Distributed Systems

The second half of *Concurrent and Distributed Systems*

https://www.cl.cam.ac.uk/teaching/current/ConcDisSys

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Computer Science Tripos, Part IB

Lecture 5

Replication

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- Keeping a copy of the same data on multiple nodes
- Databases, filesystems, caches, . . .
- A node that has a copy of the data is called a **replica**

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Compare to **RAID** (Redundant Array of Independent Disks): replication within a single computer

- RAID has single controller; in distributed system, each node acts independently
- Replicas can be distributed around the world, near users

Retrying state updates

User A: The moon is not actually made of cheese!

👍 Like   12,300 people like this.

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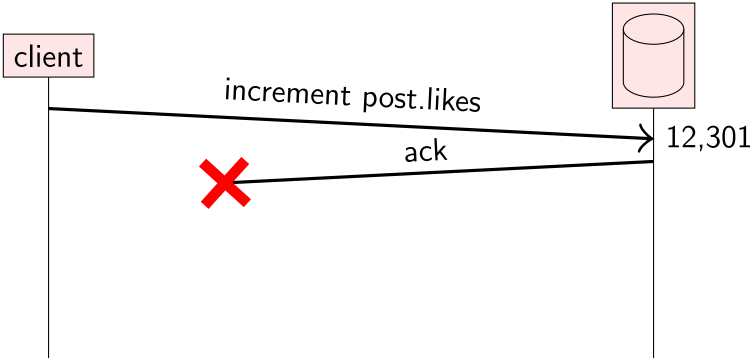

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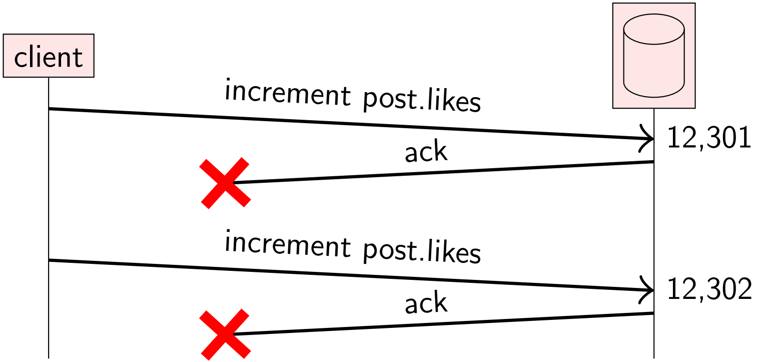

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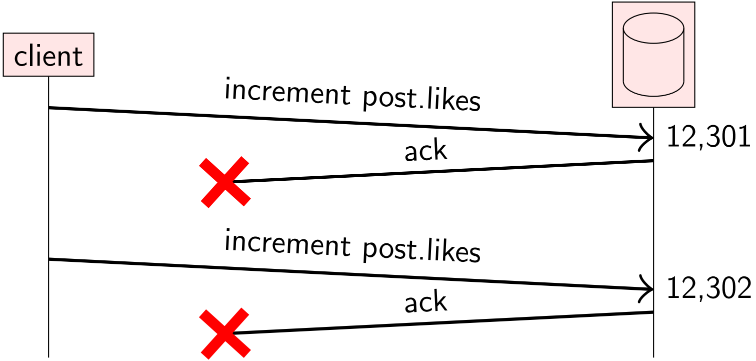
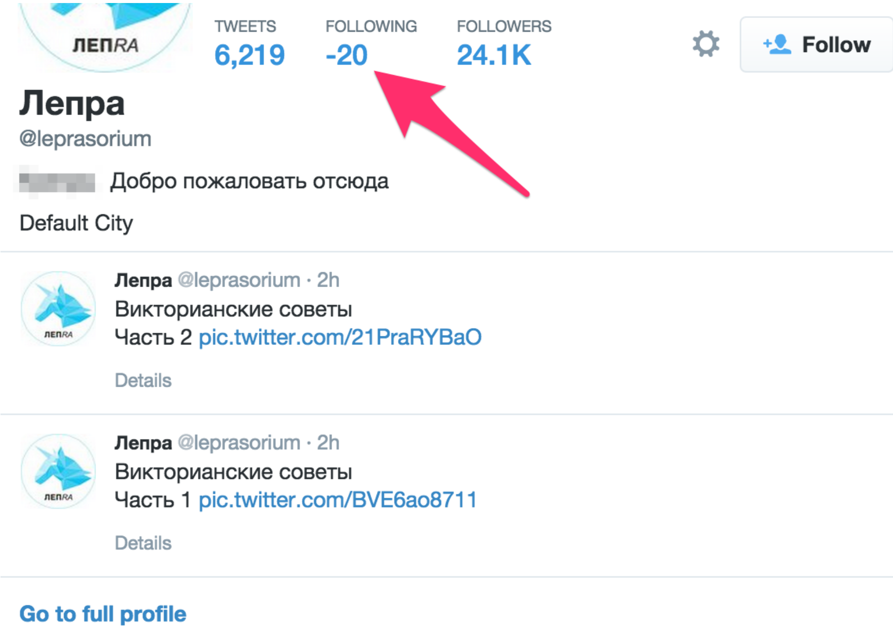


Deduplicating requests requires that the database tracks which requests it has already seen (in stable storage)



TWEETS 6,219

FOLLOWING -20

FOLLOWERS 24.1K

Лепра

@leprasorium

[redacted] Добро пожаловать отсюда

Default City

Лепра @leprasorium · 2h

Викторианские советы
Часть 2 pic.twitter.com/21PraRYBaO

Details

Лепра @leprasorium · 2h

Викторианские советы
Часть 1 pic.twitter.com/BVE6ao8711

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Idempotence

A function f is idempotent if $f(x) = f(f(x))$.

- **Not idempotent:** $f(likeCount) = likeCount + 1$
- **Idempotent:** $f(likeSet) = likeSet \cup \{userID\}$

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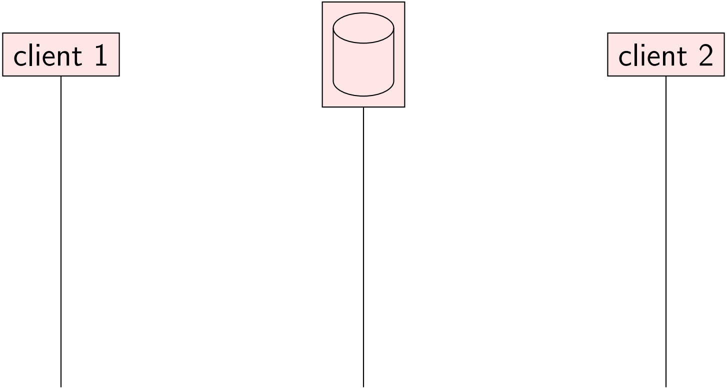
Choice of retry behaviour:

