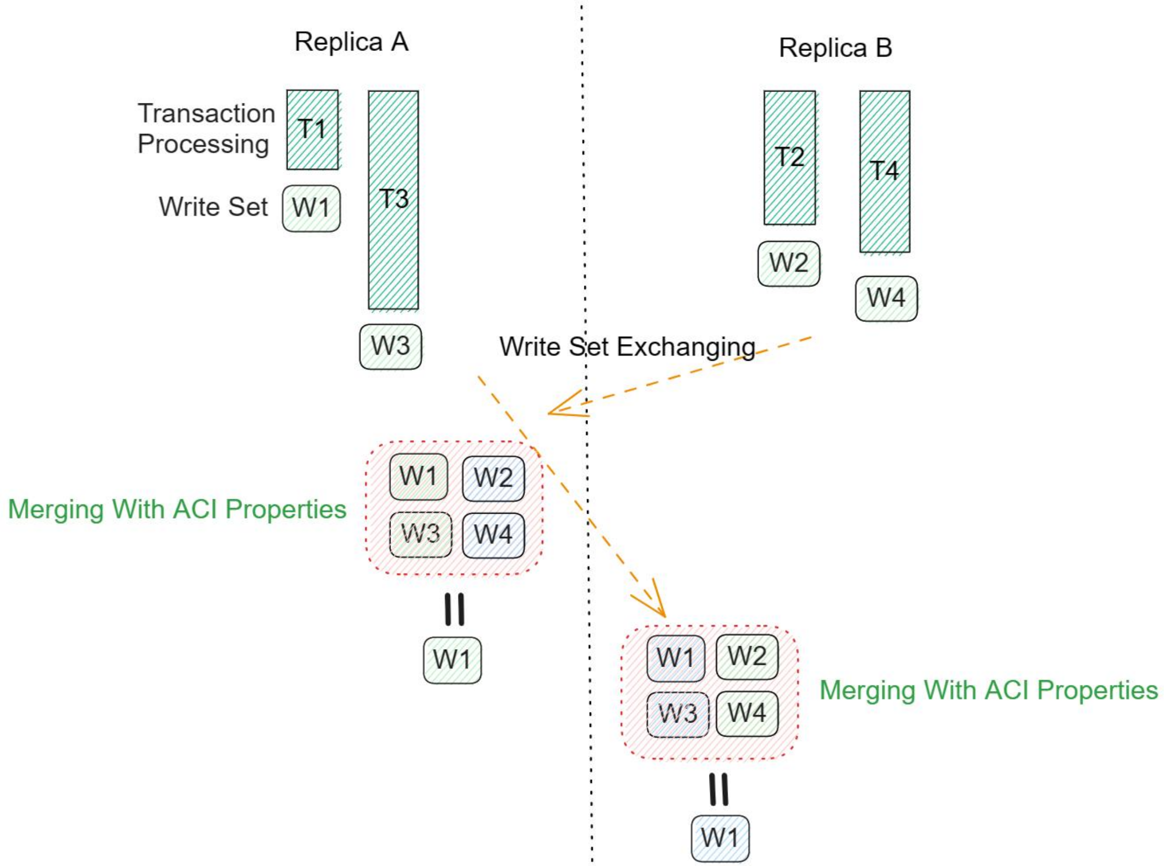
Coordination-Free Conflicts Processing Under Multi-Master architecture by Using ACI Properties

Challenge 2 & Solution

Eventual Consistency:

- Data inconsistent
- Not suitable for OLTP

Require strong consistency



Coordination-Free Conflicts Processing Under Multi-Master architecture by Using ACI Properties

Challenge 2 & Solution

Strong Consistency:

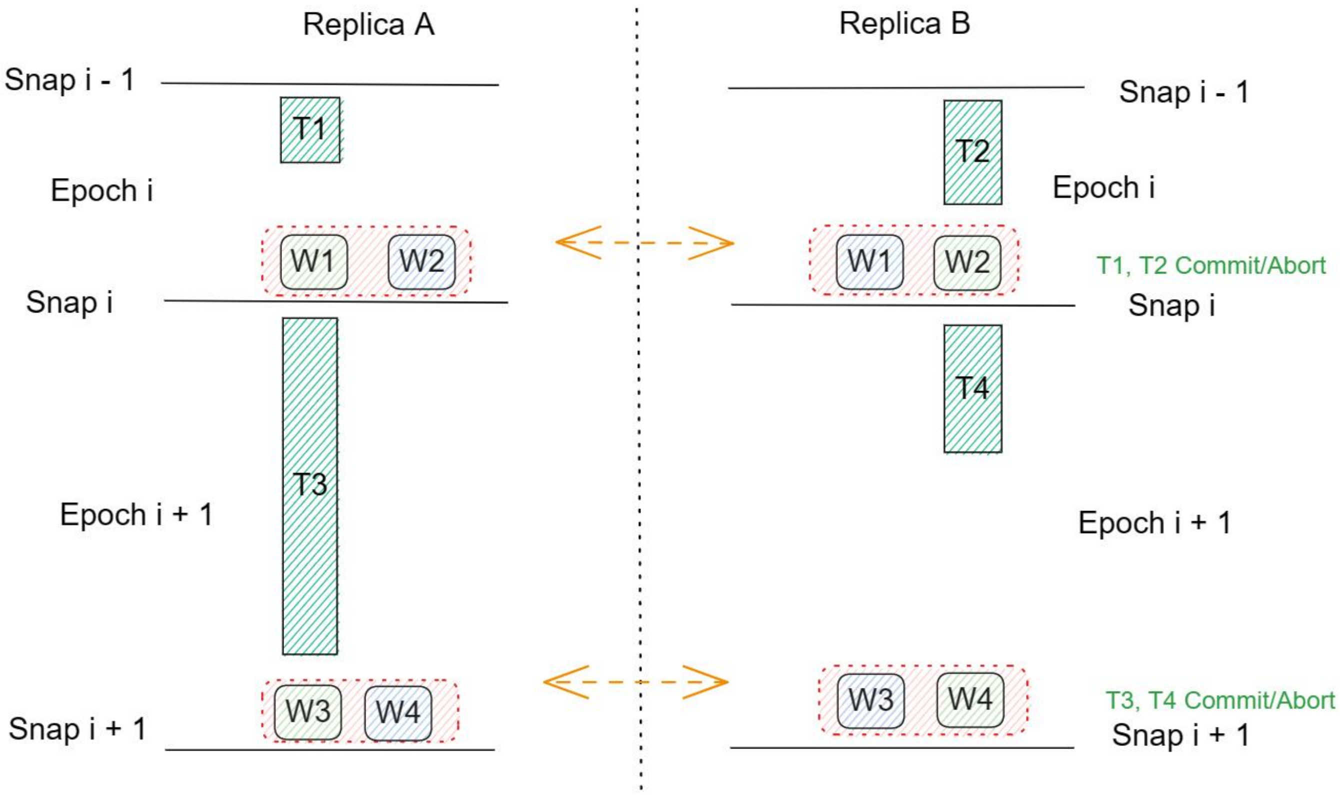
- Eventual consistency is not suitable in OLTP

Method: Epoch-Based processing

- Epoch-Based synchronization
- Execute transactions epoch by epoch

Effect:

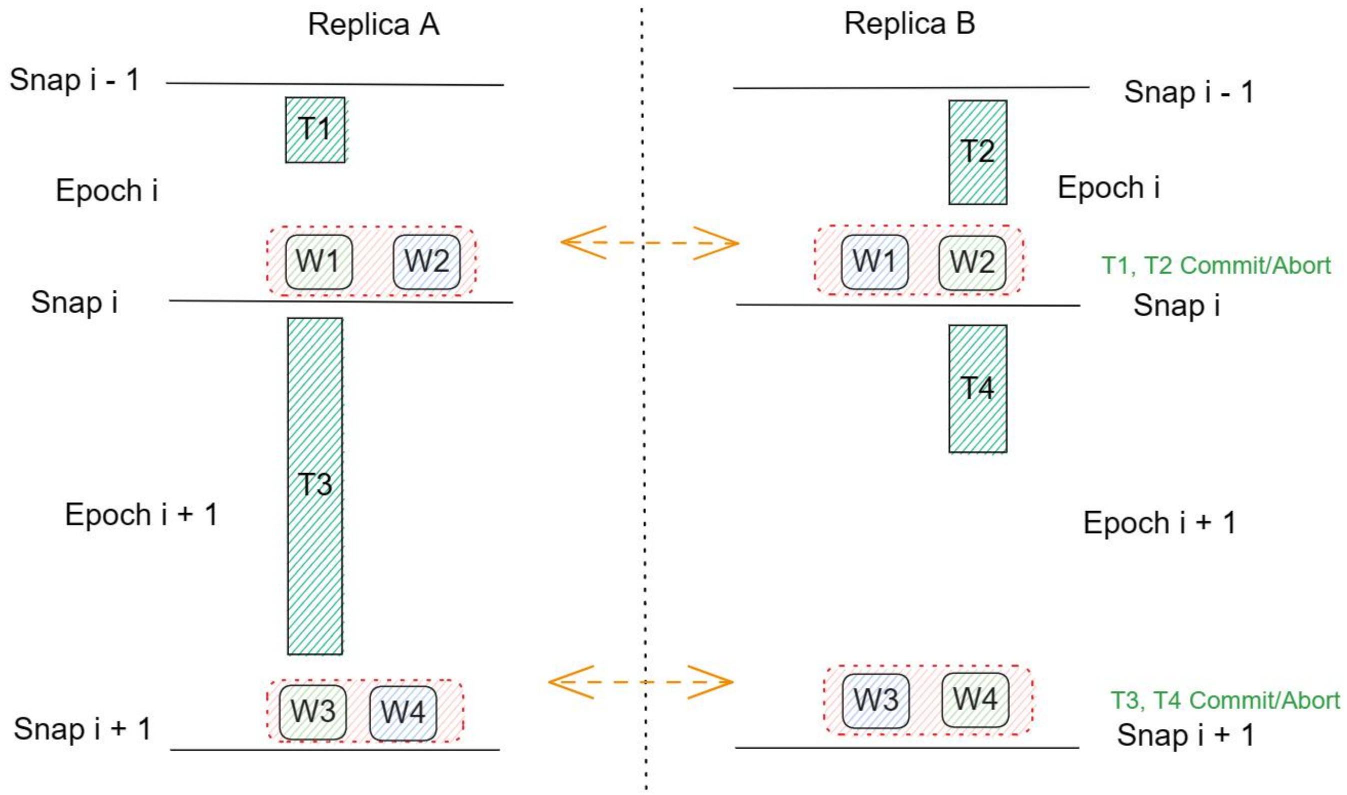
- Sequential consistency per-epoch basis



Challenge 3 & Solution

Performance:

- Epoch-Based execution
- Imbalanced workload e.g. long transaction



Challenge 3 & Solution

Performance:

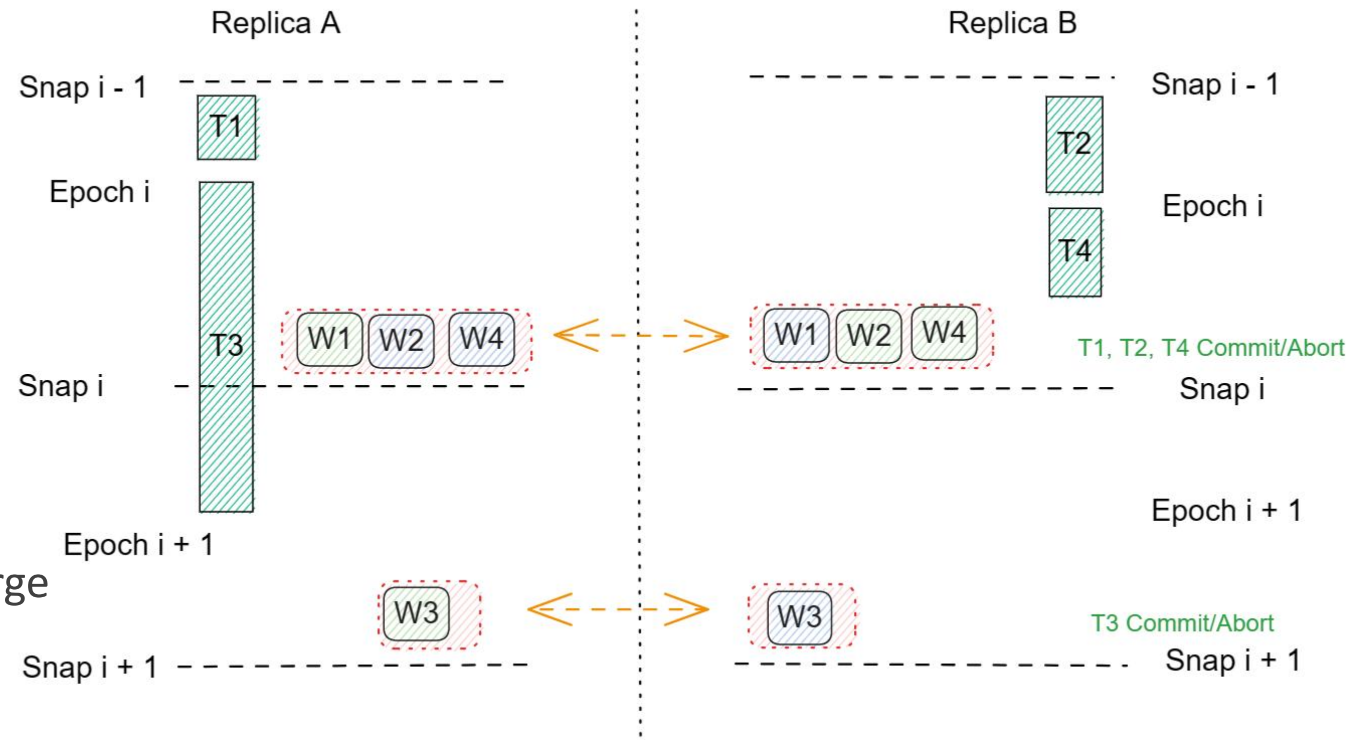
- Epoch-Based execution
- Imbalanced workload e.g. long transaction

Method:

- Multi-Master Epoch-Based OCC

Effect:

- High throughput, low latency
- long transaction does not affect epoch merge



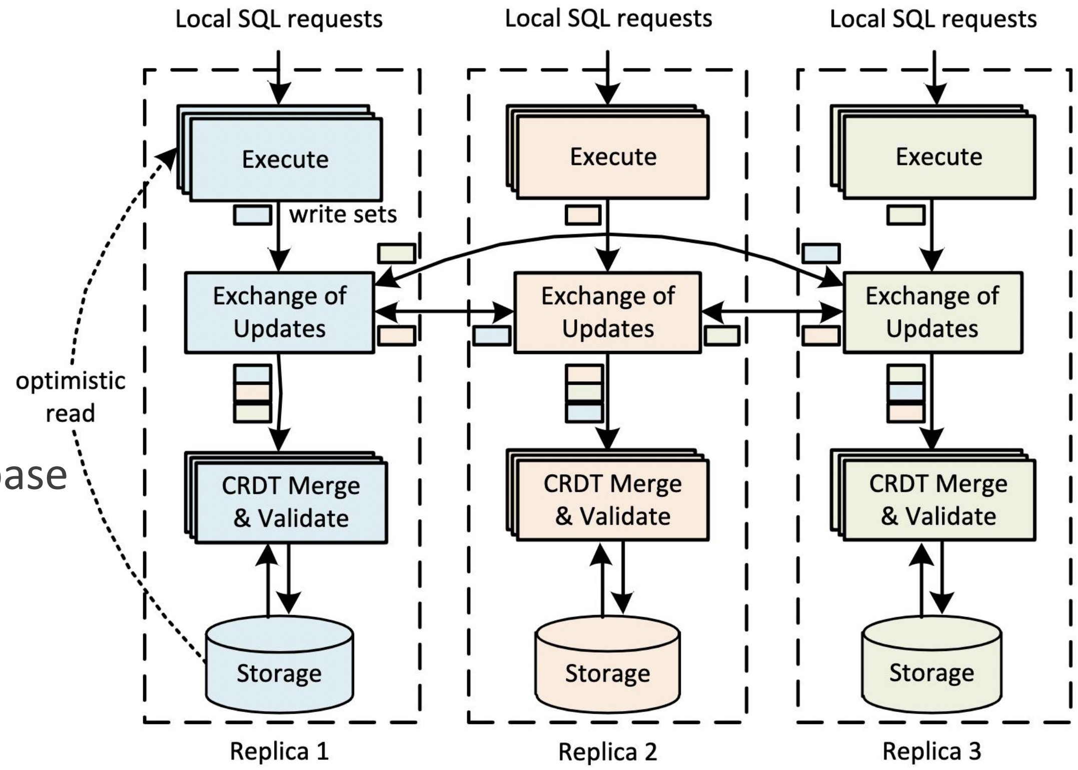
GeoGauss A Cross-Region Multi-master Distributed Database

Epoch-based multi-master OCC:

- Coordination-Free transaction processing
- Epoch-Based merge
- Optimistic execution

GeoGauss:

- Cross-Region Multi-Master Distributed Relational Database
- Based on openGauss MOT[vldb2020]



