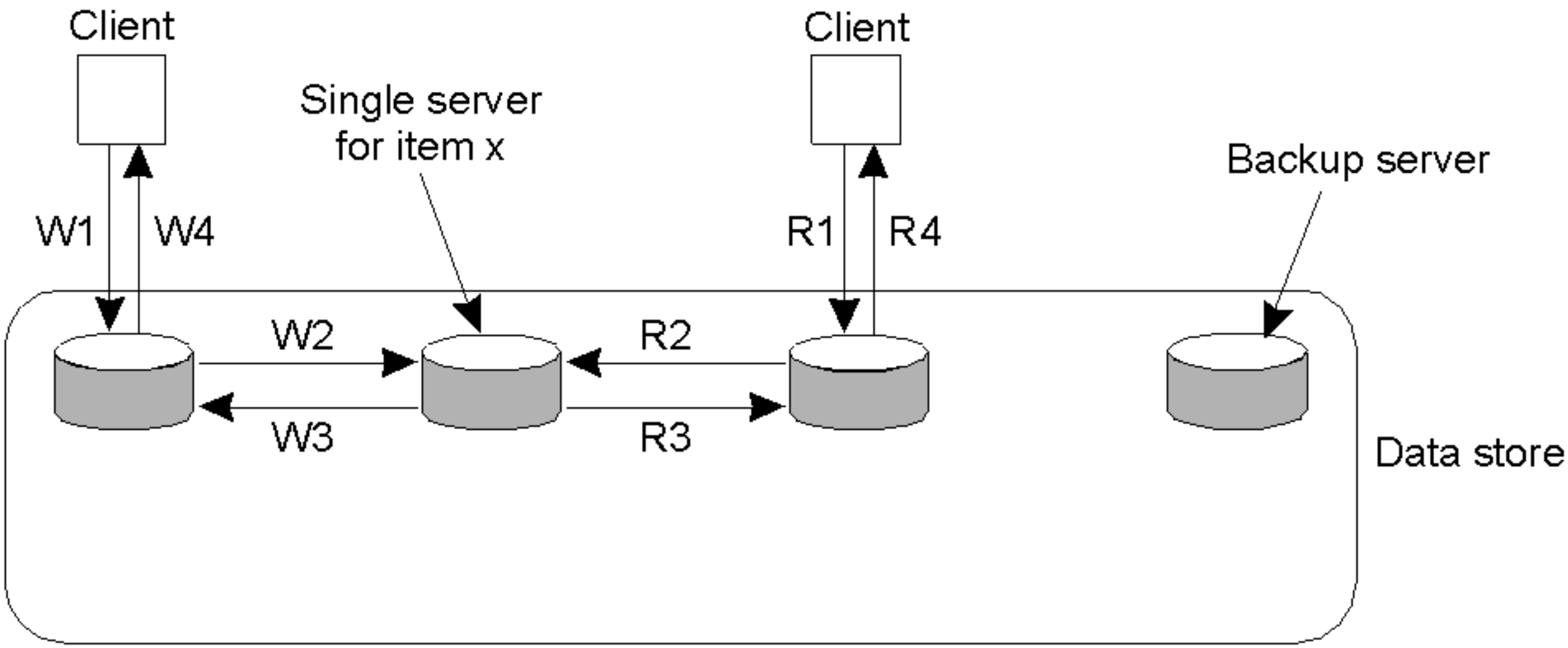
Agenda

- Consistency protocols
- Clocks, logical clocks, state vectors
- Optimistic replication
  - CVS, Subversion
  - Duplicated databases

Consistency protocols

- Describe implementation of a specific consistency model
- Primary-based protocols
  - Each data item x has an associated primary responsible for coordinating write operations on x
  - Remote-write protocols
  - Local-write protocols
- Replicated-write protocols
  - Write operations can be carried out at multiple replicas
  - Active replication
  - Quorum-based protocols

Remote-Write Protocols (1)