- **At-most-once** semantics:
  send request, don't retry, update may not happen
- **At-least-once** semantics:
  retry request until acknowledged, may repeat update
- **Exactly-once** semantics:
  retry $+$ idempotence or deduplication

Adding and then removing again



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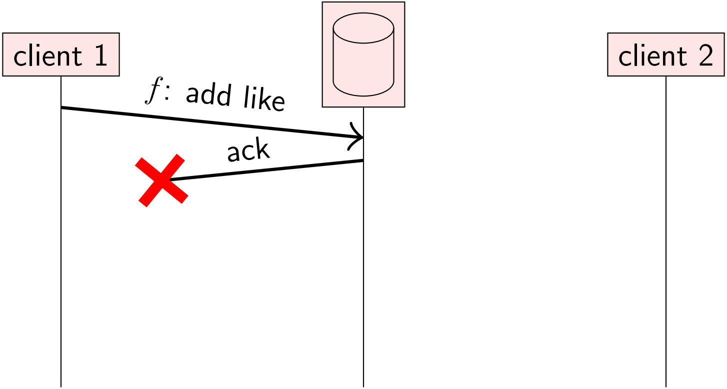

$$f(likes) = likes \cup \{userID\}$$

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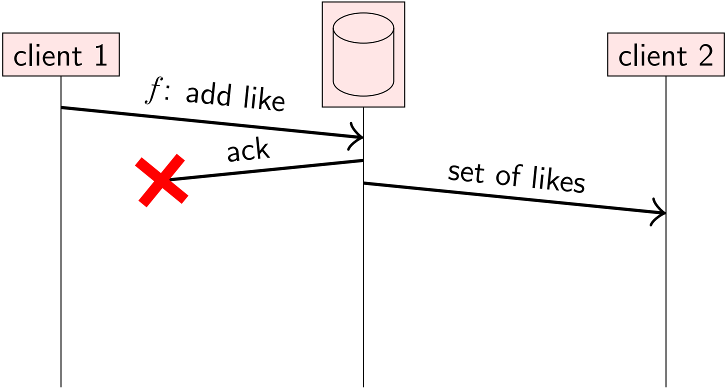

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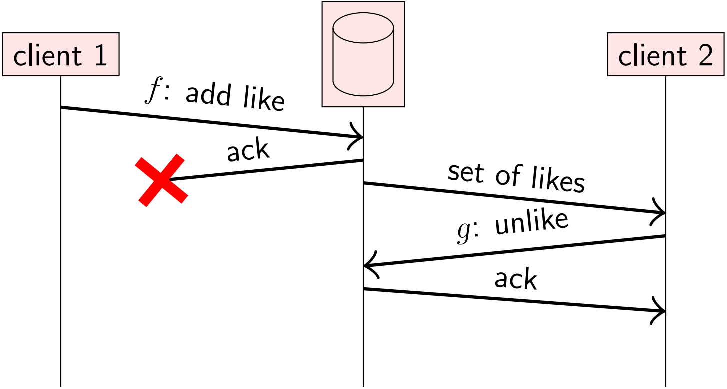

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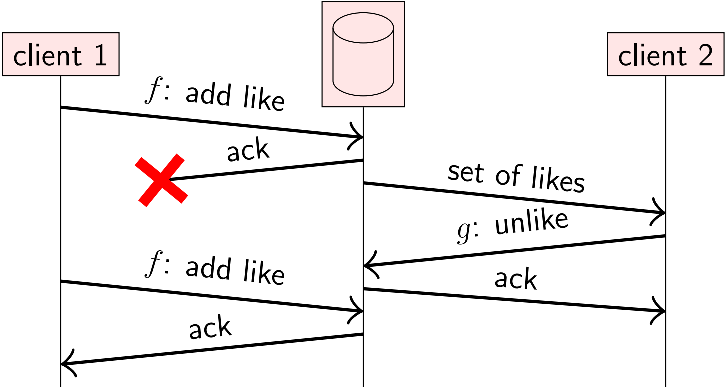

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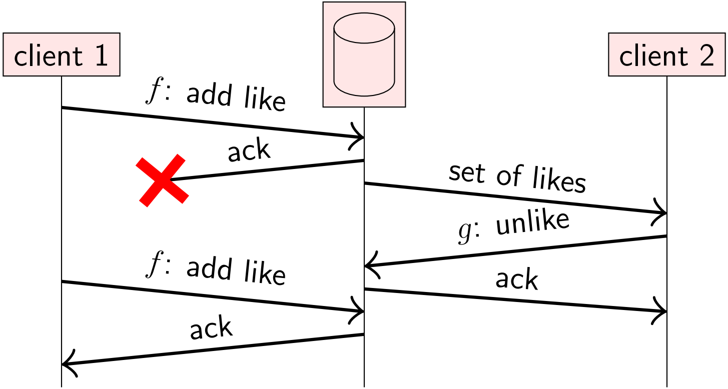
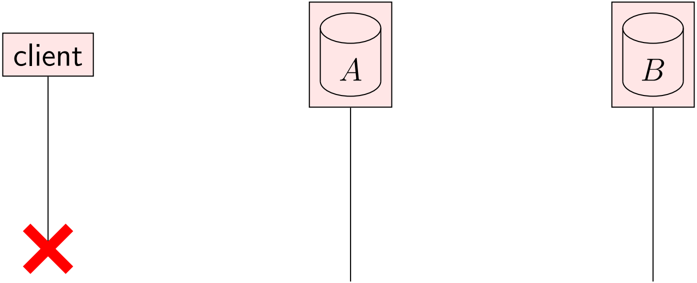


$f(likes) = likes \cup \{userID\}$
$g(likes) = likes \setminus \{userID\}$
Idempotent? $f(f(x)) = f(x)$ but $f(g(f(x)) \neq g(f(x))$

Another problem with adding and removing



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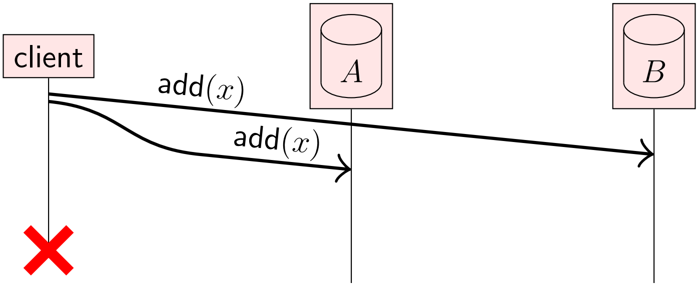