Replica a

x=1, cen=0, csn=0	y=0, cen=0, csn=0

cen: commit epoch number

csn: commit sequence number

Replica b

x=1, cen=0, csn=0	y=0, cen=0, csn=0

Replica a	x=1, cen=0, csn=0	y=0, cen=0, csn=0

T1 {$R_x(1)$ $W_x(2)$}

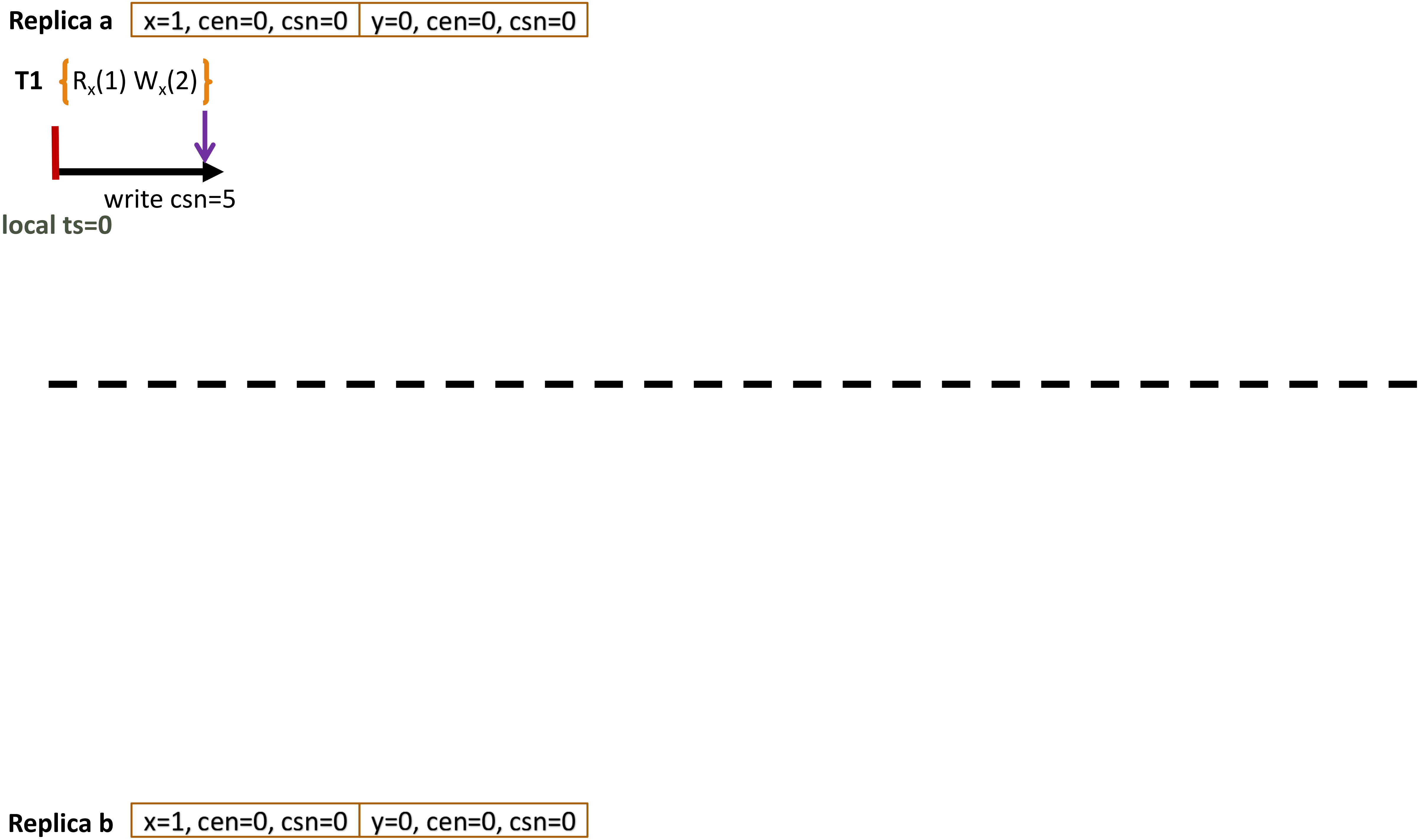
T1 execution,

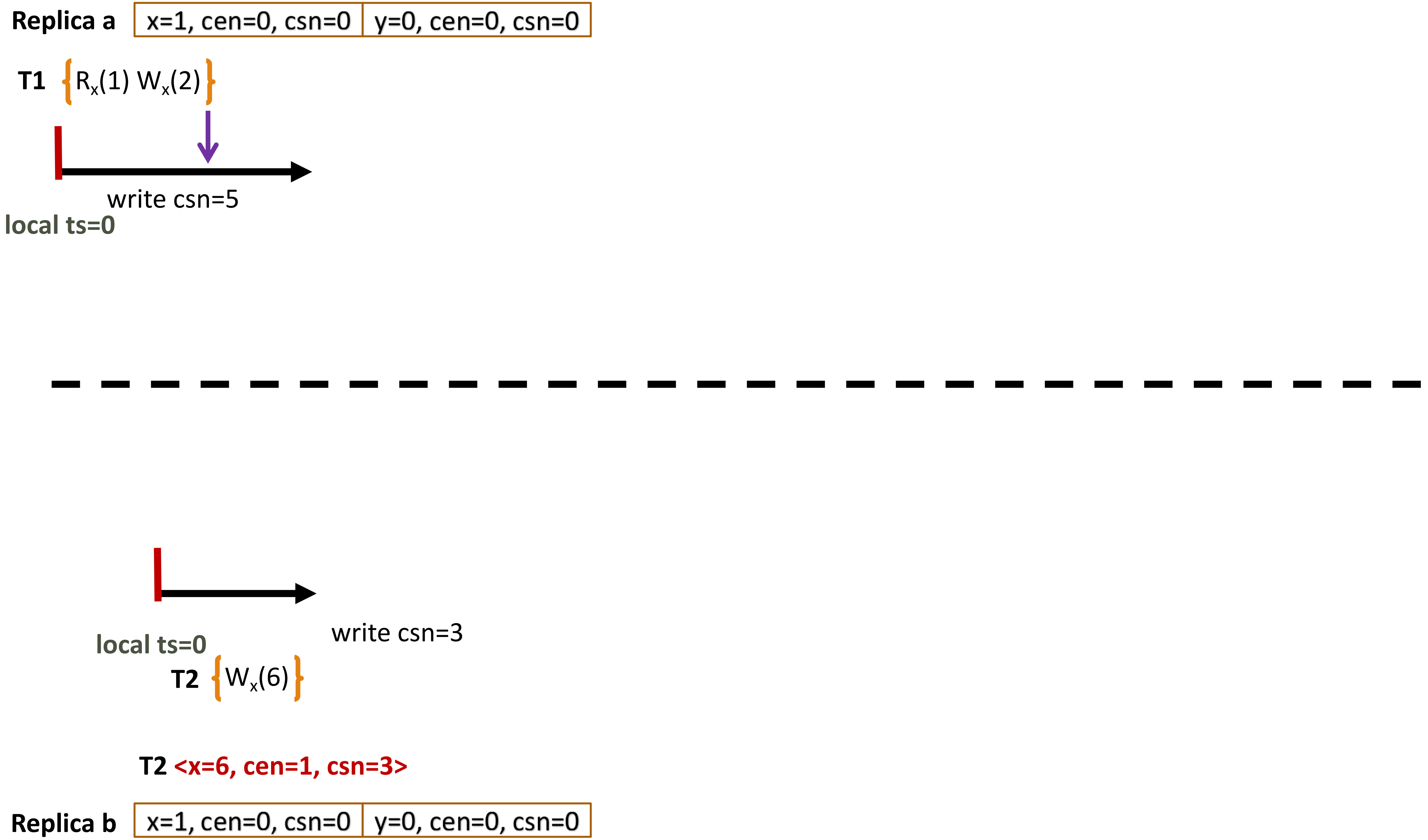
T1’s updates <x=2, cen=1, csn=5>

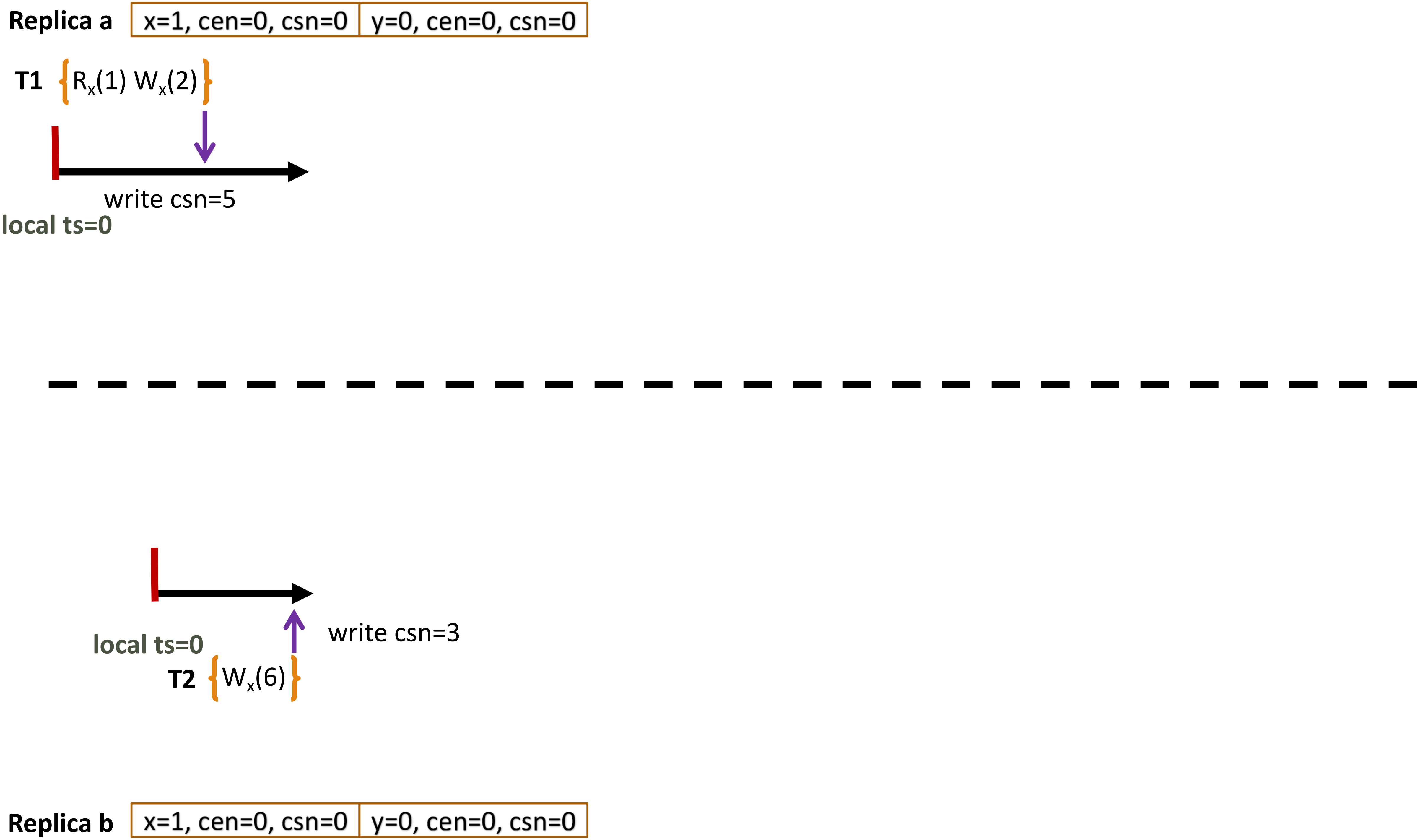
write csn=5

local ts=0

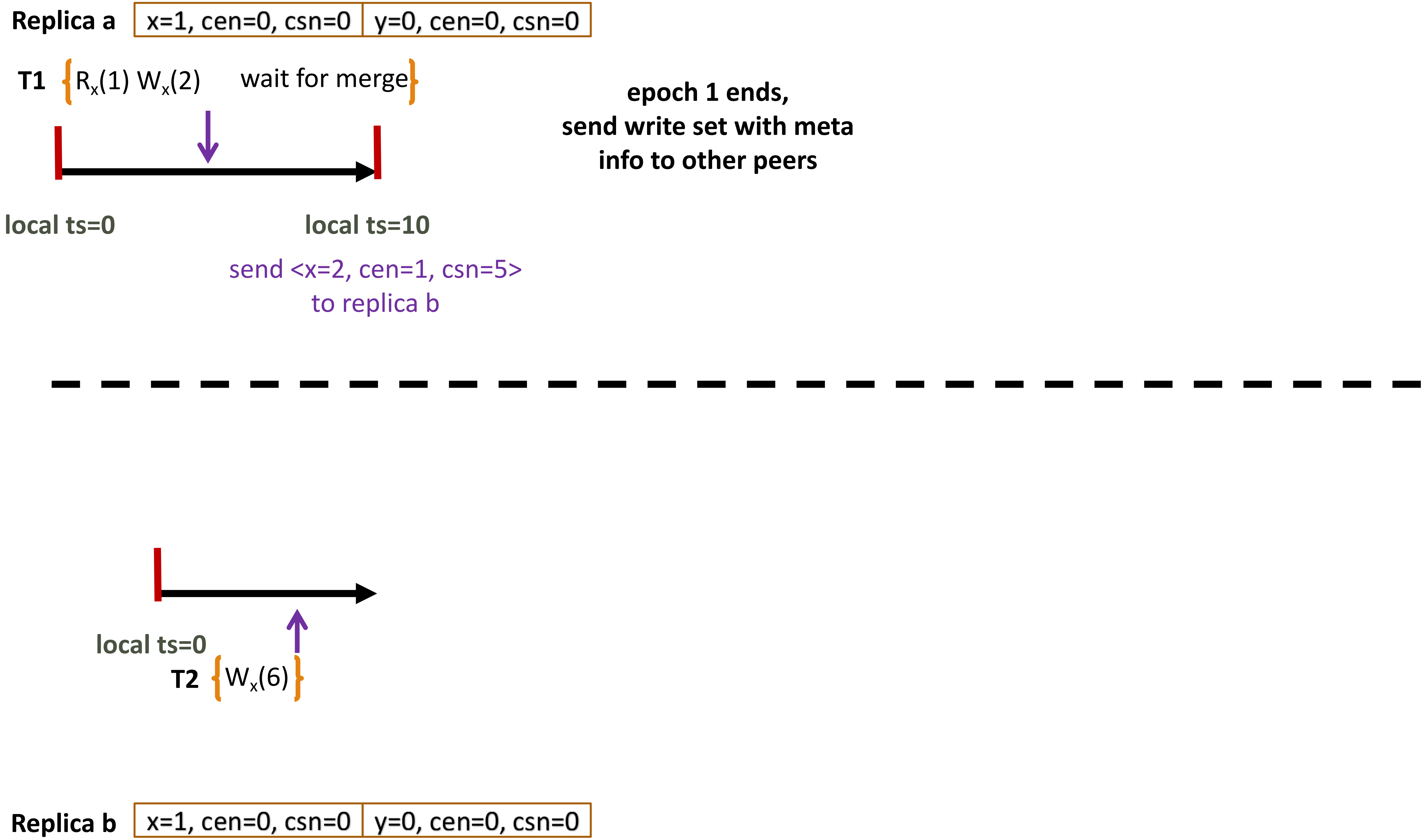
Replica b	x=1, cen=0, csn=0	y=0, cen=0, csn=0

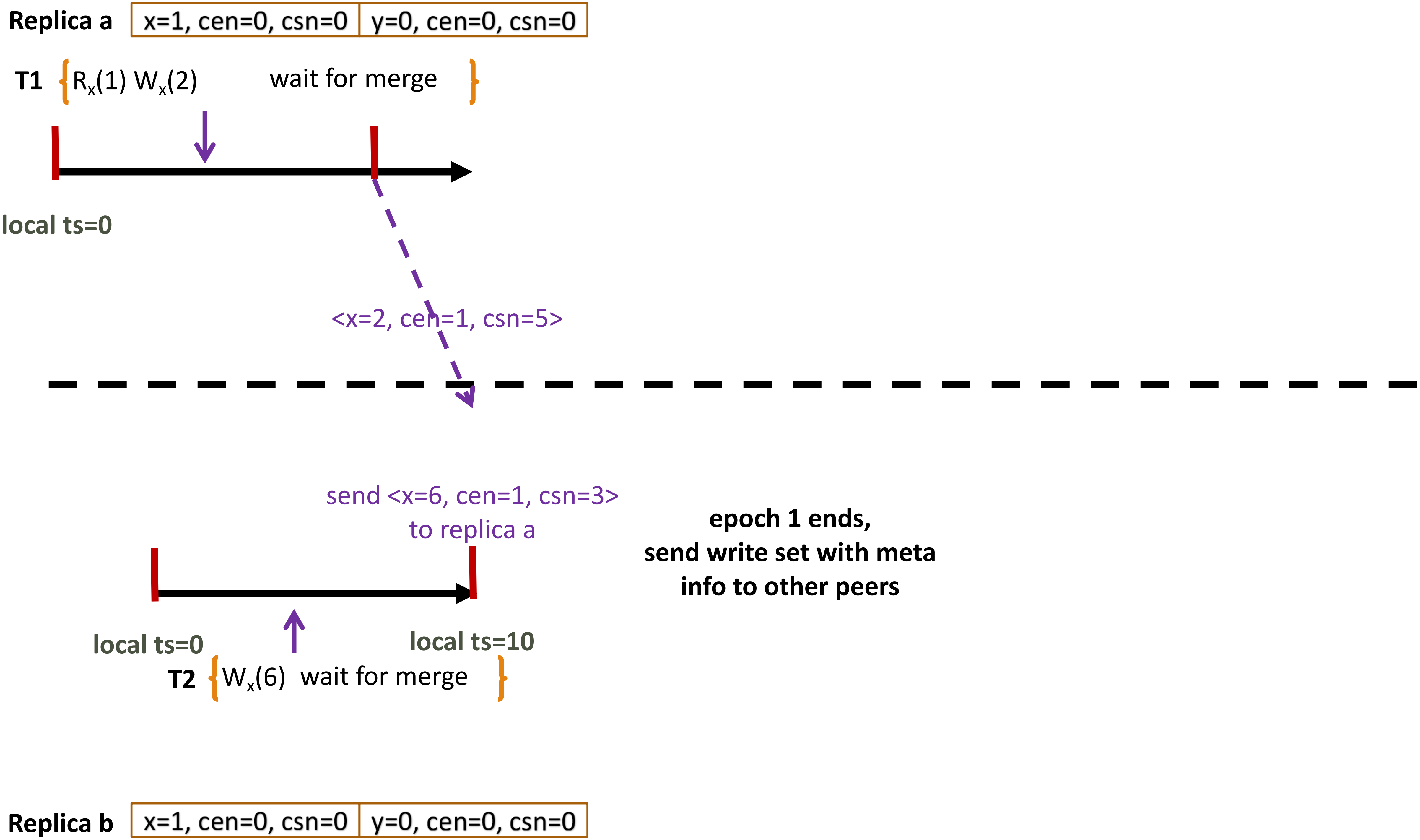

Replica a
x=1, cen=0, csn=0
y=0, cen=0, csn=0
T1
$R_x(1)$ $W_x(2)$
write csn=5
local ts=0
Replica b
x=1, cen=0, csn=0
y=0, cen=0, csn=0