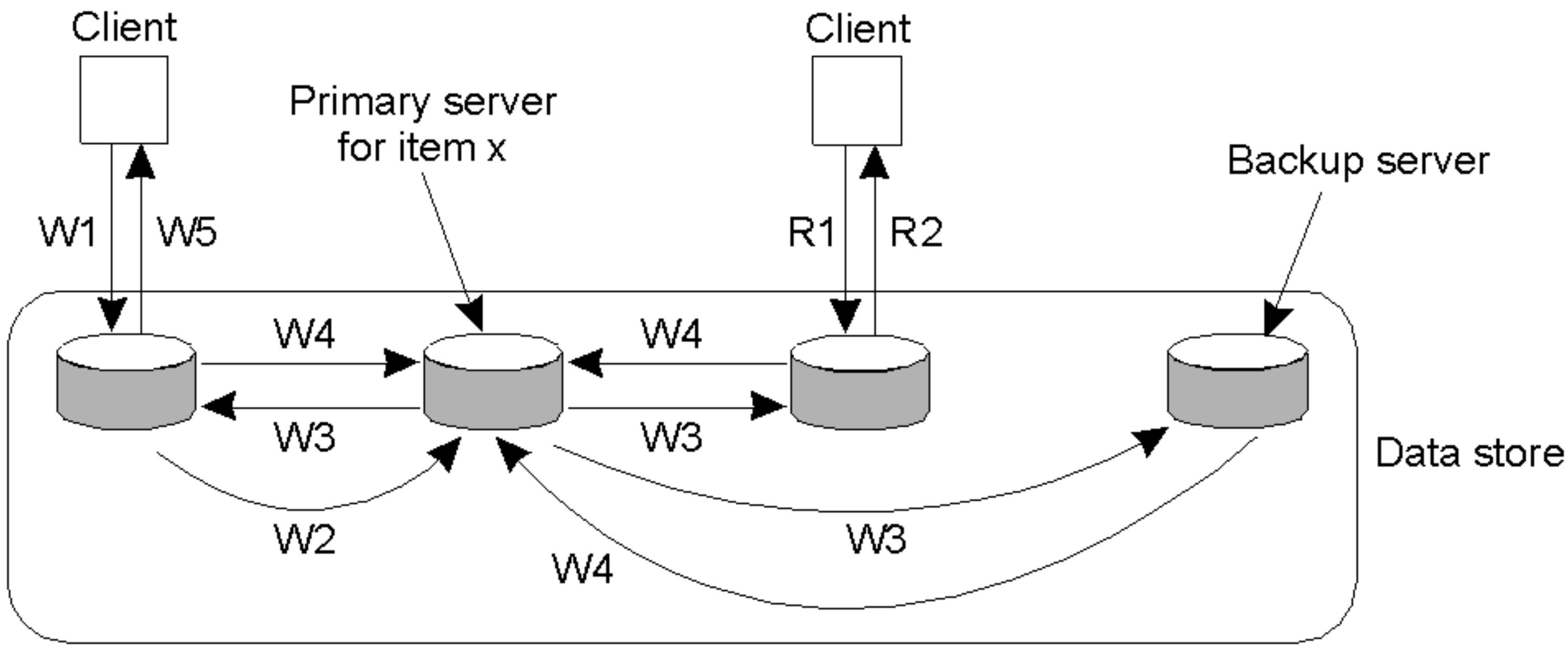


W1. Write request
W2. Forward request to server for x
W3. Acknowledge write completed
W4. Acknowledge write completed

R1. Read request
R2. Forward request to server for x
R3. Return response
R4. Return response

- Primary-based remote-write protocol with a fixed server to which all read and write operations are forwarded.