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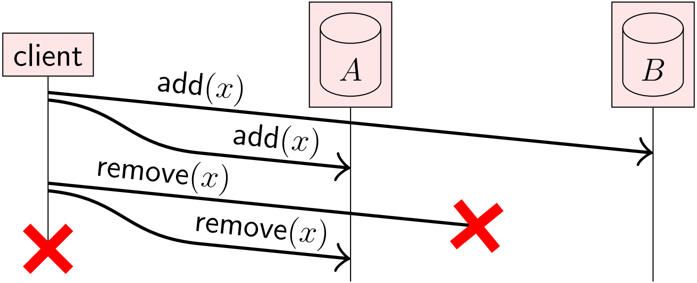

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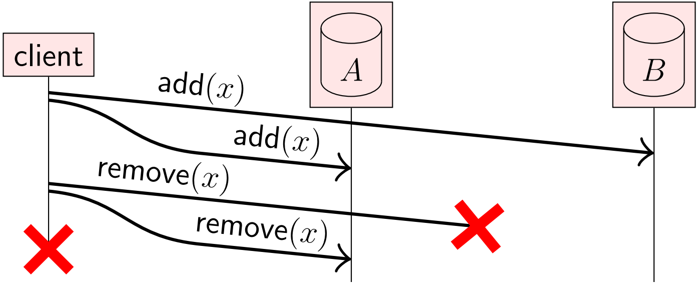

Final state ($x \notin A$, $x \in B$) is the same as in this case:

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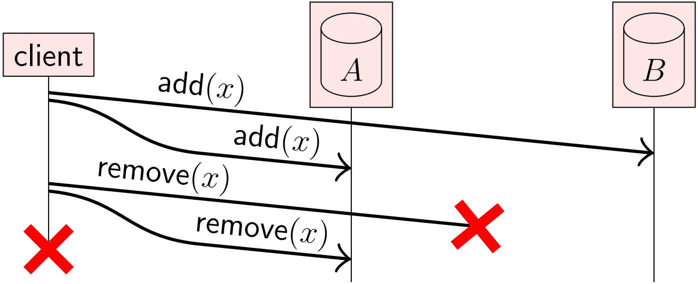

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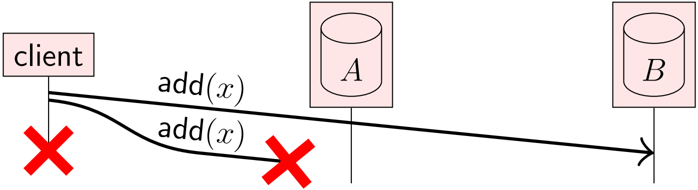
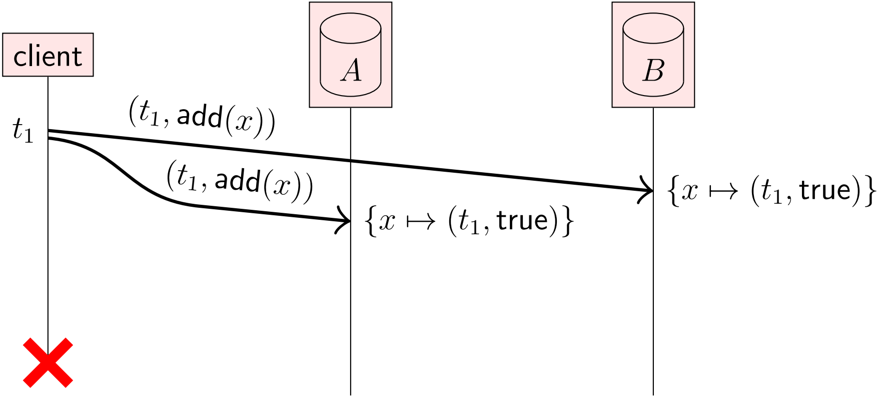


Timestamps and tombstones


client
A
B
t_1
$(t_1, \mathsf{add}(x))$
$(t_1, \mathsf{add}(x))$
$\{x \mapsto (t_1, \mathsf{true})\}$
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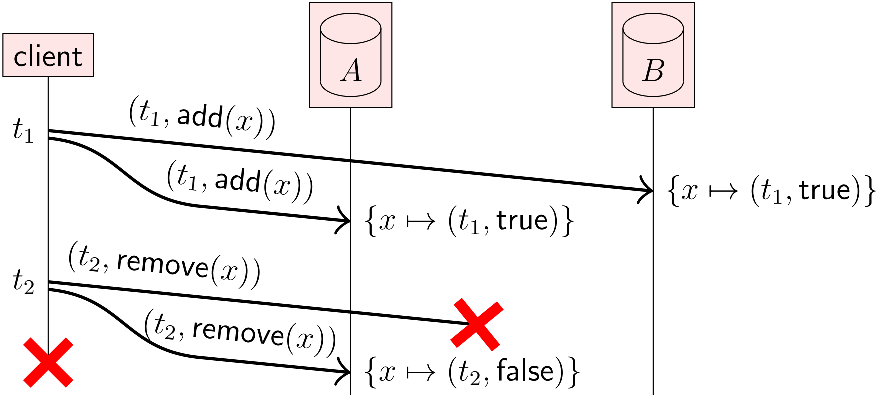
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t_2
$(t_2, \mathsf{remove}(x))$
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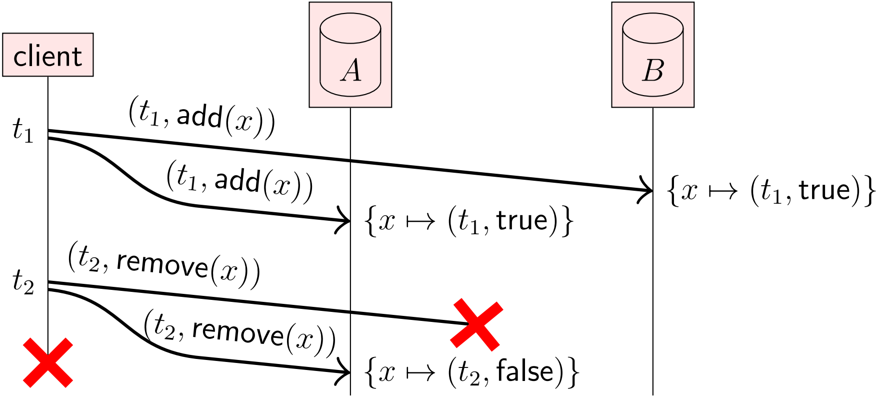
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"remove(x)" doesn't actually remove x: it labels x with "false" to indicate it is invisible (a **tombstone**)

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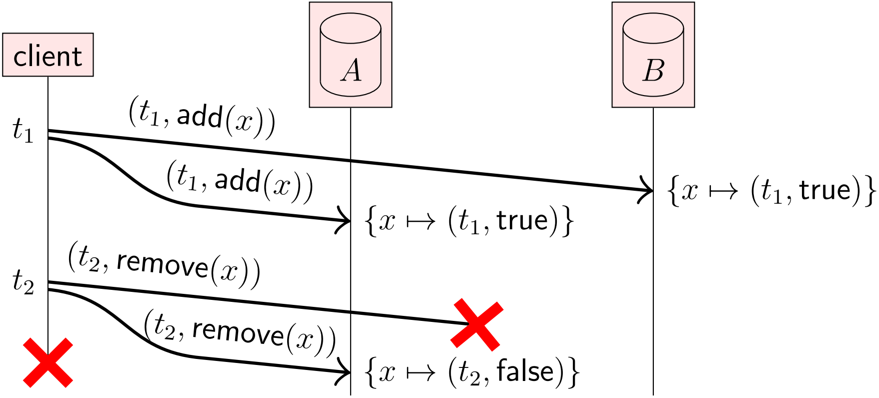
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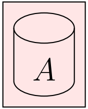
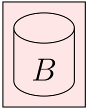
Every record has **logical timestamp** of last write

Reconciling replicas

Replicas periodically communicate among themselves to check for any inconsistencies.