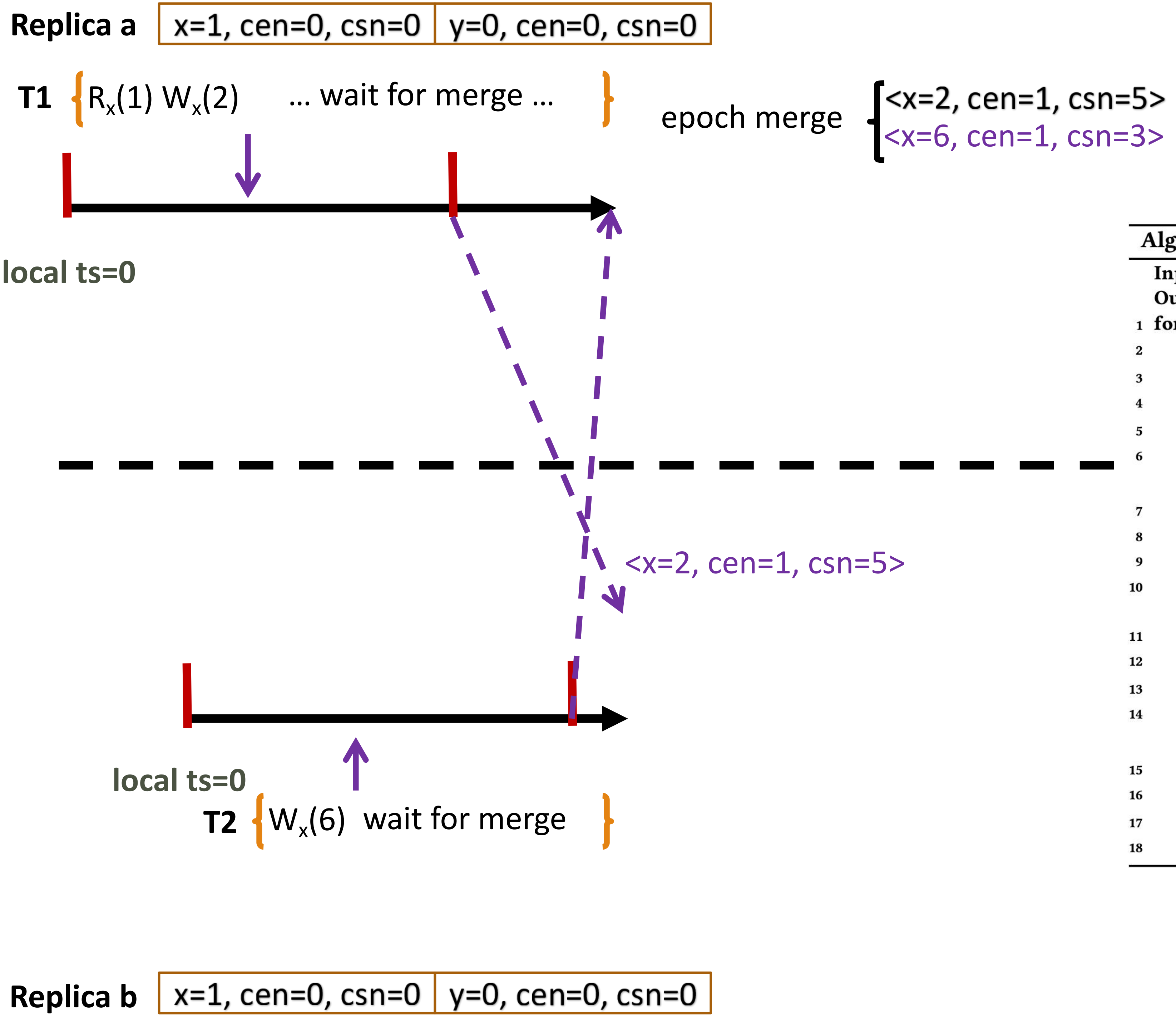

Replica a
x=1, cen=0, csn=0
y=0, cen=0, csn=0
T1 {$R_x(1)$ $W_x(2)$}
write csn=5
local ts=0
local ts=0
write csn=3
T2 {$W_x(6)$}
T2 <x=6, cen=1, csn=3>
Replica b
x=1, cen=0, csn=0
y=0, cen=0, csn=0



Replica a
x=1, cen=0, csn=0
y=0, cen=0, csn=0
T1
$R_x(1)$ $W_x(2)$
write csn=5
local ts=0
local ts=0
write csn=3
T2
$W_x(6)$
Replica b
x=1, cen=0, csn=0
y=0, cen=0, csn=0


Replica a
x=1, cen=0, csn=0
y=0, cen=0, csn=0
T1
R_x(1) W_x(2)
wait for merge
epoch 1 ends,
send write set with meta
info to other peers
local ts=0
local ts=10
send <x=2, cen=1, csn=5>
to replica b
local ts=0
T2
W_x(6)
Replica b
x=1, cen=0, csn=0
y=0, cen=0, csn=0

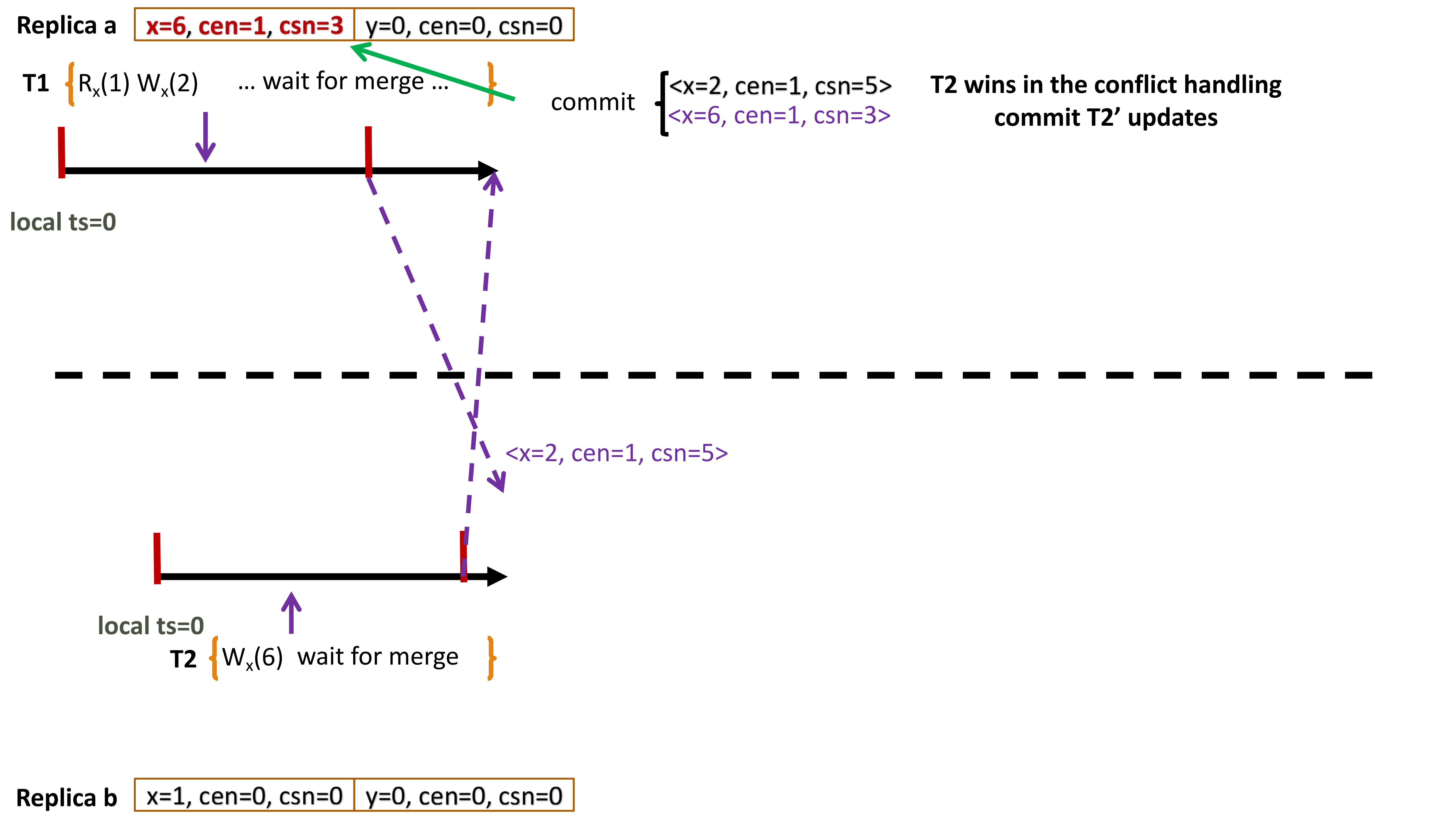

Replica a
x=1, cen=0, csn=0
y=0, cen=0, csn=0
T1
R_x(1) W_x(2)
wait for merge
local ts=0
<x=2, cen=1, csn=5>
send <x=6, cen=1, csn=3>
to replica a
epoch 1 ends,
send write set with meta
info to other peers
local ts=0
local ts=10
T2
W_x(6) wait for merge
Replica b
x=1, cen=0, csn=0
y=0, cen=0, csn=0



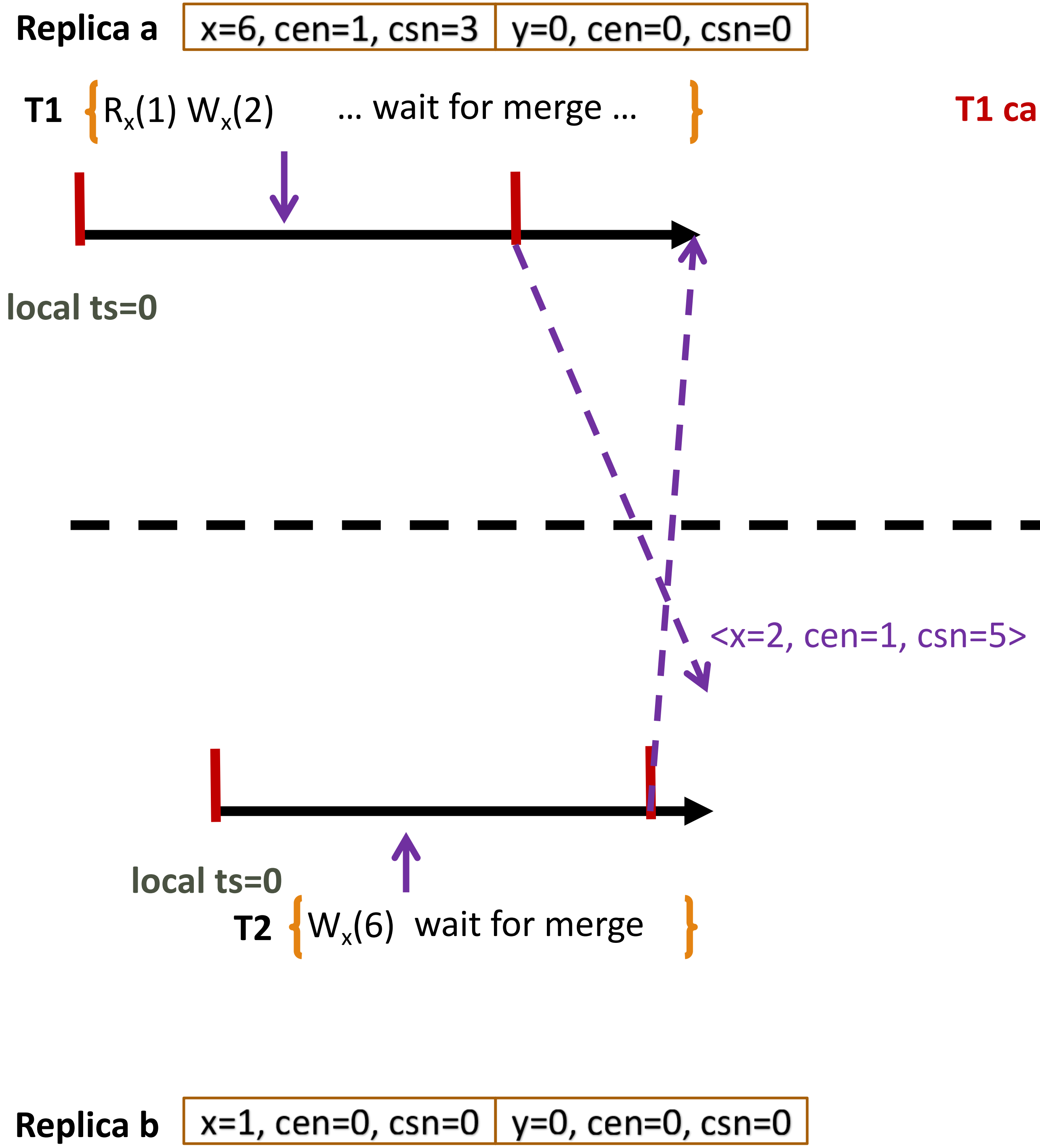
remote updates arrive, merge with local updates

Algorithm 2: DeltaCRDTMerge

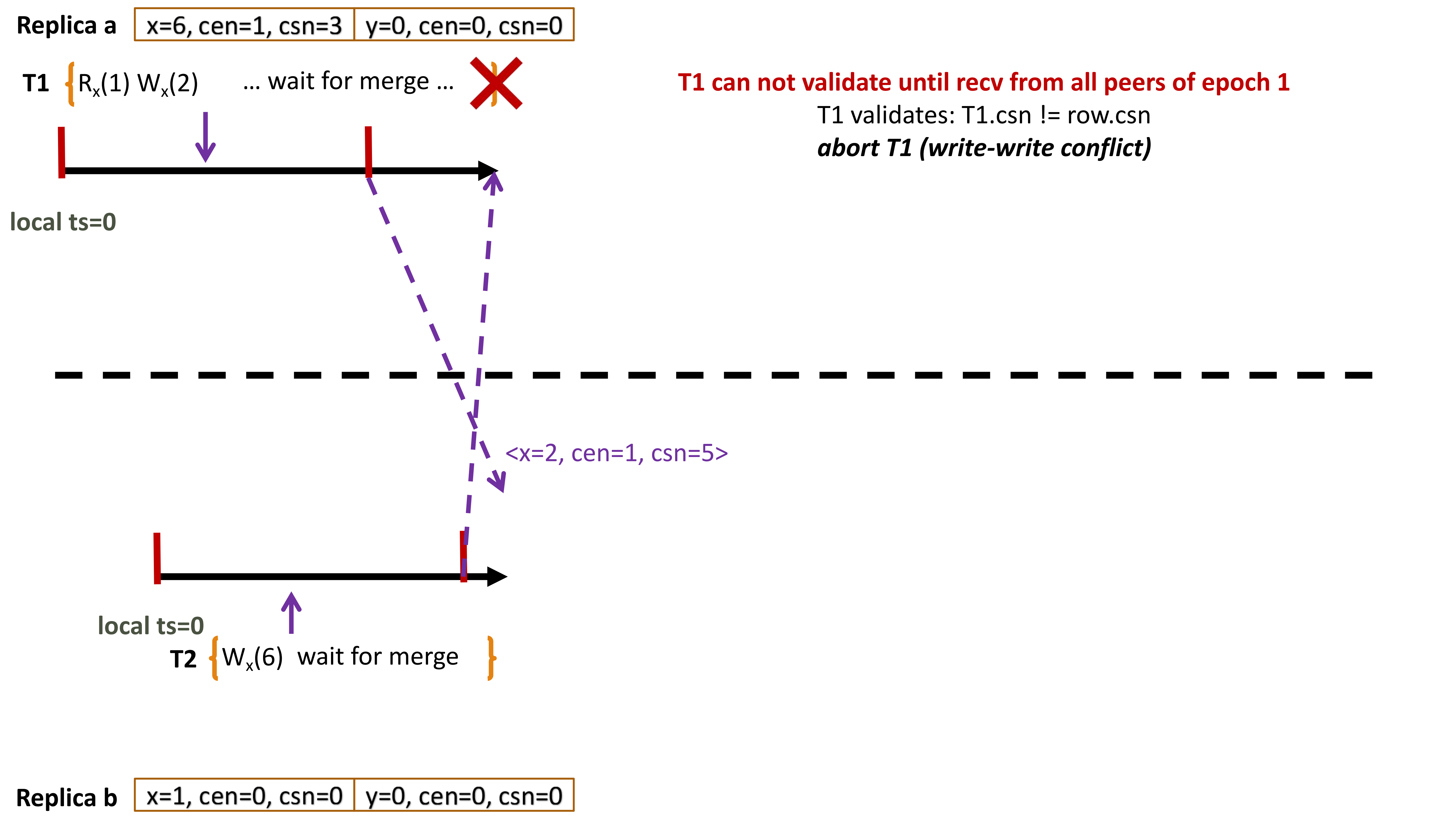
```
Input: a transaction's T.{sen, csn, cen, WS}, current row headers
Output: updated row headers
for each record in T.WS do
    row = FindRow(record.key);
    if row == null then
        Abort T; //row is deleted by other threads
    if row.cen < T.cen then
        //row is not pre-written in current epoch
         row.{sen, csn, cen} = T.{sen, csn, cen};
    else if row.cen == T.cen then
        if row.sen == T.sen then
            if row.csn > T.csn then
                //first write wins
                 row.{sen, csn, cen} = T.{sen, csn, cen};
            else
                Abort T;
        else if row.sen < T.sen then
            //shorter transaction wins
             row.{sen, csn, cen} = T.{sen, csn, cen};
        else
            Abort T;
    else
        //row.cen > T.cen will never happen
```