Remote-Write Protocols (2)



W1. Write request
W2. Forward request to primary
W3. Tell backups to update
W4. Acknowledge update
W5. Acknowledge write completed

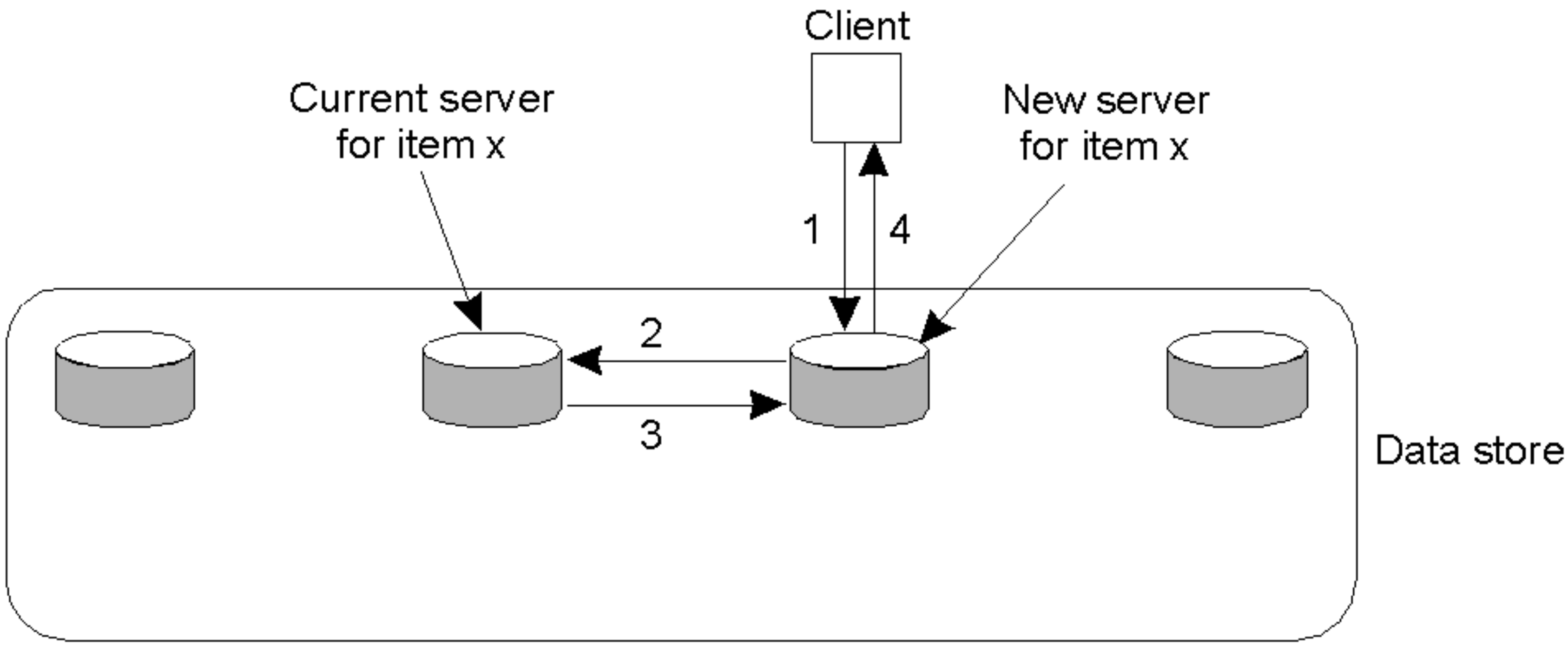
R1. Read request
R2. Response to read

- **The principle of primary-backup protocol.**

Remote-Write Protocols (3)

- Primary-backup protocol implements update as a blocking operation
- Alternative solution: non-blocking protocol
  - As soon as primary updated the local copy of x, it returns an acknowledgement
  - After that ask backup servers to perform the update
  - Fault tolerance concerns
- Implementation of sequential consistency