$\{x \mapsto (t_2, \textsf{false})\}$



$\{x \mapsto (t_1, \textsf{true})\}$

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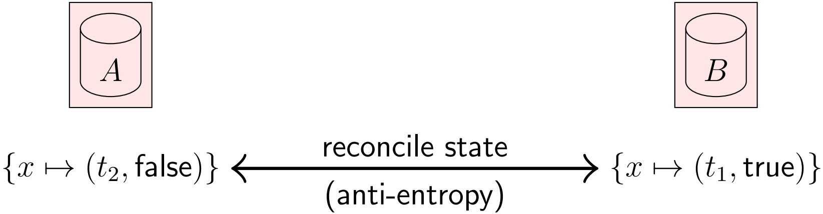

$\{x \mapsto (t_2, \text{false})\}$ reconcile state (anti-entropy) $\{x \mapsto (t_1, \text{true})\}$

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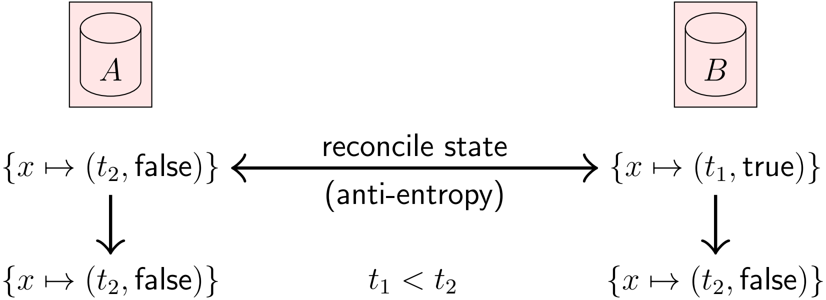

A

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reconcile state

(anti-entropy)

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$t_1 < t_2$

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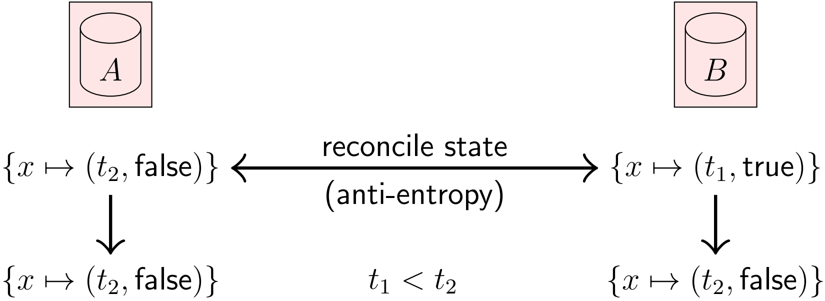
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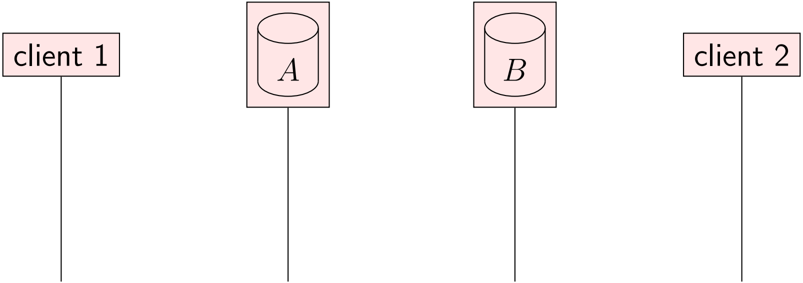
Propagate the record with the latest timestamp,
discard the records with earlier timestamps
(for a given key).

Concurrent writes by different clients



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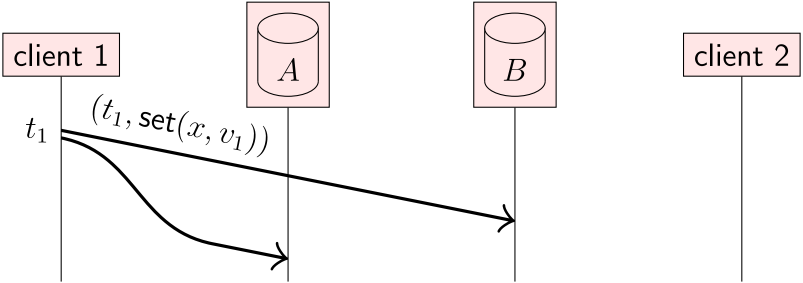

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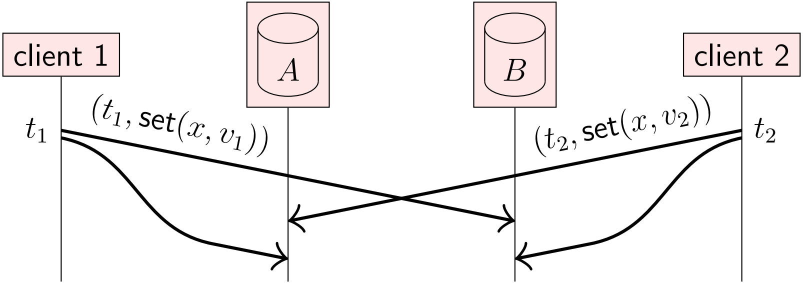

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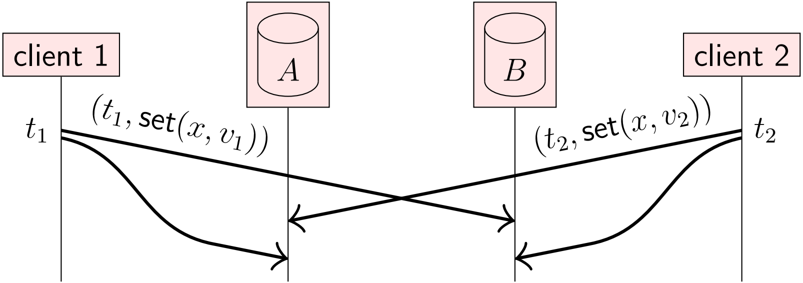