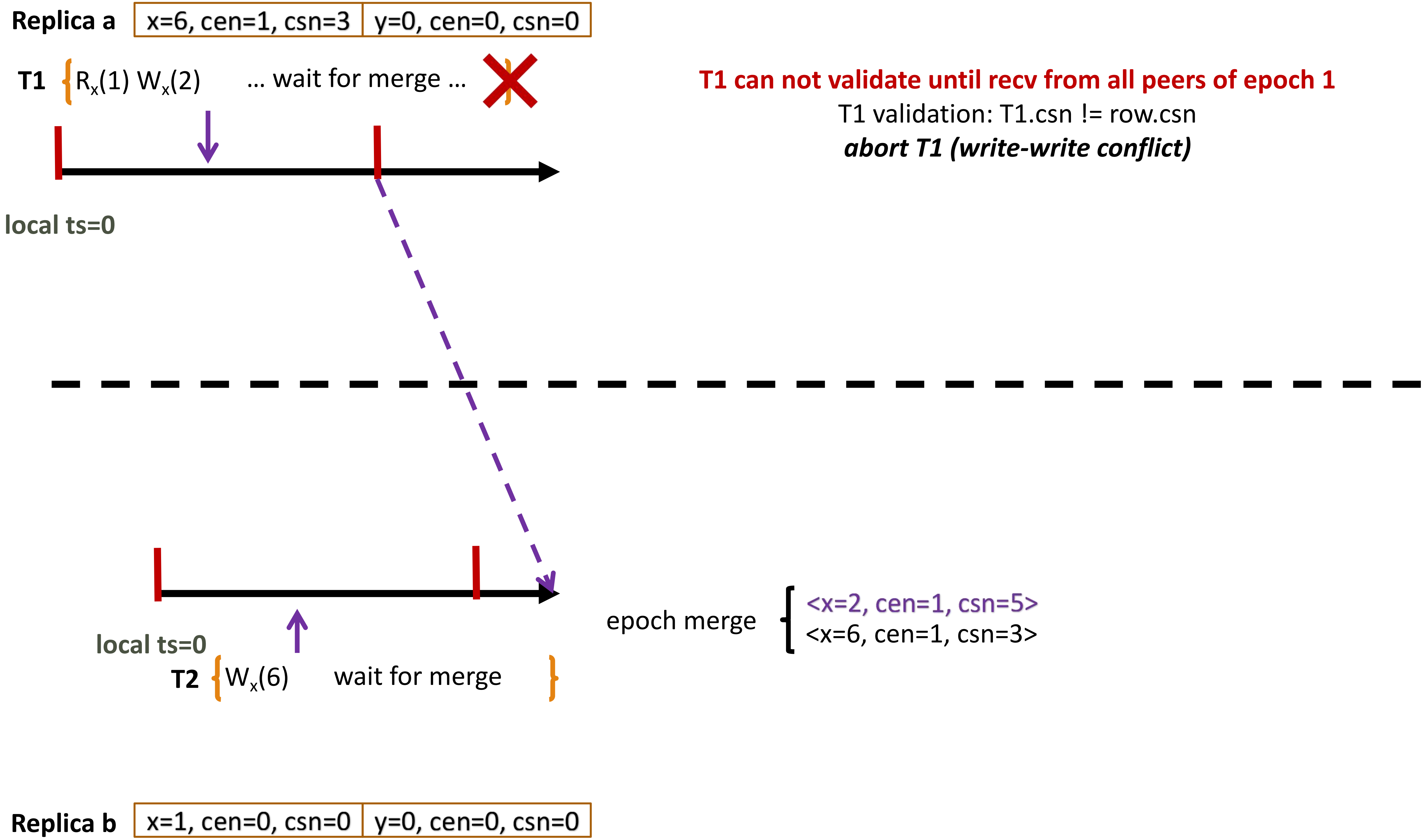


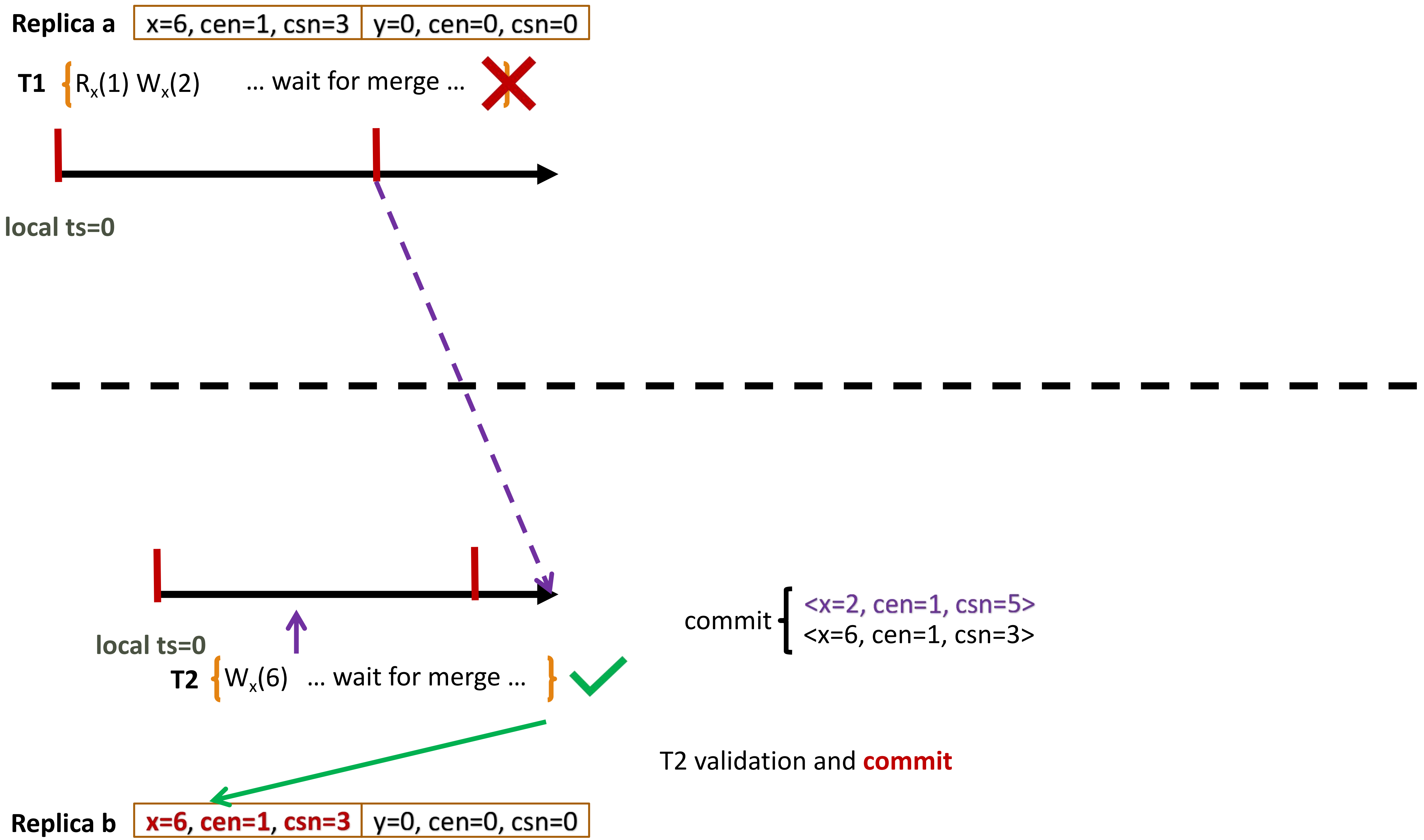
Replica a
x=6, cen=1, csn=3
y=0, cen=0, csn=0
T1
$R_x(1)$ $W_x(2)$
… wait for merge …
commit
<x=2, cen=1, csn=5>
<x=6, cen=1, csn=3>
T2 wins in the conflict handling
commit T2’ updates
local ts=0
<x=2, cen=1, csn=5>
local ts=0
T2
$W_x(6)$ wait for merge
Replica b
x=1, cen=0, csn=0
y=0, cen=0, csn=0



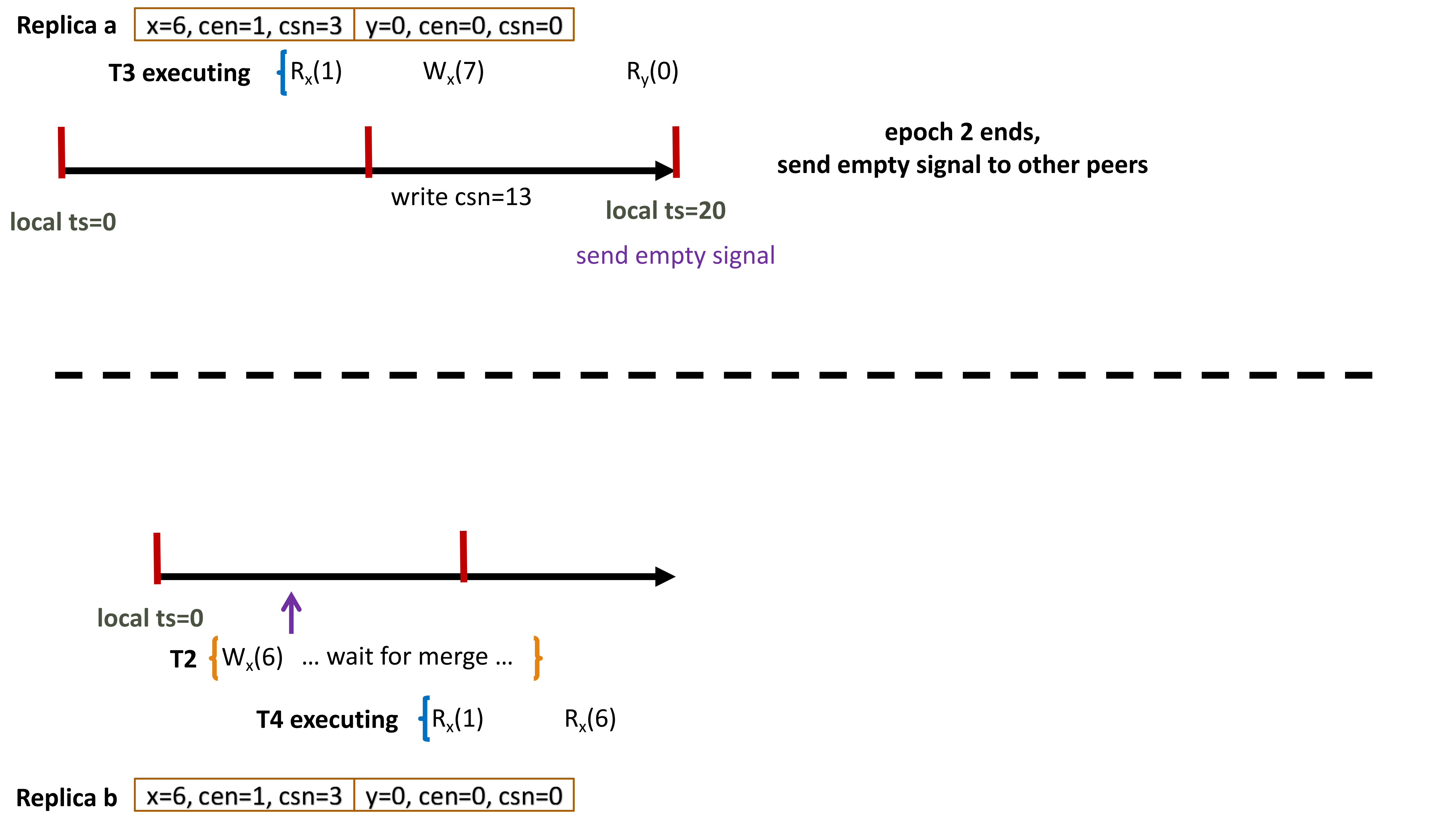
T1 can not validate until recv from all peers of epoch 1

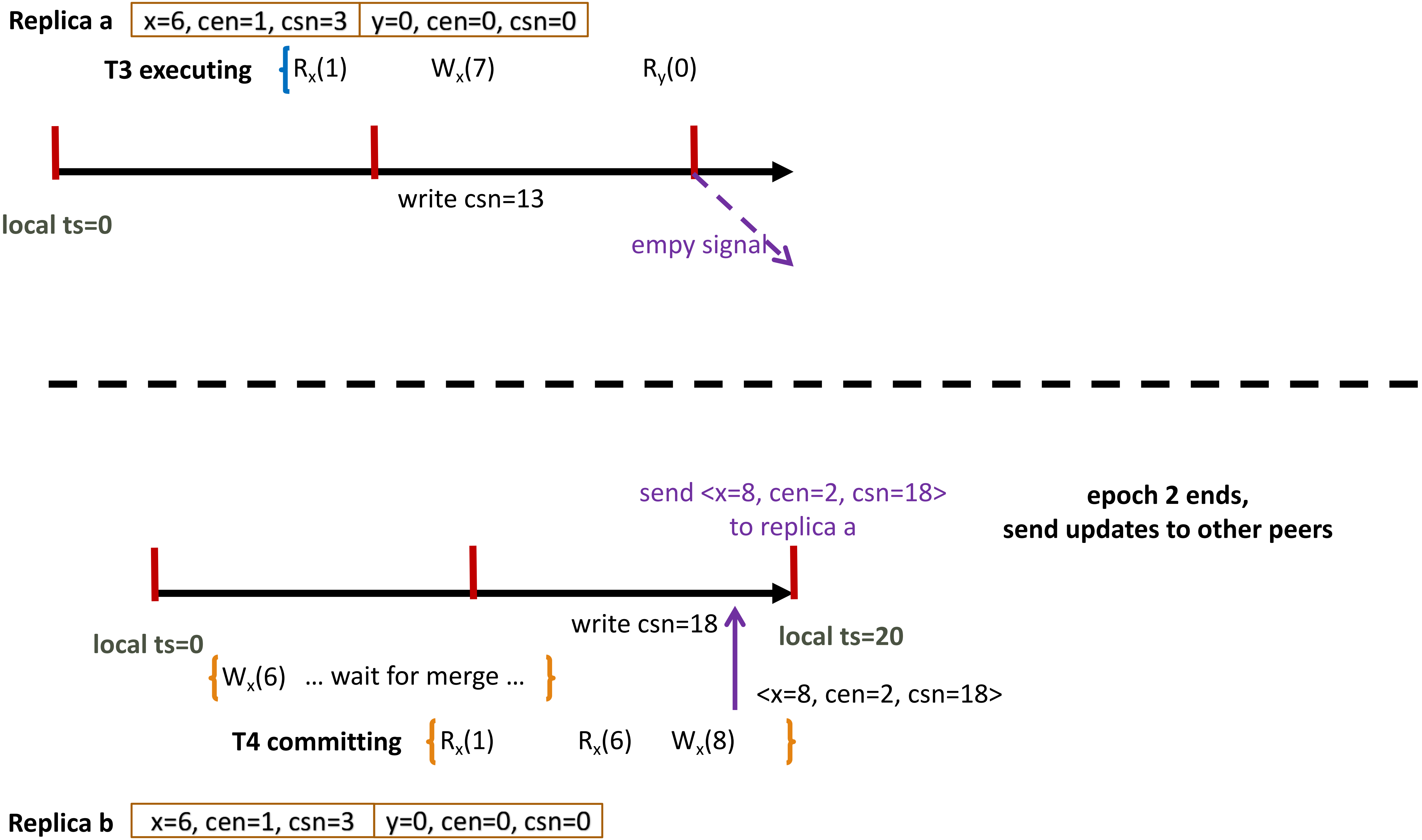

Replica a
x=6, cen=1, csn=3
y=0, cen=0, csn=0
T1
Rx(1) Wx(2)
… wait for merge …
T1 can not validate until recv from all peers of epoch 1
T1 validates: T1.csn != row.csn
abort T1 (write-write conflict)
local ts=0
<x=2, cen=1, csn=5>
local ts=0
T2
Wx(6) wait for merge
Replica b
x=1, cen=0, csn=0
y=0, cen=0, csn=0


Replica a
x=6, cen=1, csn=3
y=0, cen=0, csn=0
T1
$R_x(1)$ $W_x(2)$
… wait for merge …
T1 can not validate until recv from all peers of epoch 1
T1 validation: T1.csn != row.csn
abort T1 (write-write conflict)
local ts=0
local ts=0
T2
$W_x(6)$
wait for merge
epoch merge
<x=2, cen=1, csn=5>
<x=6, cen=1, csn=3>
Replica b
x=1, cen=0, csn=0
y=0, cen=0, csn=0