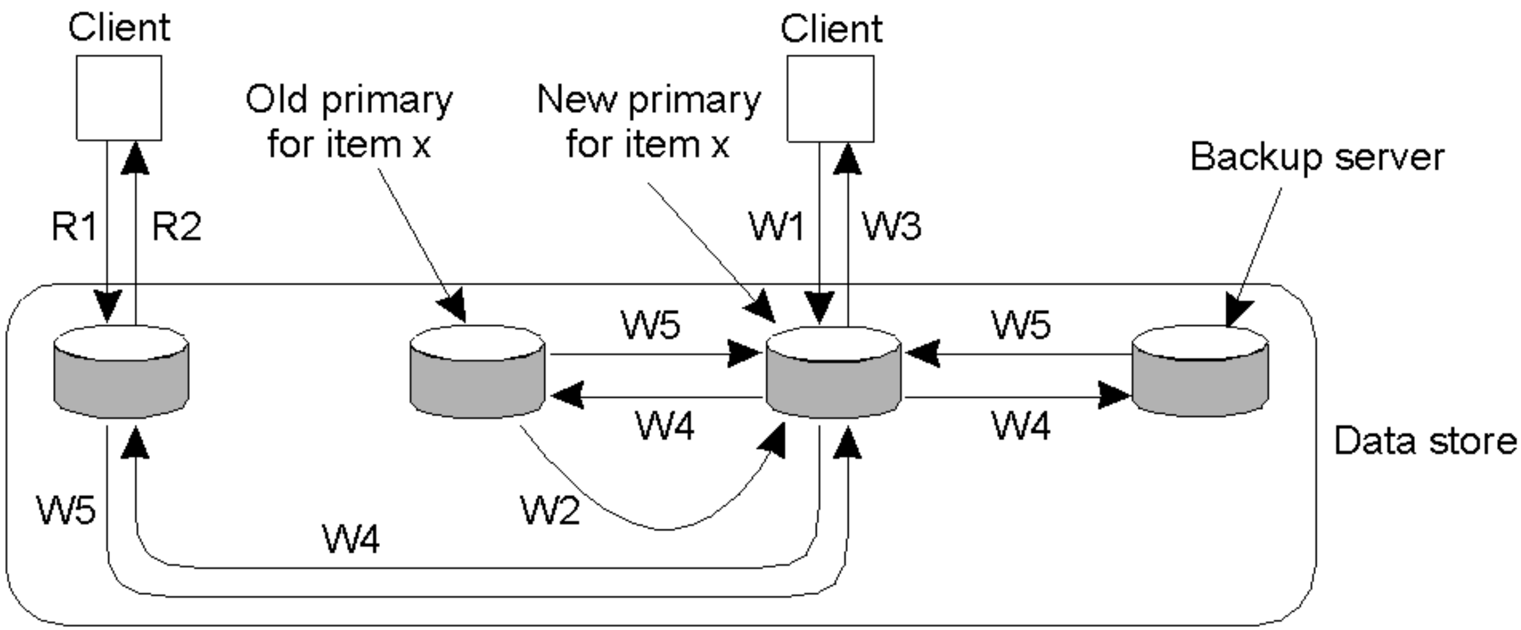
Local-Write Protocols (1)



1. Read or write request
2. Forward request to current server for x
3. Move item x to client's server
4. Return result of operation on client's server

- Primary-based local-write protocol in which a single copy is migrated between processes
- Disadvantage: keeping track where each data item currently is

Local-Write Protocols (2)



W1. Write request
W2. Move item x to new primary
W3. Acknowledge write completed
W4. Tell backups to update
W5. Acknowledge update