Two common approaches:

- **Last writer wins** (LWW):
  Use timestamps with total order (e.g. Lamport clock)
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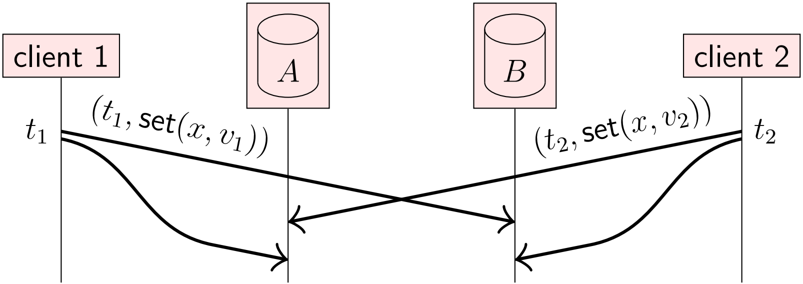

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  Use timestamps with total order (e.g. Lamport clock)
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- **Multi-value register**:
  Use timestamps with partial order (e.g. vector clock)
  v_2 replaces v_1 if $t_2 > t_1$; preserve both $\{v_1, v_2\}$ if $t_1 \parallel t_2$

Probability of faults

A replica may be **unavailable** due to network partition or node fault (e.g. crash, hardware problem).

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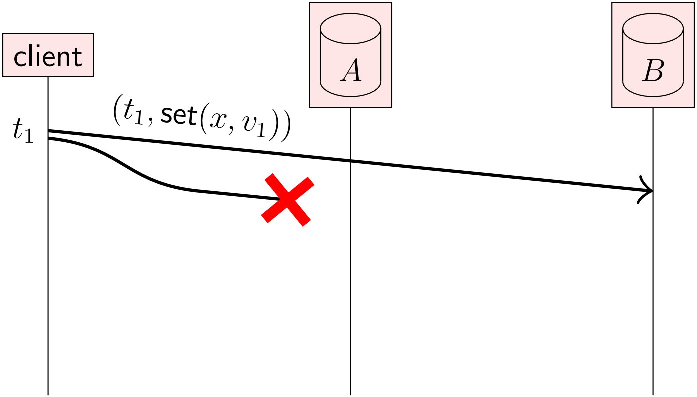
Example with $p = 0.01$:

replicas n	$P(\geq 1$ faulty$)$	$P(\geq \frac{n+1}{2}$ faulty$)$	$P($all n faulty$)$
1	0.01	0.01	0.01
3	0.03	$3 \cdot 10^{-4}$	10^{-6}
5	0.049	$1 \cdot 10^{-5}$	10^{-10}
100	0.63	$6 \cdot 10^{-74}$	10^{-200}

Read-after-write consistency



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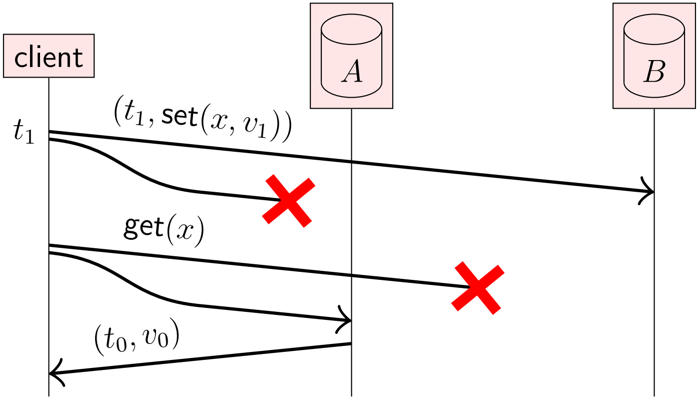

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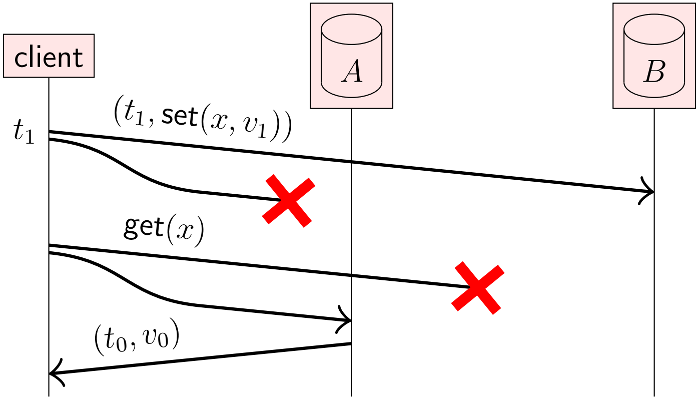

Writing to one replica, reading from another: client does not read back the value it has written

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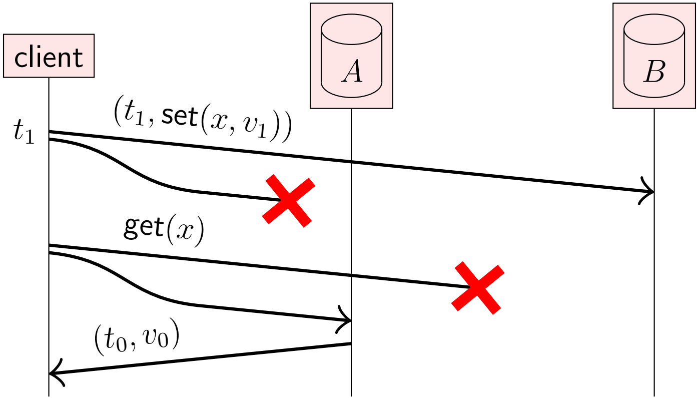
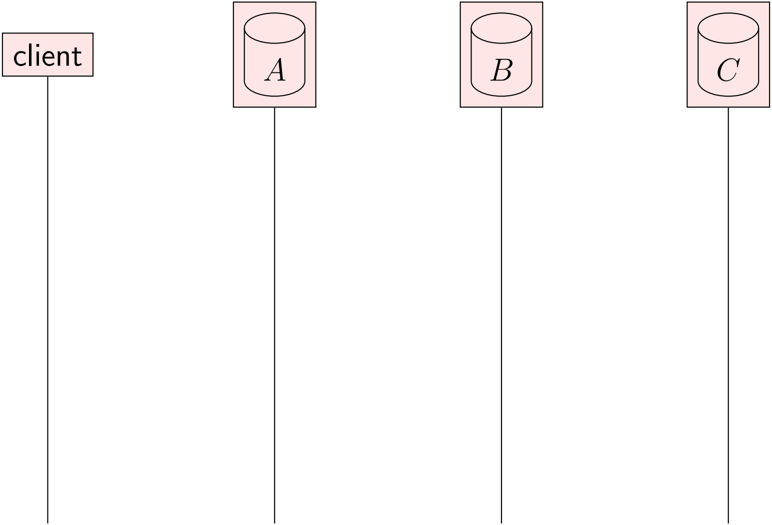