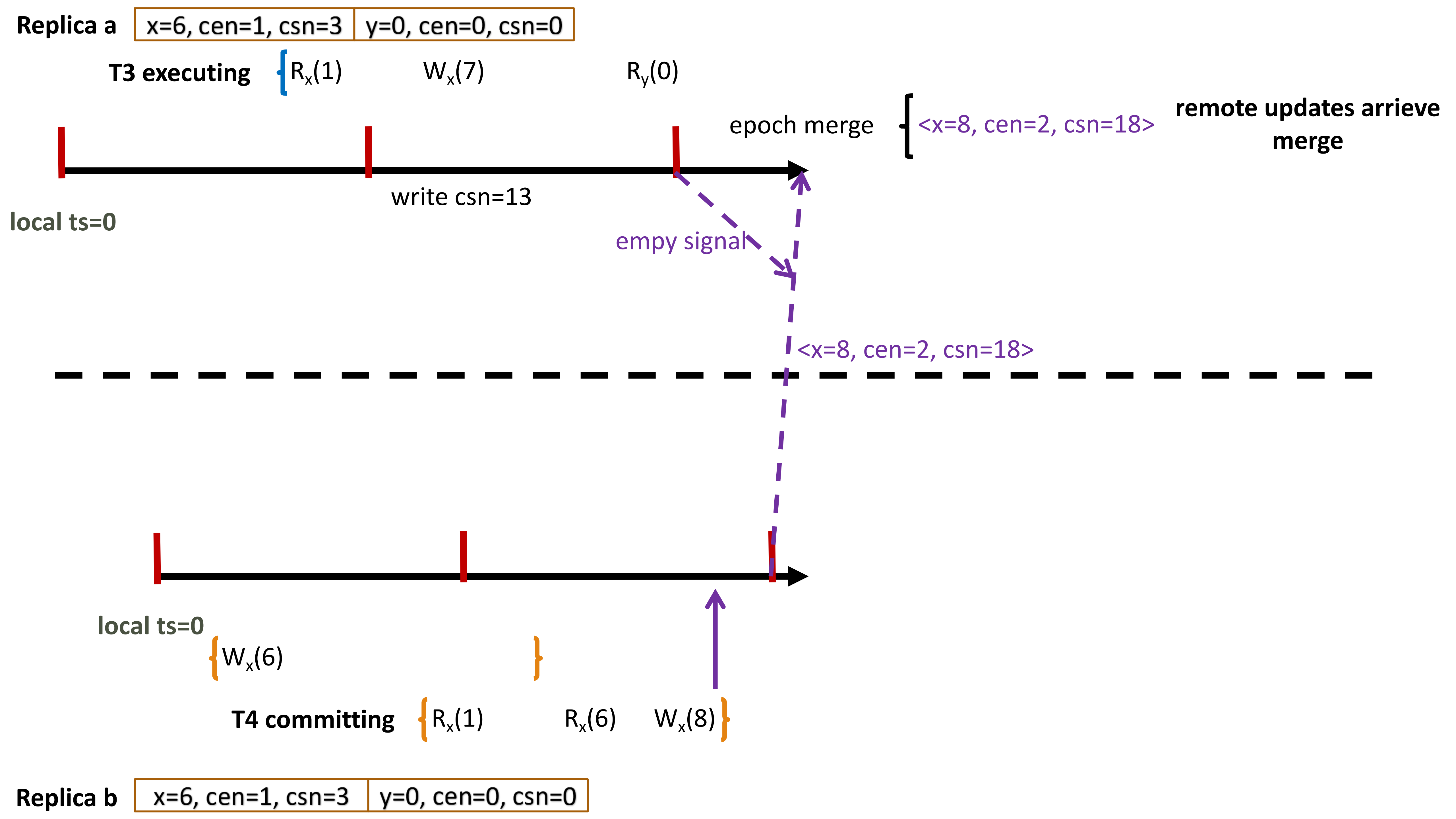


Replica a
x=6, cen=1, csn=3
y=0, cen=0, csn=0
T1
Rx(1) Wx(2)
… wait for merge …
local ts=0
local ts=0
T2
Wx(6)
… wait for merge …
commit
<x=2, cen=1, csn=5>
<x=6, cen=1, csn=3>
T2 validation and commit
Replica b
x=6, cen=1, csn=3
y=0, cen=0, csn=0

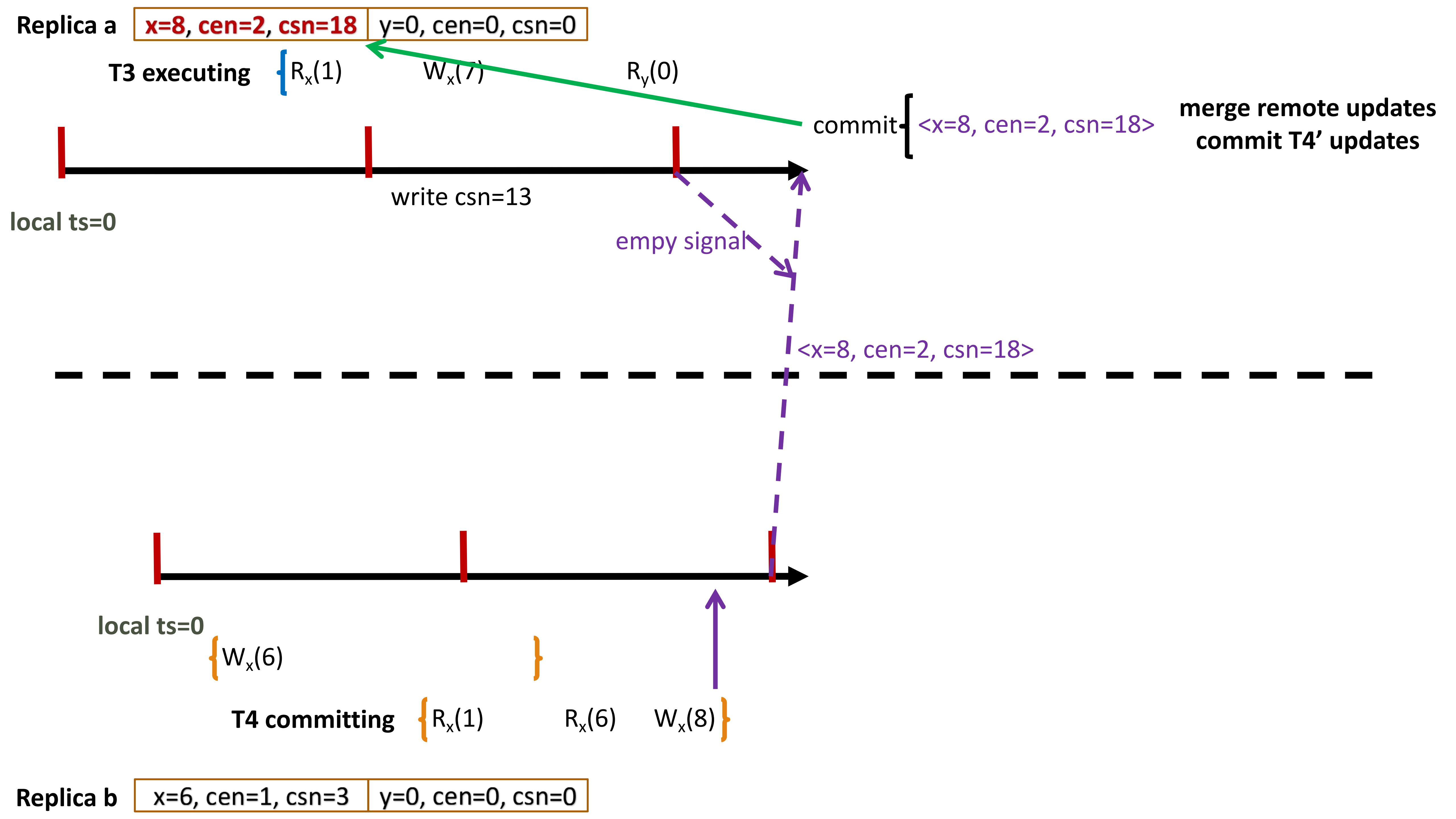

Replica a
x=6, cen=1, csn=3
y=0, cen=0, csn=0
T3 executing
$R_x(1)$
$W_x(7)$
$R_y(0)$
epoch 2 ends,
send empty signal to other peers
write csn=13
local ts=0
local ts=20
send empty signal
local ts=0
T2
$W_x(6)$
… wait for merge …
T4 executing
$R_x(1)$
$R_x(6)$
Replica b
x=6, cen=1, csn=3
y=0, cen=0, csn=0

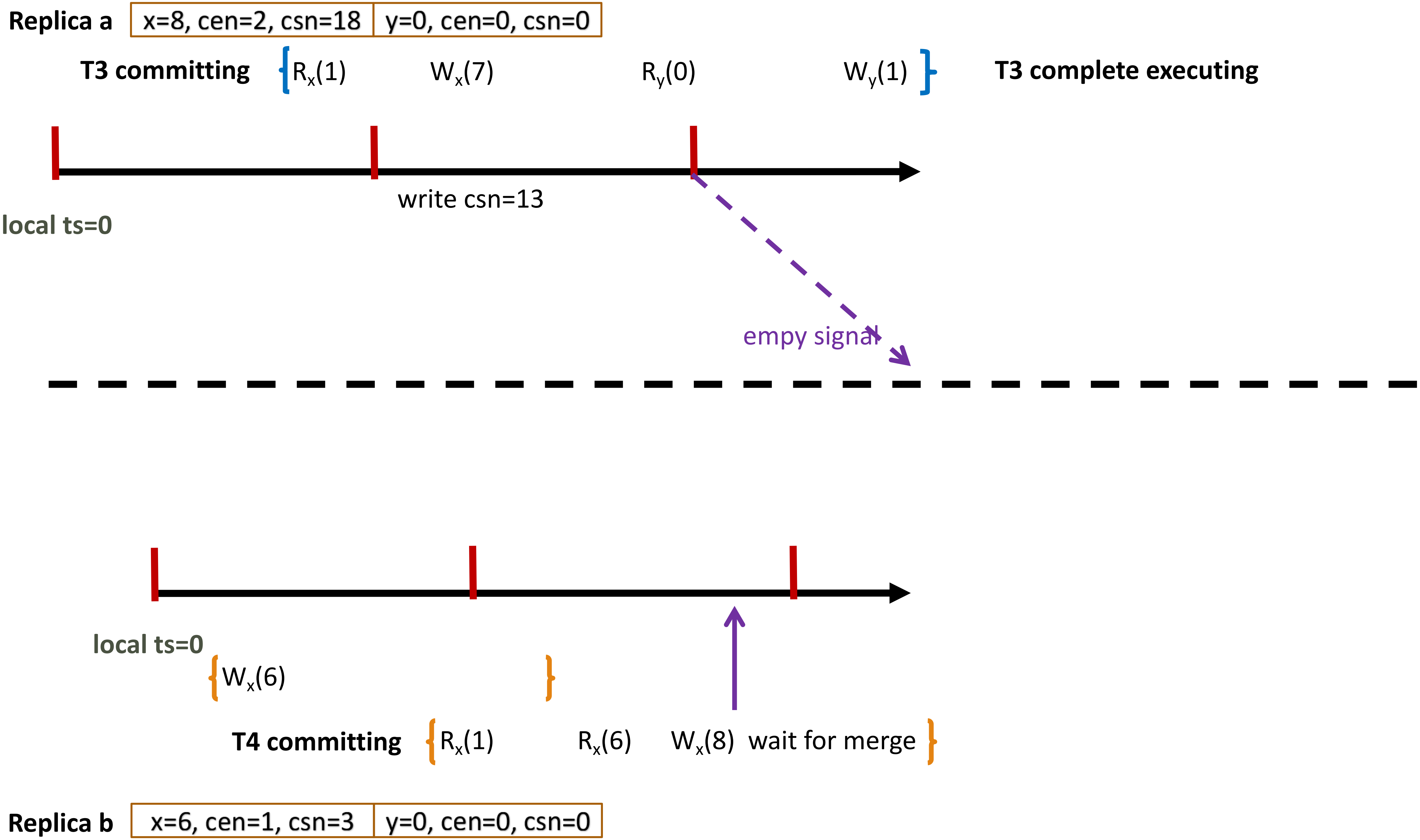


Replica a
x=6, cen=1, csn=3
y=0, cen=0, csn=0
T3 executing
$R_x(1)$
$W_x(7)$
$R_y(0)$
write csn=13
local ts=0
empy signal
send <x=8, cen=2, csn=18>
to replica a
epoch 2 ends,
send updates to other peers
write csn=18
local ts=20
local ts=0
$W_x(6)$ … wait for merge …
<x=8, cen=2, csn=18>
T4 committing
$R_x(1)$
$R_x(6)$
$W_x(8)$
Replica b
x=6, cen=1, csn=3
y=0, cen=0, csn=0

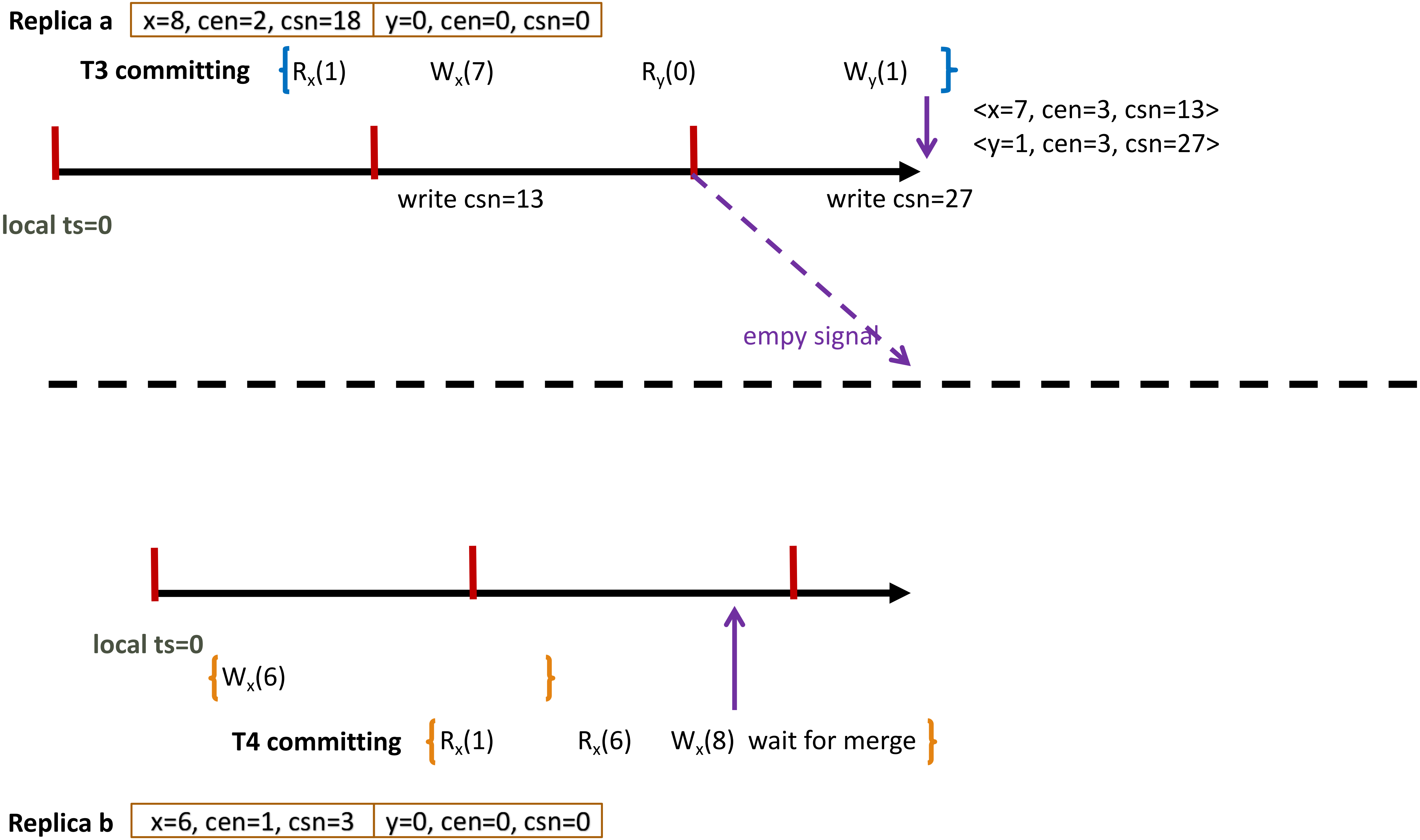


Replica a
x=6, cen=1, csn=3
y=0, cen=0, csn=0
T3 executing
$R_x(1)$
$W_x(7)$
$R_y(0)$
epoch merge
<x=8, cen=2, csn=18>
remote updates arrieve merge
write csn=13
local ts=0
empy signal
<x=8, cen=2, csn=18>
local ts=0
$W_x(6)$
T4 committing
$R_x(1)$
$R_x(6)$
$W_x(8)$
Replica b
x=6, cen=1, csn=3
y=0, cen=0, csn=0