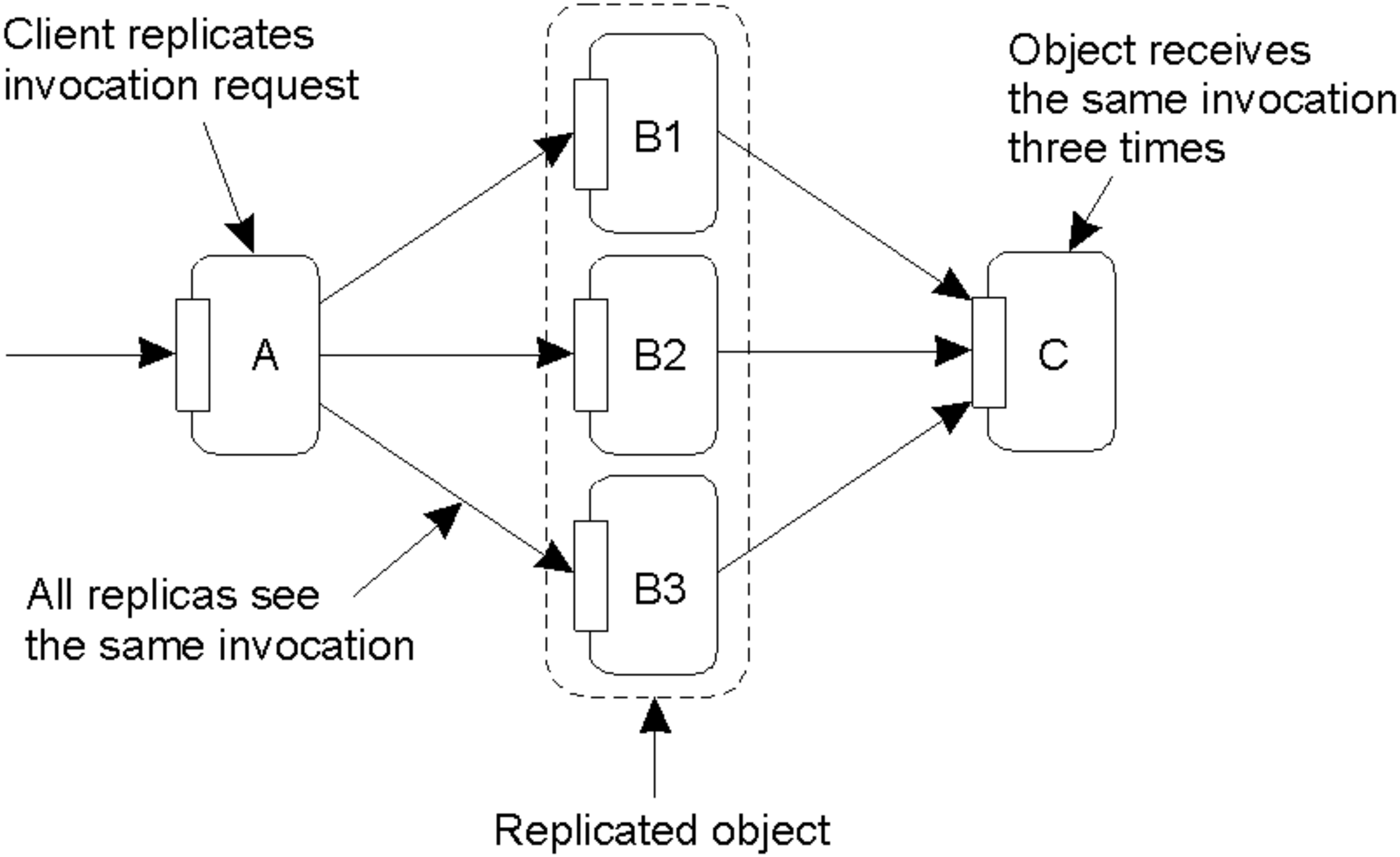
R1. Read request
R2. Response to read

- Primary-backup protocol in which the primary migrates to the process wanting to perform an update
- Advantage if nonblocking protocol: write operations carried locally, while reading can access local copies
- Protocol suitable for mobile computers