Writing to one replica, reading from another: client does not read back the value it has written

Require writing to/reading from both replicas $\Longrightarrow$ cannot write/read if one replica is unavailable

Quorum (2 out of 3)



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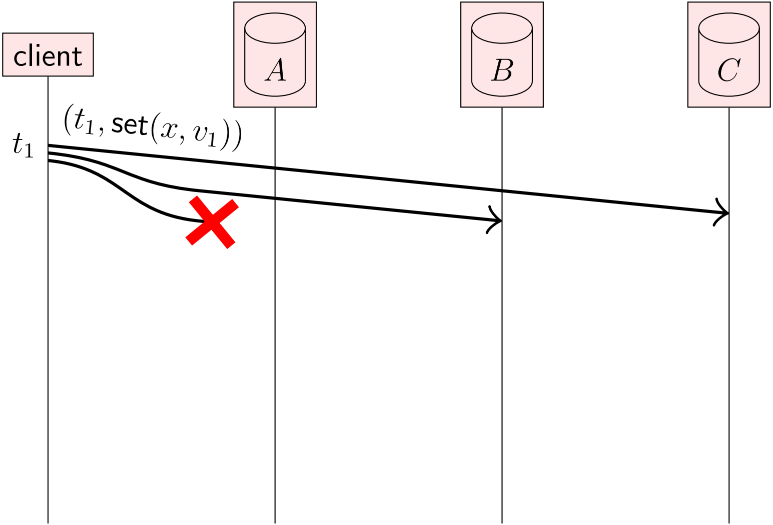

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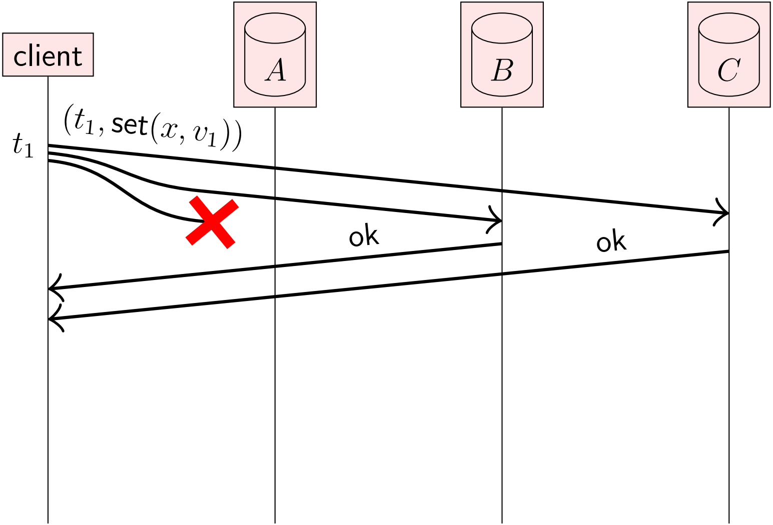

Write succeeds on B and C

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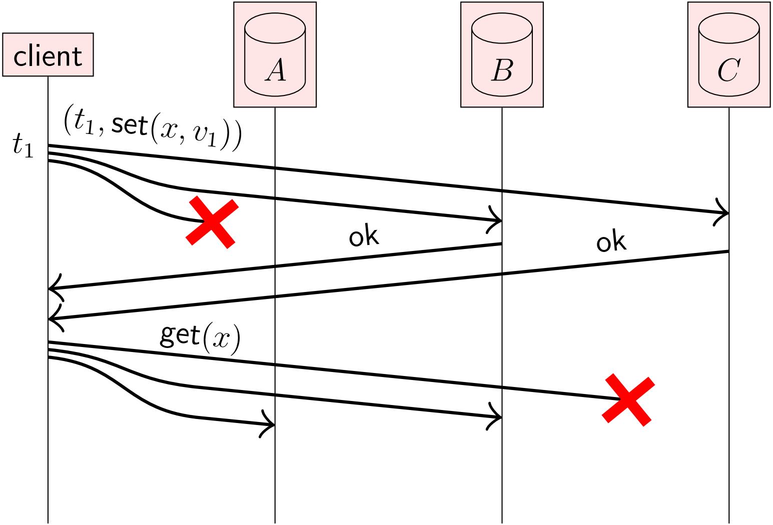

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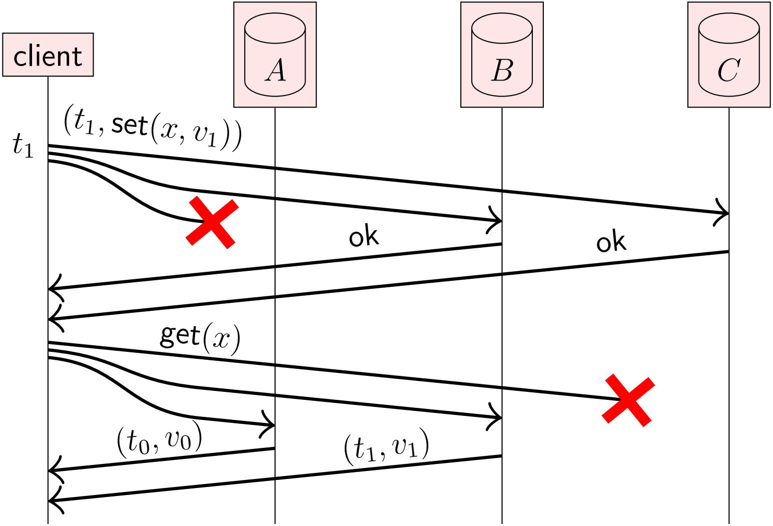

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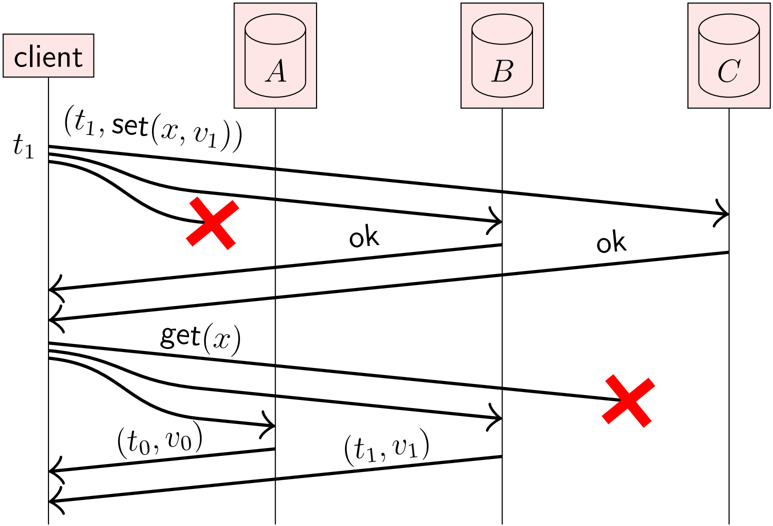