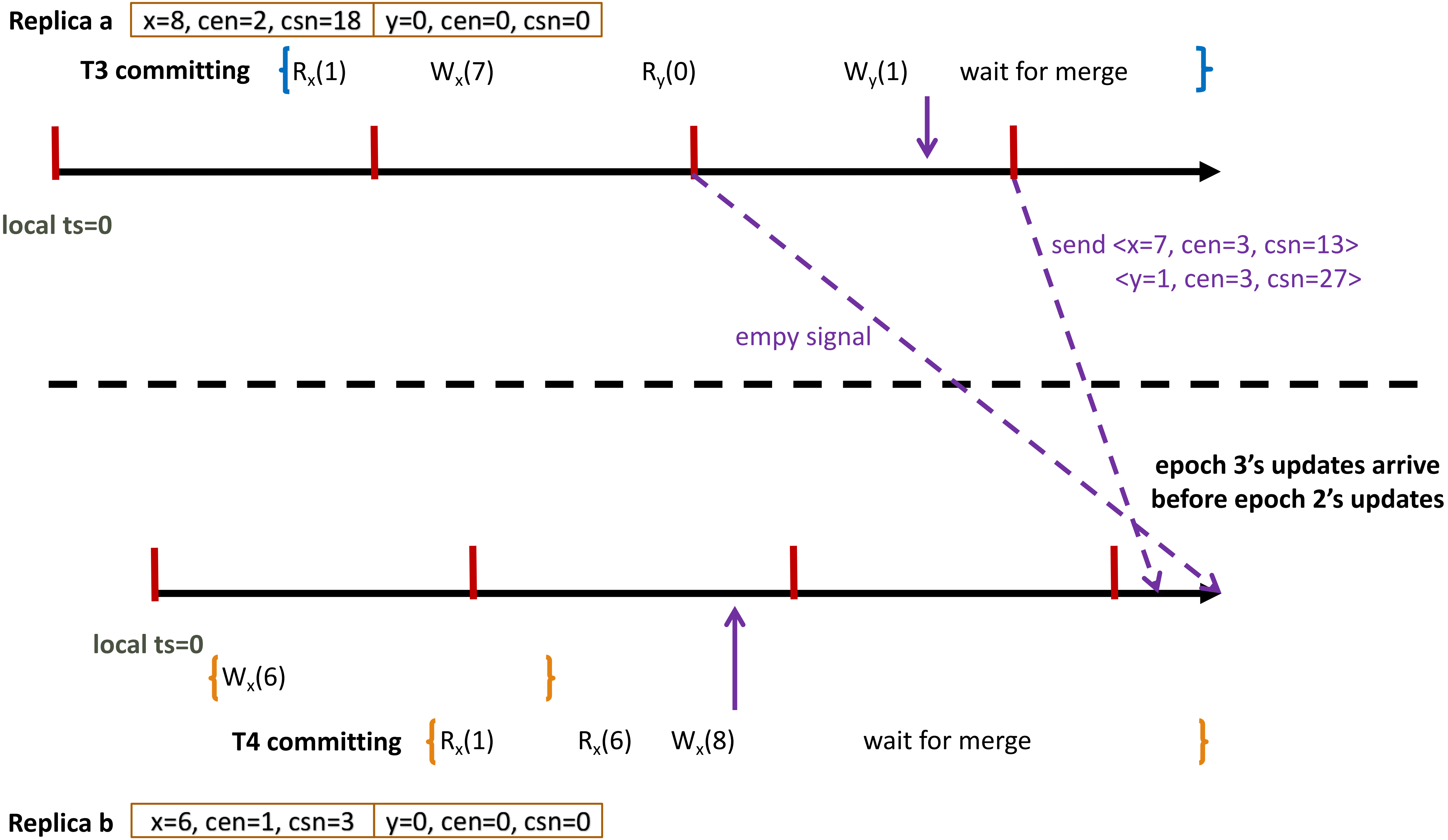

Replica a
x=8, cen=2, csn=18
y=0, cen=0, csn=0
T3 executing
$R_x(1)$
$W_x(7)$
$R_y(0)$
commit
<x=8, cen=2, csn=18>
merge remote updates
commit T4' updates
write csn=13
local ts=0
empy signal
<x=8, cen=2, csn=18>
local ts=0
$W_x(6)$
T4 committing
$R_x(1)$
$R_x(6)$
$W_x(8)$
Replica b
x=6, cen=1, csn=3
y=0, cen=0, csn=0

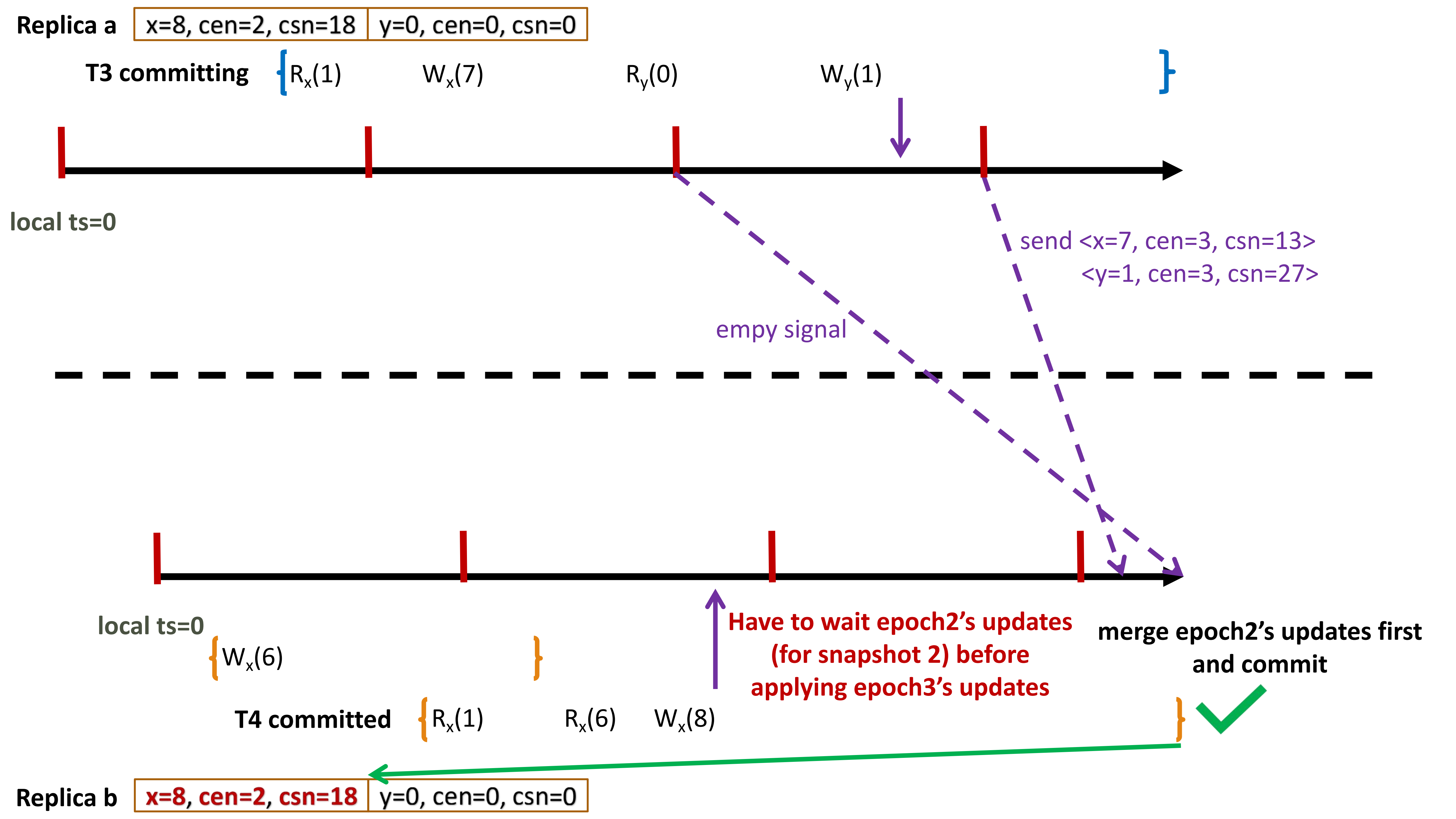


Replica a
x=8, cen=2, csn=18
y=0, cen=0, csn=0
T3 committing
$R_x(1)$
$W_x(7)$
$R_y(0)$
$W_y(1)$
T3 complete executing
write csn=13
local ts=0
empy signal
local ts=0
$W_x(6)$
T4 committing
$R_x(1)$
$R_x(6)$
$W_x(8)$
wait for merge
Replica b
x=6, cen=1, csn=3
y=0, cen=0, csn=0

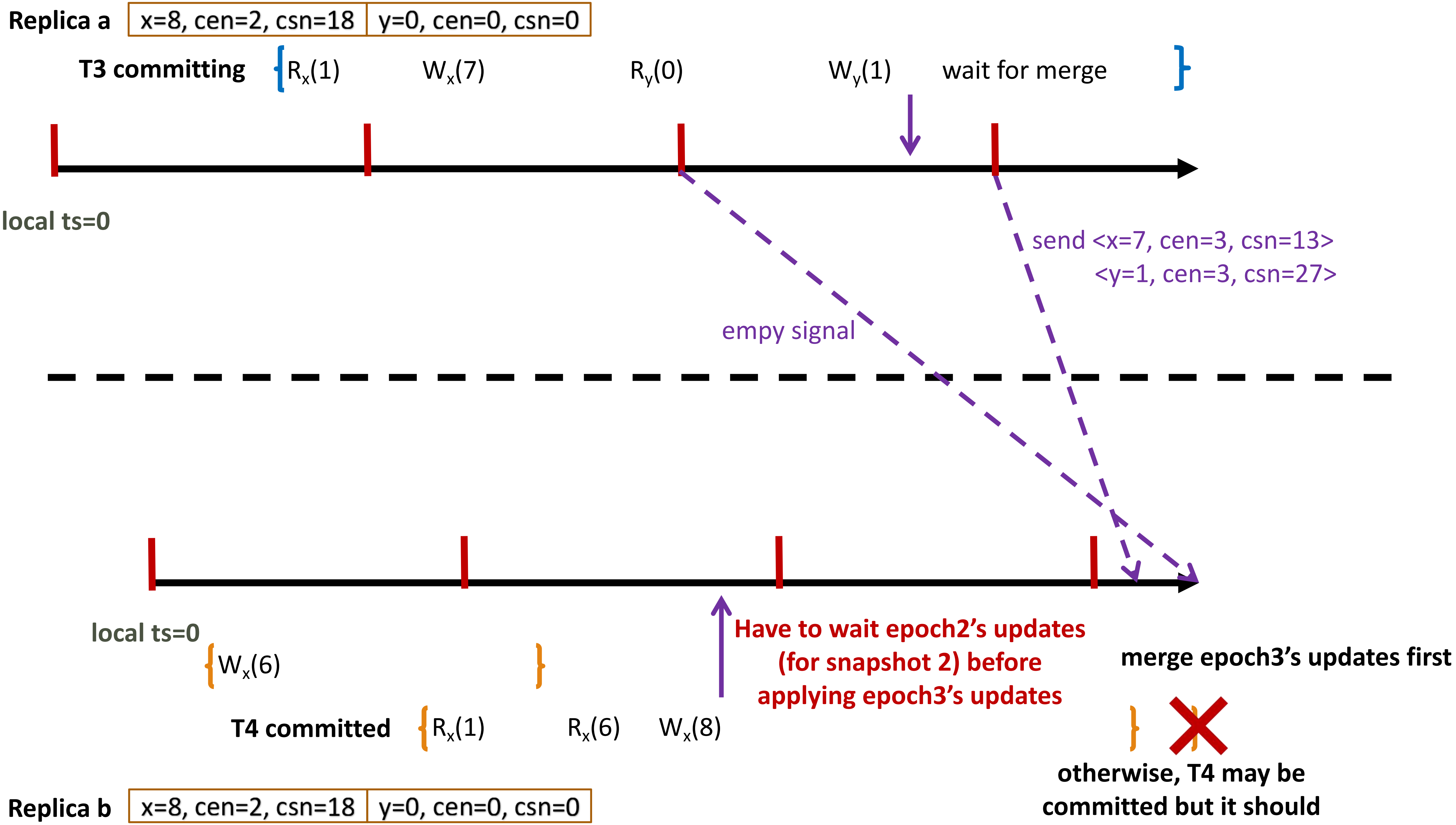


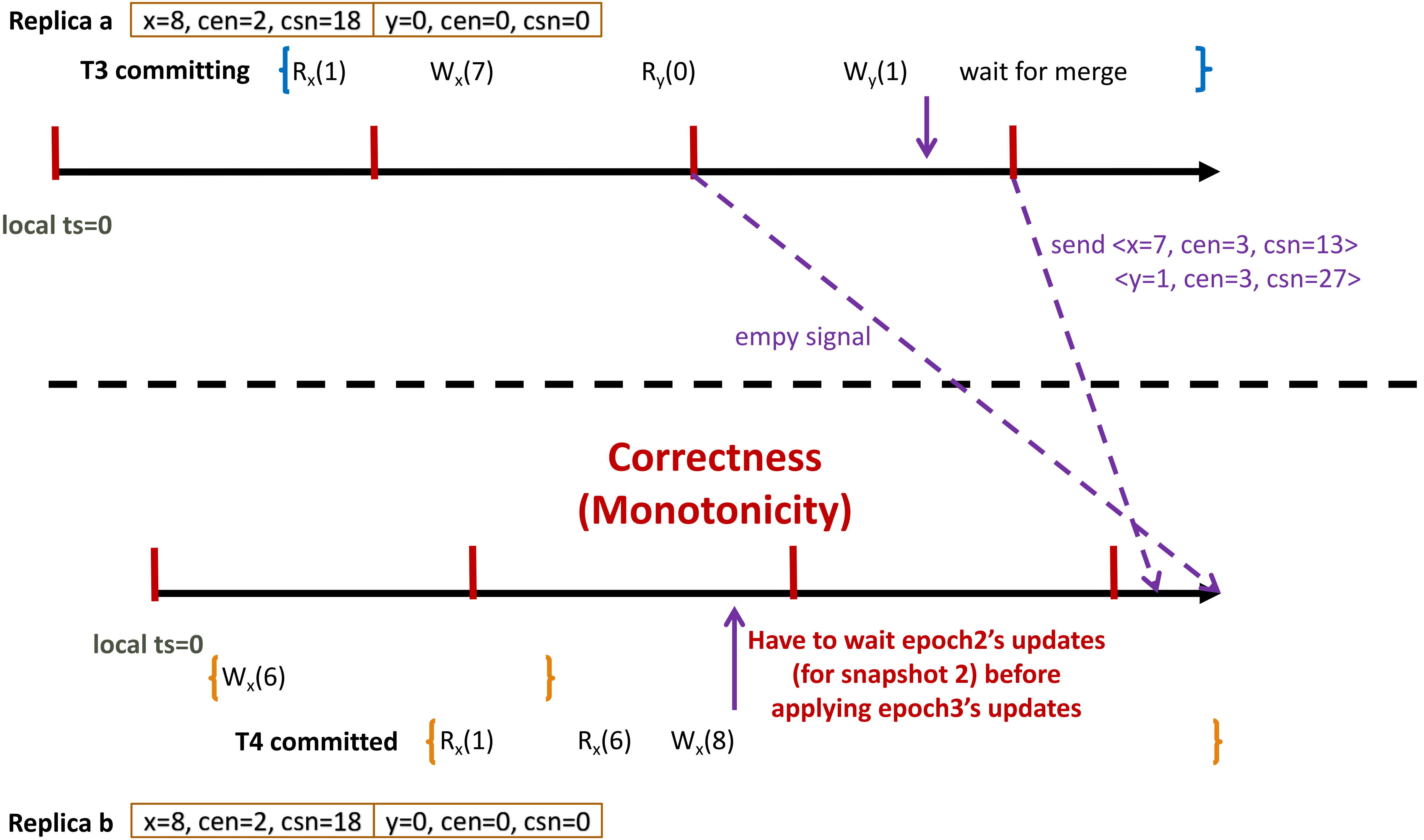
Replica a
x=8, cen=2, csn=18
y=0, cen=0, csn=0
T3 committing
$R_x(1)$
$W_x(7)$
$R_y(0)$
$W_y(1)$
<x=7, cen=3, csn=13>
<y=1, cen=3, csn=27>
write csn=13
write csn=27
local ts=0
empy signal
local ts=0
$W_x(6)$
T4 committing
$R_x(1)$
$R_x(6)$
$W_x(8)$
wait for merge
Replica b
x=6, cen=1, csn=3
y=0, cen=0, csn=0

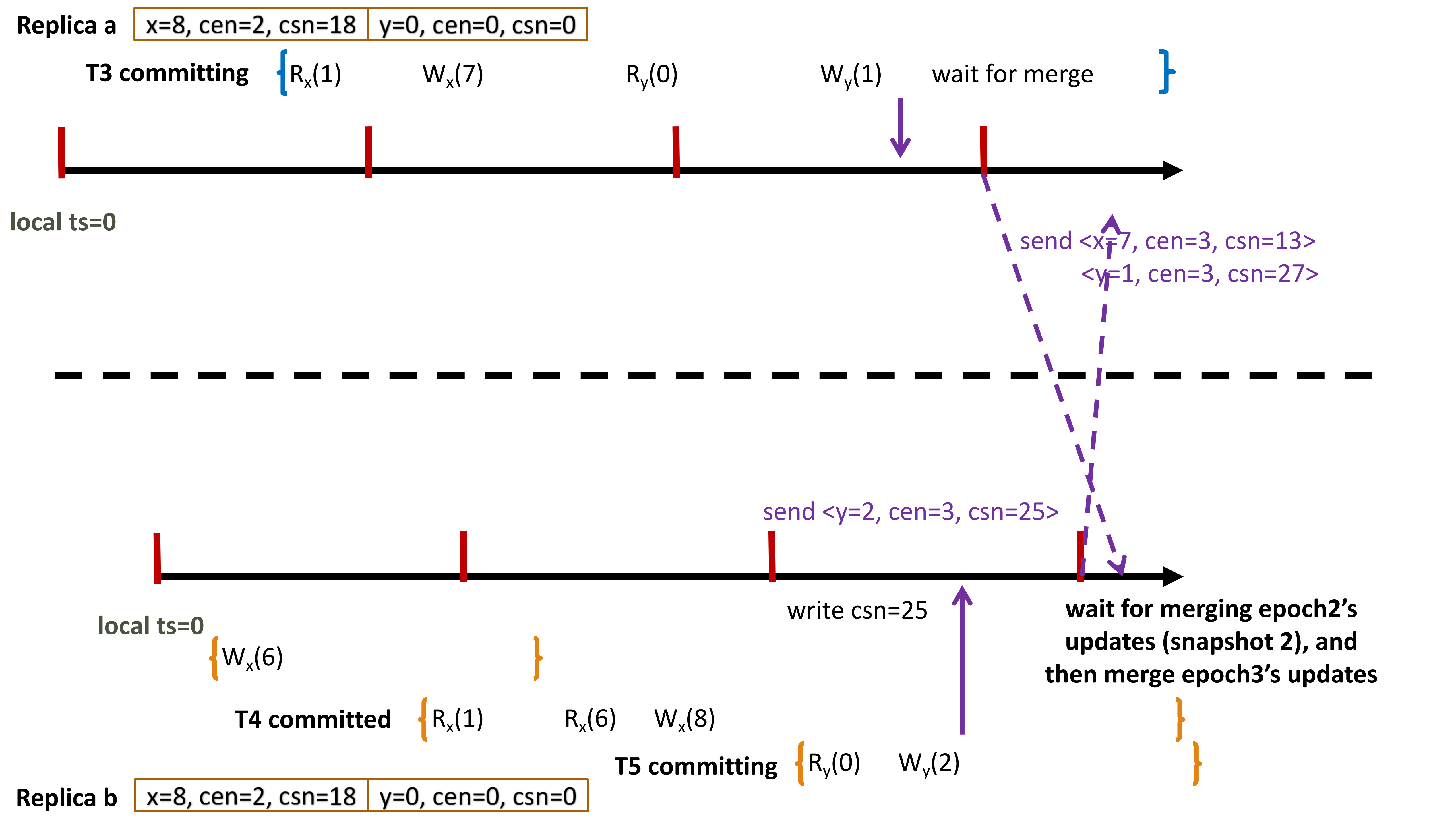

Replica a
x=8, cen=2, csn=18
y=0, cen=0, csn=0
T3 committing
$R_x(1)$
$W_x(7)$
$R_y(0)$
$W_y(1)$
wait for merge
local ts=0
send <x=7, cen=3, csn=13>
<y=1, cen=3, csn=27>
empy signal
epoch 3's updates arrive
before epoch 2's updates
local ts=0
$W_x(6)$
T4 committing
$R_x(1)$
$R_x(6)$
$W_x(8)$
wait for merge
Replica b
x=6, cen=1, csn=3
y=0, cen=0, csn=0