Write succeeds on B and C; read succeeds on A and B

Choose between (t_0, v_0) and (t_1, v_1) based on timestamp

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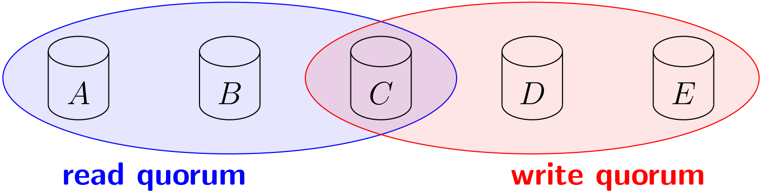

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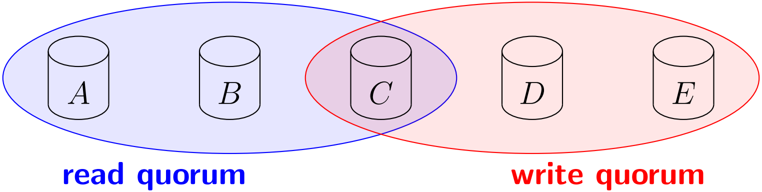
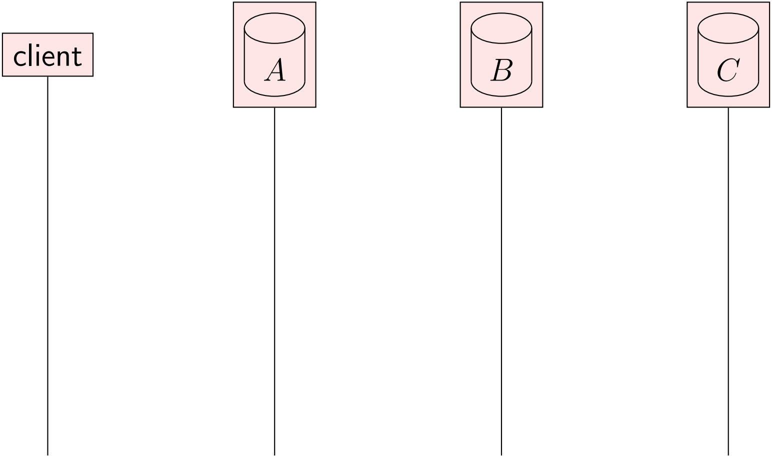
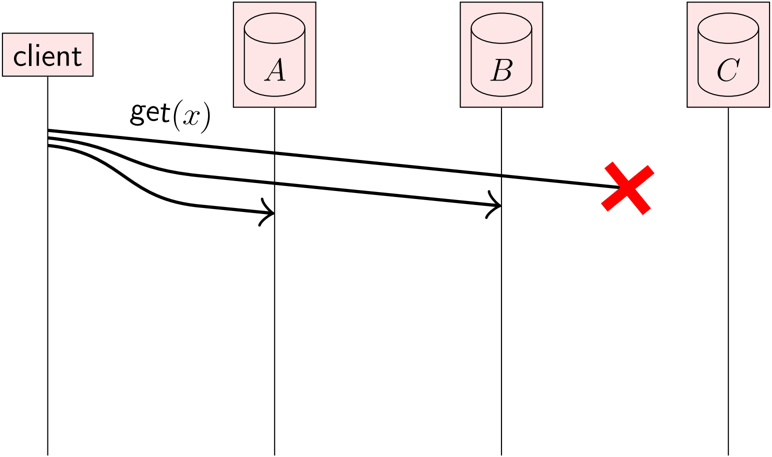
- Read quorum and write quorum share ≥ 1 replica
- Typical: $r = w = \frac{n+1}{2}$ for $n = 3, 5, 7, \ldots$ (majority)
- Reads can tolerate $n - r$ unavailable replicas, writes $n - w$



Read repair



Read repair



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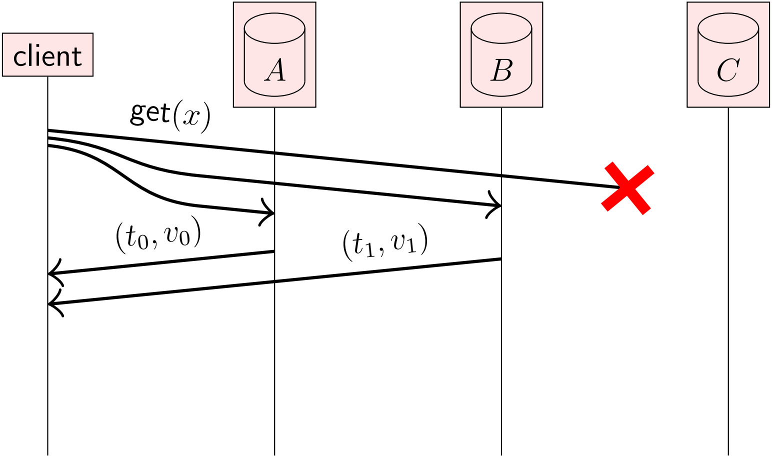

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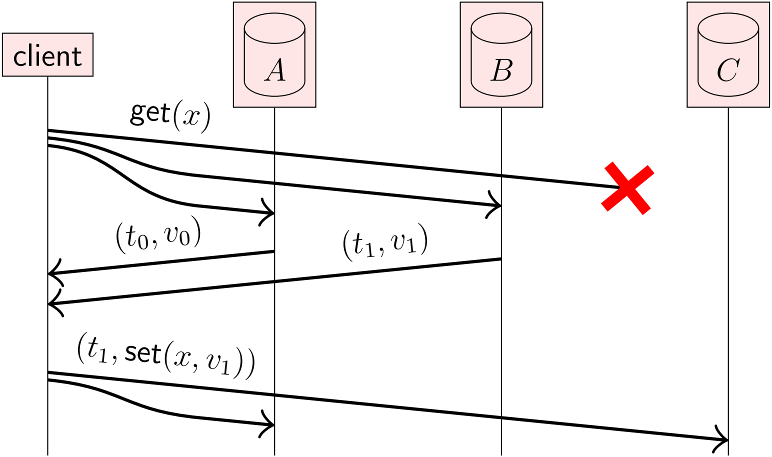

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Client helps **propagate** (t_1, v_1) to other replicas.

State machine replication

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What about stronger broadcast models?

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- Applying an update is deterministic
- Replica is a **state machine**: starts in fixed initial state, goes through same sequence of state transitions in the same order $\Longrightarrow$ all replicas end up in the same state

State machine replication

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on request to perform update $u$ do
    send $u$ via FIFO-total order broadcast
end on

on delivering $u$ through FIFO-total order broadcast do
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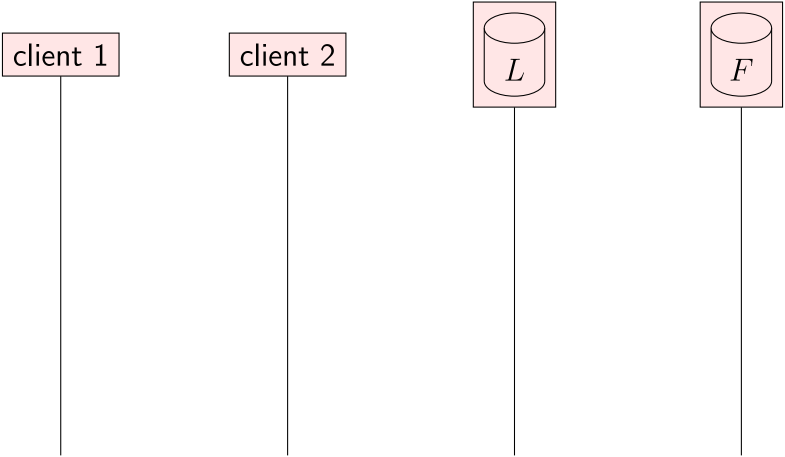
- Need fault-tolerant total order broadcast: see lecture 6

Database leader replica

Leader database replica L ensures total order broadcast



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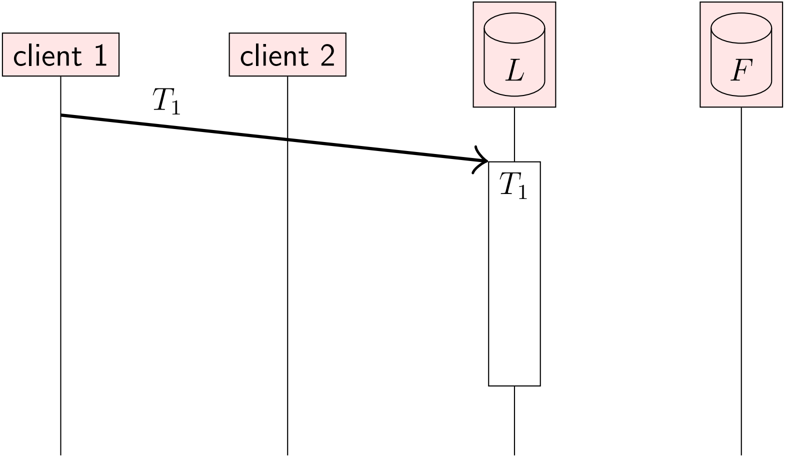

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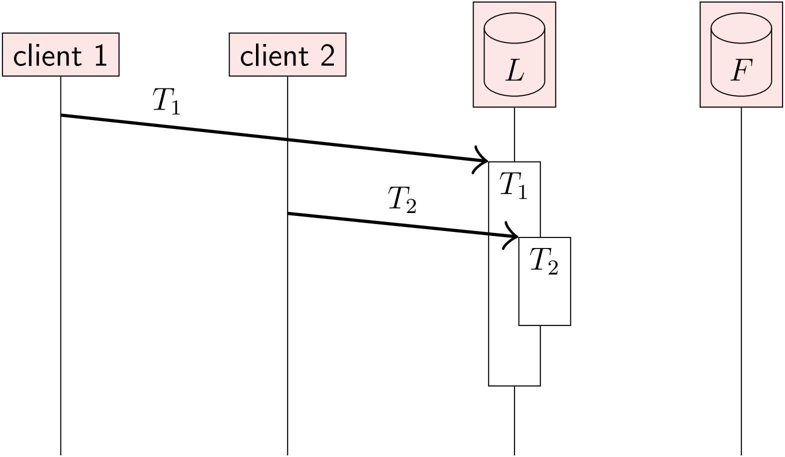

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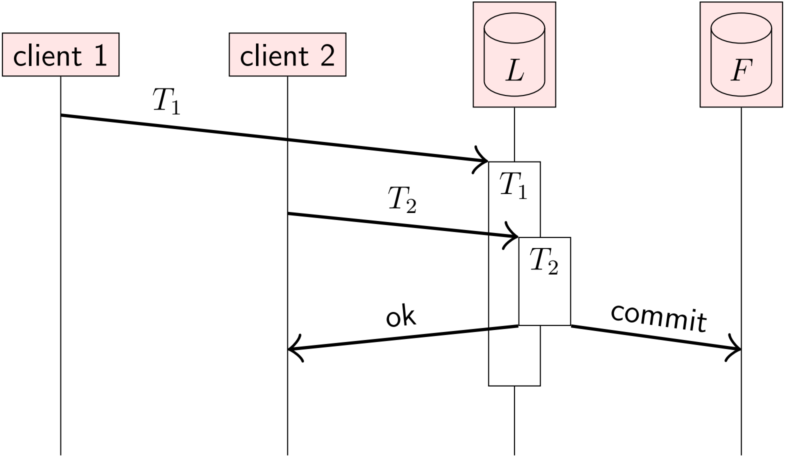

Follower F applies transaction log in commit order

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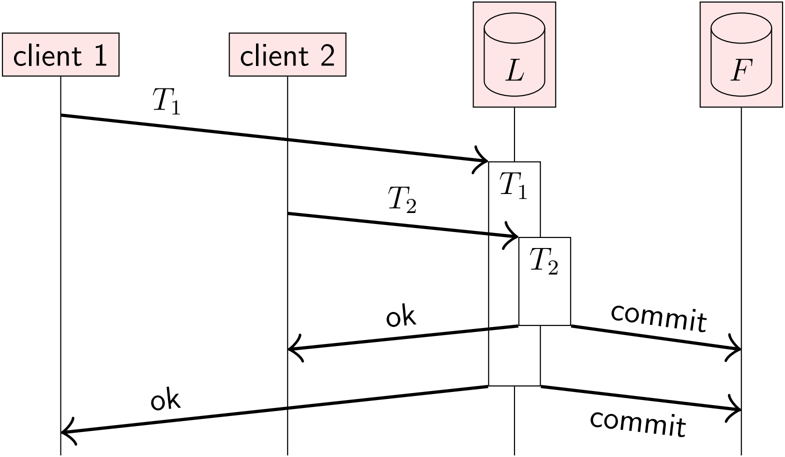

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Replication using causal (and weaker) broadcast

State machine replication uses (FIFO-)total order broadcast.
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causal	deterministic, concurrent updates commute
reliable	deterministic, all updates commute
best-effort	deterministic, commutative, idempotent, tolerates message loss