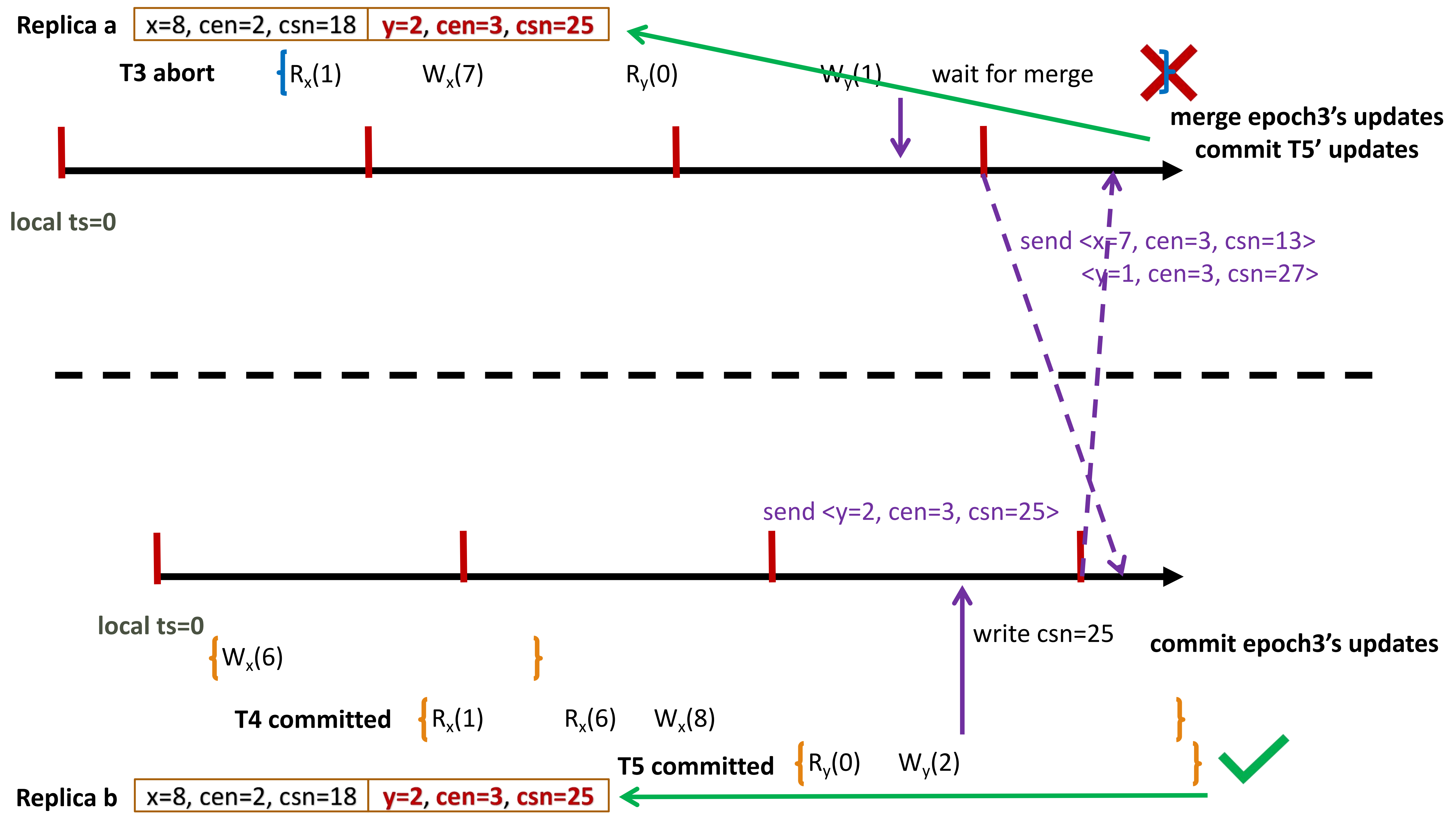
Replica a
x=8, cen=2, csn=18
y=0, cen=0, csn=0
T3 committing
$R_x(1)$
$W_x(7)$
$R_y(0)$
$W_y(1)$
local ts=0
send <x=7, cen=3, csn=13>
<y=1, cen=3, csn=27>
empy signal
local ts=0
$W_x(6)$
Have to wait epoch2's updates
(for snapshot 2) before
applying epoch3's updates
merge epoch2's updates first
and commit
T4 committed
$R_x(1)$
$R_x(6)$
$W_x(8)$
Replica b
x=8, cen=2, csn=18
y=0, cen=0, csn=0


Replica a
x=8, cen=2, csn=18
y=0, cen=0, csn=0
T3 committing
$R_x(1)$
$W_x(7)$
$R_y(0)$
$W_y(1)$
wait for merge
local ts=0
send <x=7, cen=3, csn=13>
<y=1, cen=3, csn=27>
empy signal
local ts=0
$W_x(6)$
Have to wait epoch2's updates
(for snapshot 2) before
applying epoch3's updates
merge epoch3's updates first
T4 committed
$R_x(1)$
$R_x(6)$
$W_x(8)$
otherwise, T4 may be
committed but it should
Replica b
x=8, cen=2, csn=18
y=0, cen=0, csn=0

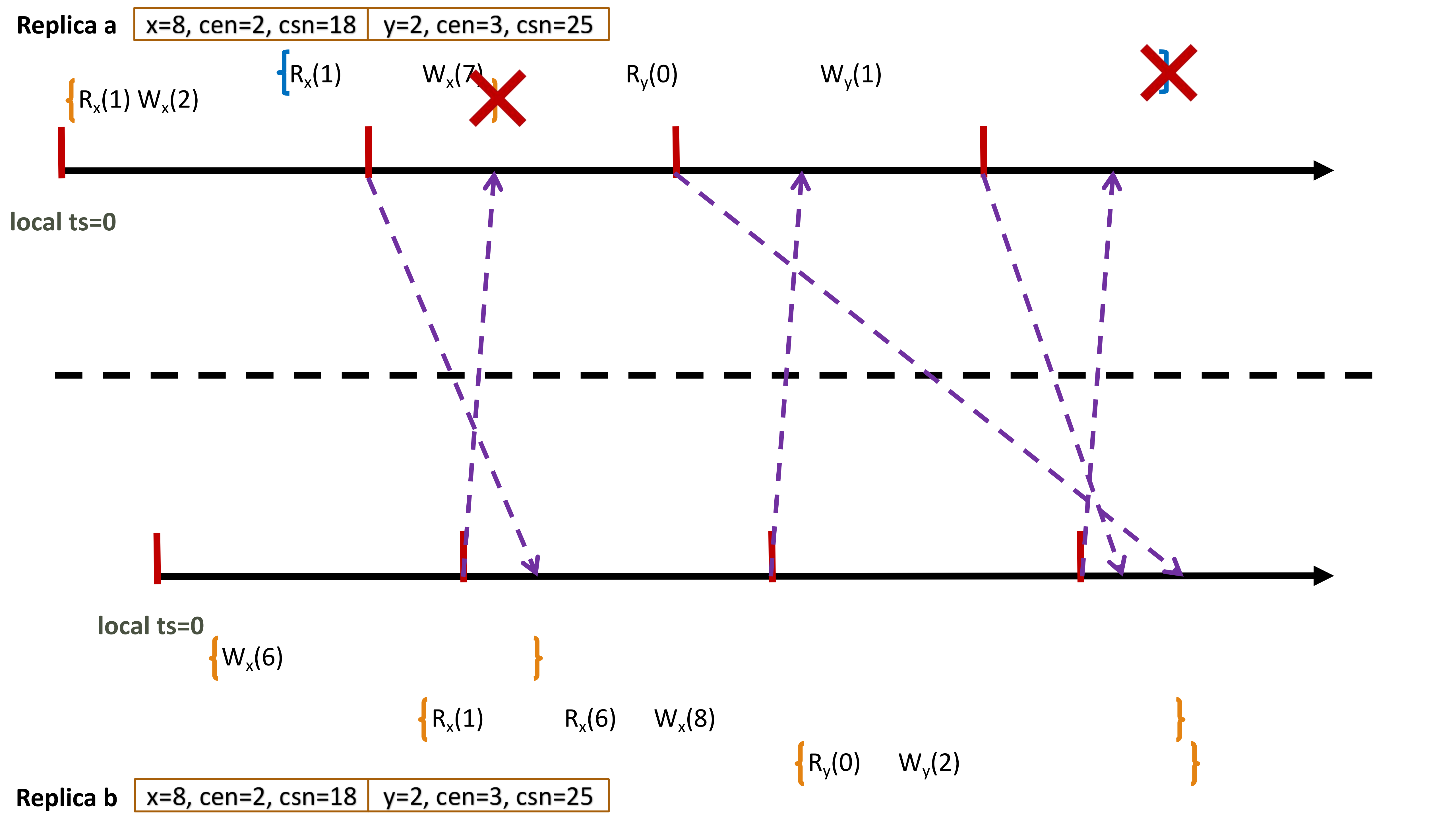

Replica a
x=8, cen=2, csn=18
y=0, cen=0, csn=0
T3 committing
$R_x(1)$
$W_x(7)$
$R_y(0)$
$W_y(1)$
wait for merge
local ts=0
send <x=7, cen=3, csn=13>
<y=1, cen=3, csn=27>
empy signal
Correctness
(Monotonicity)
local ts=0
$W_x(6)$
Have to wait epoch2's updates
(for snapshot 2) before
applying epoch3's updates
T4 committed
$R_x(1)$
$R_x(6)$
$W_x(8)$
Replica b
x=8, cen=2, csn=18
y=0, cen=0, csn=0



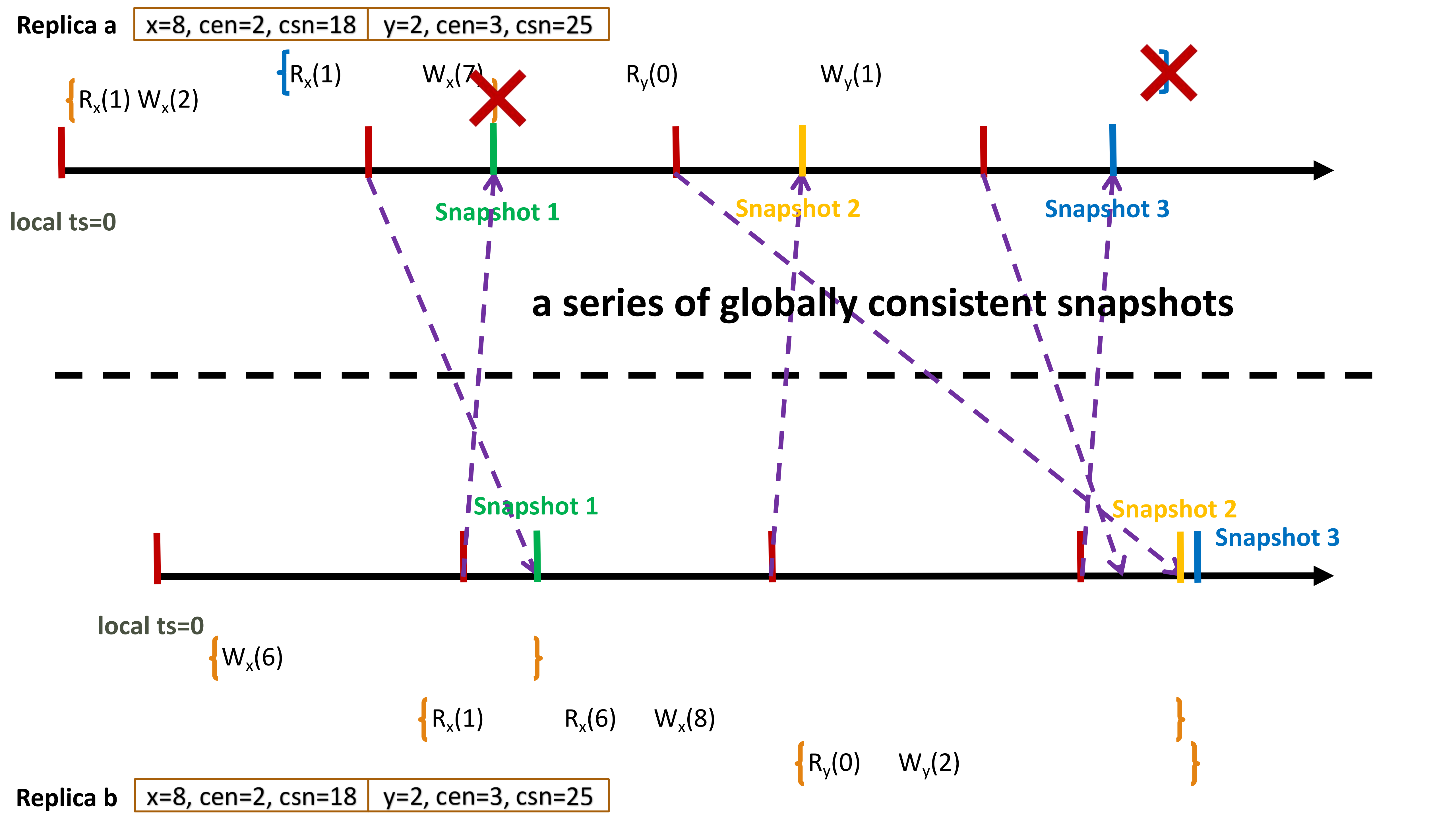
Replica a
x=8, cen=2, csn=18
y=0, cen=0, csn=0
T3 committing
$R_x(1)$
$W_x(7)$
$R_y(0)$
$W_y(1)$
wait for merge
local ts=0
send <x=7, cen=3, csn=13>
<y=1, cen=3, csn=27>
send <y=2, cen=3, csn=25>
write csn=25
wait for merging epoch2's updates (snapshot 2), and then merge epoch3's updates
local ts=0
$W_x(6)$
T4 committed
$R_x(1)$
$R_x(6)$
$W_x(8)$
T5 committing
$R_y(0)$
$W_y(2)$
Replica b
x=8, cen=2, csn=18
y=0, cen=0, csn=0



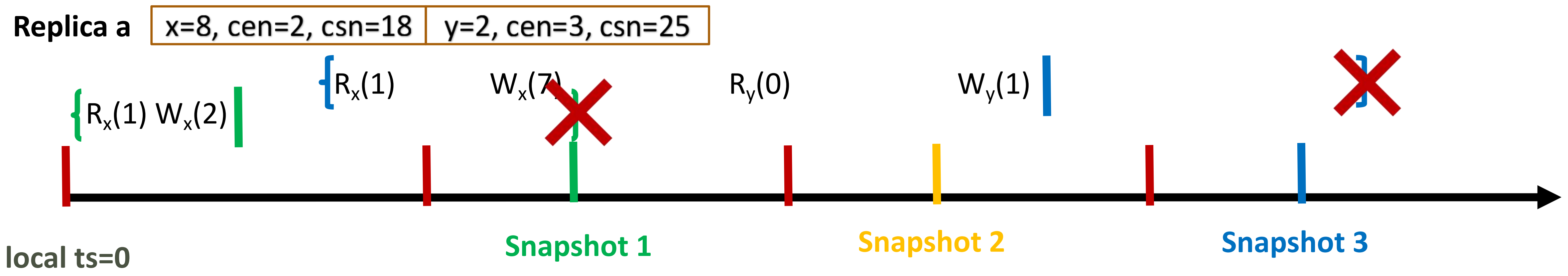
Replica a
x=8, cen=2, csn=18
y=2, cen=3, csn=25
T3 abort
Rx(1)
Wx(7)
Ry(0)
Wy(1)
wait for merge
merge epoch3's updates
commit T5' updates
local ts=0
send <x=7, cen=3, csn=13>
<y=1, cen=3, csn=27>
send <y=2, cen=3, csn=25>
local ts=0
Wx(6)
write csn=25
commit epoch3's updates
T4 committed
Rx(1)
Rx(6)
Wx(8)
T5 committed
Ry(0)
Wy(2)
Replica b
x=8, cen=2, csn=18
y=2, cen=3, csn=25



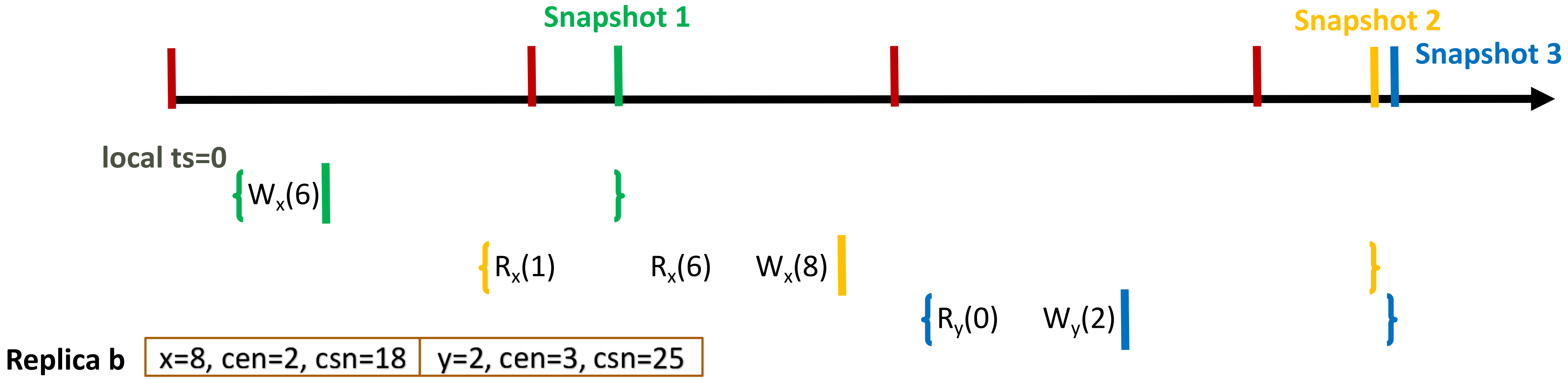
Replica a
x=8, cen=2, csn=18
y=2, cen=3, csn=25
{Rx(1)
Wx(7)
}
Ry(0)
Wy(1)
}
{Rx(1) Wx(2)
local ts=0
local ts=0
{Wx(6)
}
{Rx(1)
Rx(6)
Wx(8)
}
{Ry(0)
Wy(2)
}
Replica b
x=8, cen=2, csn=18
y=2, cen=3, csn=25



Replica a
x=8, cen=2, csn=18
y=2, cen=3, csn=25
$R_x(1)$ $W_x(2)$
$R_x(1)$
$W_x(7)$
$R_y(0)$
$W_y(1)$
local ts=0
Snapshot 1
Snapshot 2
Snapshot 3
a series of globally consistent snapshots
Snapshot 1
Snapshot 2
Snapshot 3
local ts=0
$W_x(6)$
$R_x(1)$
$R_x(6)$
$W_x(8)$
$R_y(0)$
$W_y(2)$
Replica b
x=8, cen=2, csn=18
y=2, cen=3, csn=25



Tx does not knows its commit/abort status until the snapshot of its commit epoch is generated(after merge)



More Details

More:

- DeltaCRDTMerge algorithm
- Isolation levels
- Consistency Proof
- Optimization
- Fault Tolerance
- …

GeoGauss: Strongly Consistent and Light-Coordinated OLTP for Geo-Replicated SQL Database

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GE YU, Northeastern University, China

Multinational enterprises conduct global business that has a demand for geo-distributed transactional databases. Existing state-of-the-art databases adopt a sharded master-follower replication architecture. However, the single-master serving mode incurs massive cross-region writes from clients, and the sharded architecture requires multiple round-trip acknowledgments (*e.g.*, 2PC) to ensure atomicity for cross-shard transactions. These limitations drive us to seek yet another design choice. In this paper, we propose a strongly consistent OLTP database GeoGauss with full replica multi-master architecture. To efficiently merge the updates from different master nodes, we propose a multi-master OCC that unifies data replication and concurrent transaction processing. By leveraging an epoch-based delta state merge rule and the optimistic asynchronous execution, GeoGauss ensures strong consistency with light-coordinated protocol and allows more concurrency with weak isolation, which are sufficient to meet our needs. Our geo-distributed experimental results show that GeoGauss achieves 7.06X higher throughput and 17.41X lower latency than the state-of-the-art geo-distributed database CockroachDB on the TPC-C benchmark.

CCS Concepts: • **Information systems → Relational parallel and distributed DBMSs.**

Additional Key Words and Phrases: Geo-distributed; multi-master replication; replica consistency; transaction processing; deterministic databases

ACM Reference Format:
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62

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Evaluation

Cluster Set Up:

- 3 geo-distributed nodes

  Chengdu (Southwest China),

  Shenzhen (South China),

  Zhangjiakou (North China).
- 32 vCPUs, 256G DRAM, Centos 7.6
- 100Mbps

Benchmark:

- YCSB[1]
  - YCSB-RO (100% read)
  - YCSB-MC (80% read, 20% write, $\theta = 0.9$)
- TPC-C[2]

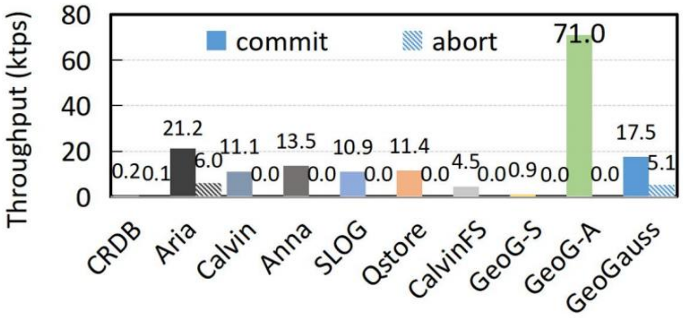
1: YCSB 10 op/txn

2: 50% New-Order – 50% Payment in Aria[VLDB2020]

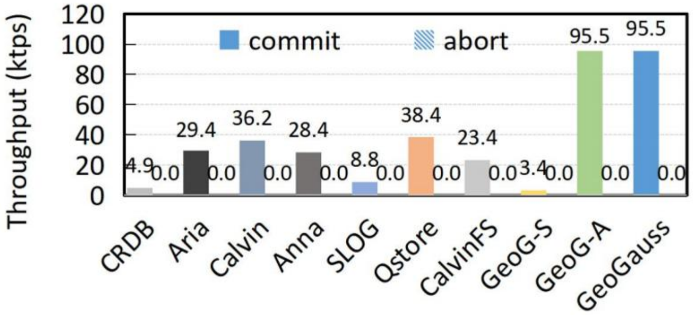
Inter- and intra-cluster ping round-trip times (latency)

	Chengdu	Shenzhen	Zhangjiakou
Chengdu (Southwest China)	0.2 ms	37.5 ms	57.4 ms
Shenzhen (South China)		0.2 ms	38.3 ms
Zhangjiakou (North China)			0.2 ms

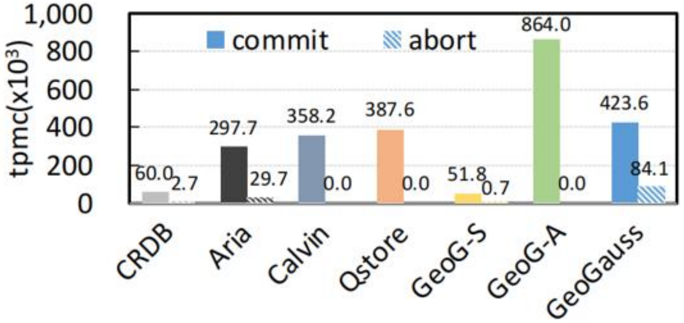
Overall Performance



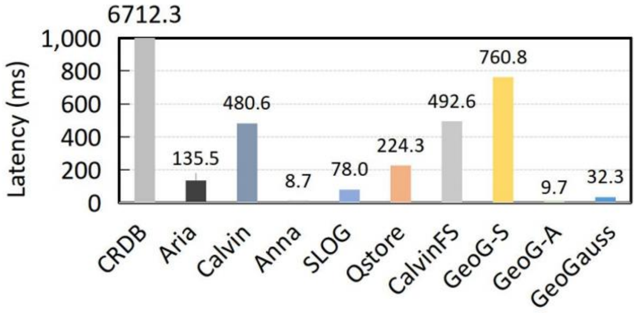
YCSB-MC Throughput



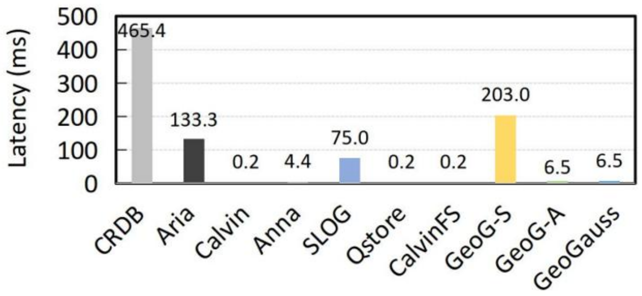
YCSB-RO Throughput



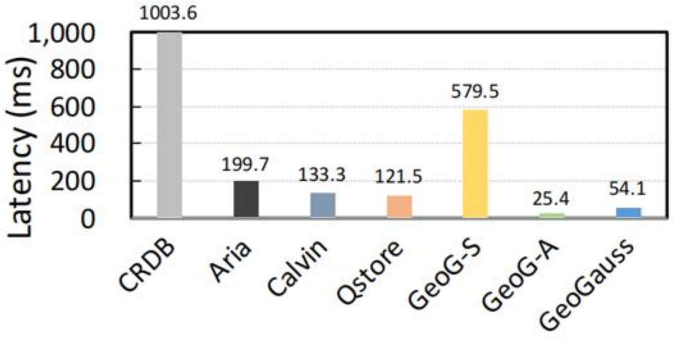
TPC-C Throughput



YCSB-MC Latency



YCSB-RO Latency



TPC-C Latency

System Breakdown

GeoG-S : *synchronous* execution and synchronous validation (*heavy coordination*)

GeoG-A : asynchronous execution and *asynchronous* validation (*eventual consistency*)

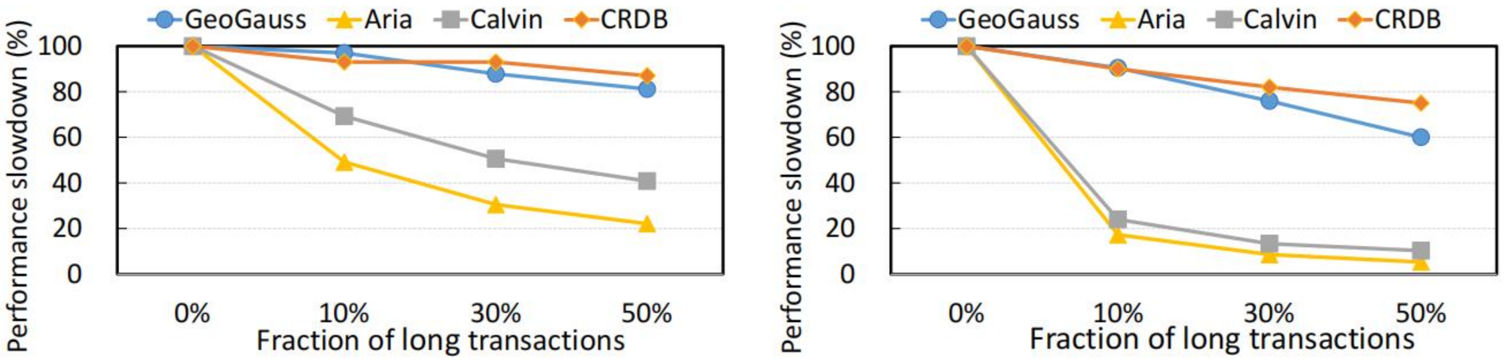
GeoGauss : asynchronous execution and synchronous validation

- Avoid long waits by asynchronous execution
- Achieve sequential consistency by synchronous validation

Table 2. Runtime breakdown of a transaction (TPC-C).

	GeoG-S	GeoG-A	GeoGauss
SQL Parse	4.6 ms	4.6 ms	4.6 ms
Execute	5.8 ms	6.5 ms	4.8 ms
Wait	**564.2 ms**	**0 ms**	**34.1 ms**
Merge	4.0 ms	10.9 ms	9.4 ms
Log	0.8 ms	6.5 ms	4.7 ms

Long Transaction



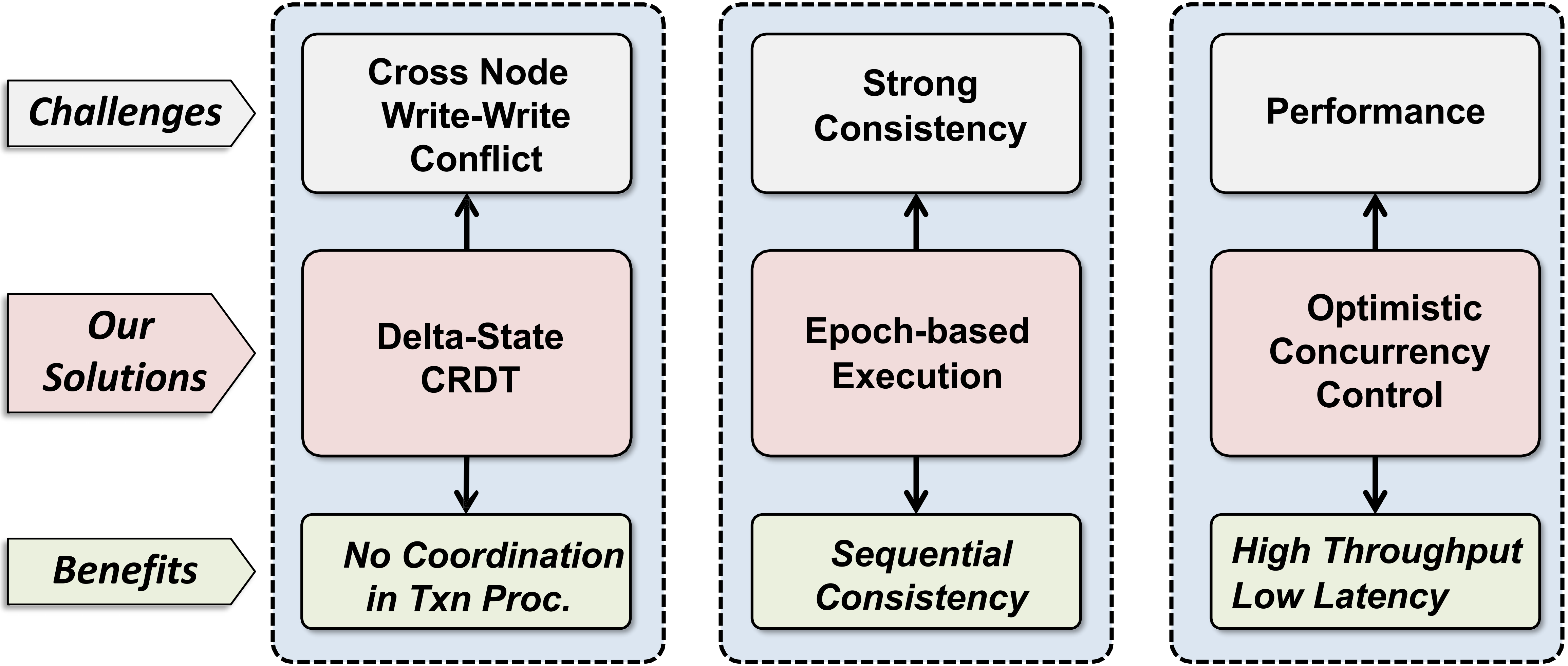
(a) Delay = 20ms (b) Delay = 100ms

Fig. 7. Effect of long transactions (YCSB-MC).

CRDB(CockroachDB) : sharded master-follower DB

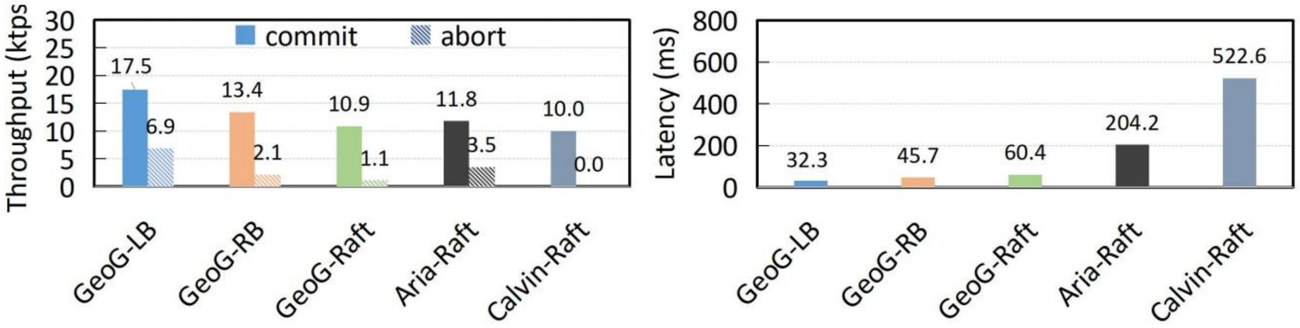
Calvin & Aria : Deterministic DB

Conclusion


Challenges
Our Solutions
Benefits
Cross Node Write-Write Conflict
Delta-State CRDT
No Coordination in Txn Proc.
Strong Consistency
Epoch-based Execution
Sequential Consistency
Performance
Optimistic Concurrency Control
High Throughput Low Latency

Thank you! Q&A

Fault tolerance



(a) throughput (b) latency

Fig. 12. Performance with fault tolerance (YCSB-MC).