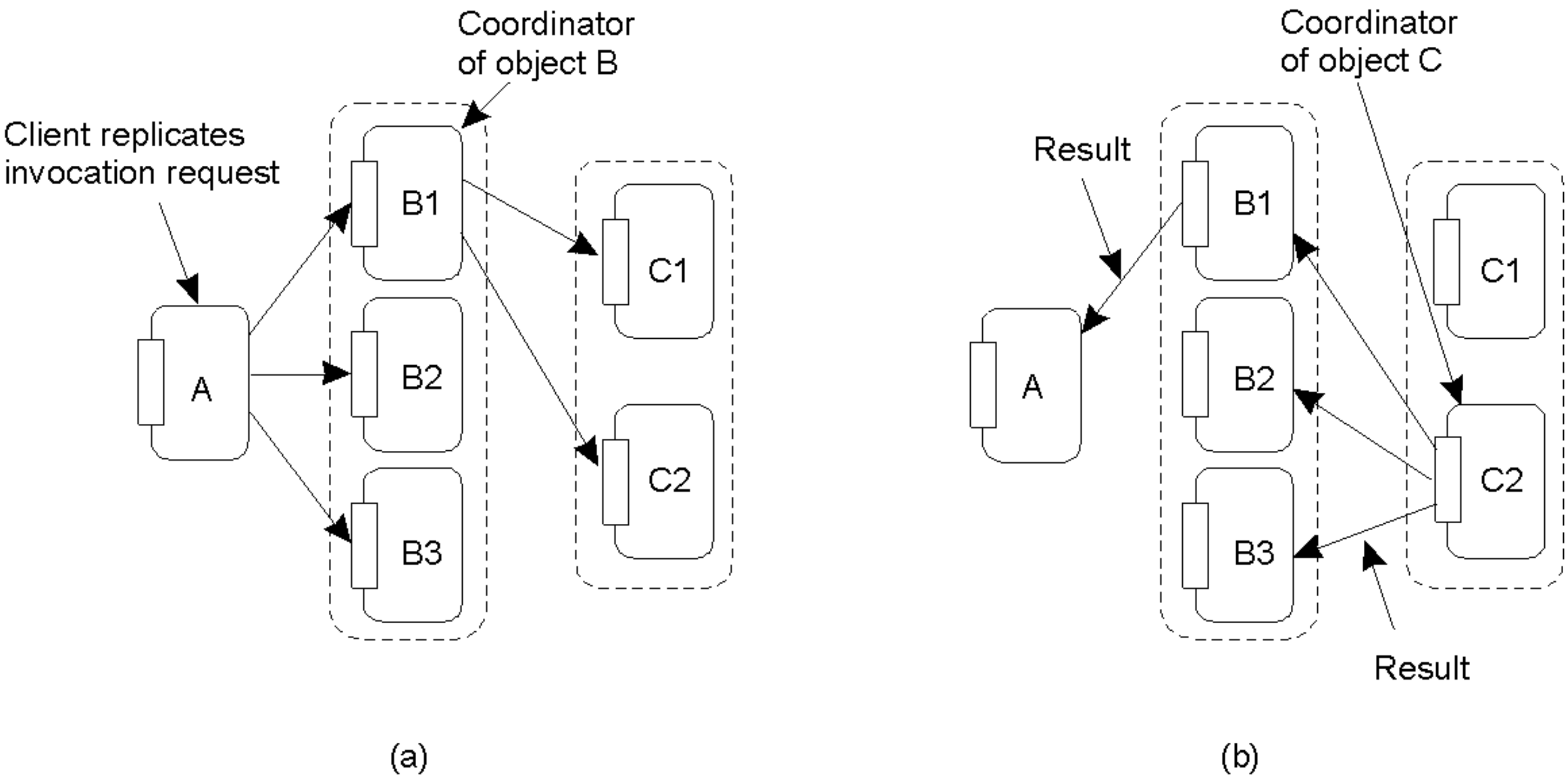
Replicated write protocols Active Replication (1)

- Operations sent to each replica
- Operations have to be carried out in the same order everywhere
  - Need of totally-ordered multicast
    - Using Lamport timestamps
    - Using a central coordinator called sequencer
- Deal with replicated invocations

Active Replication (2)



Active Replication (3)



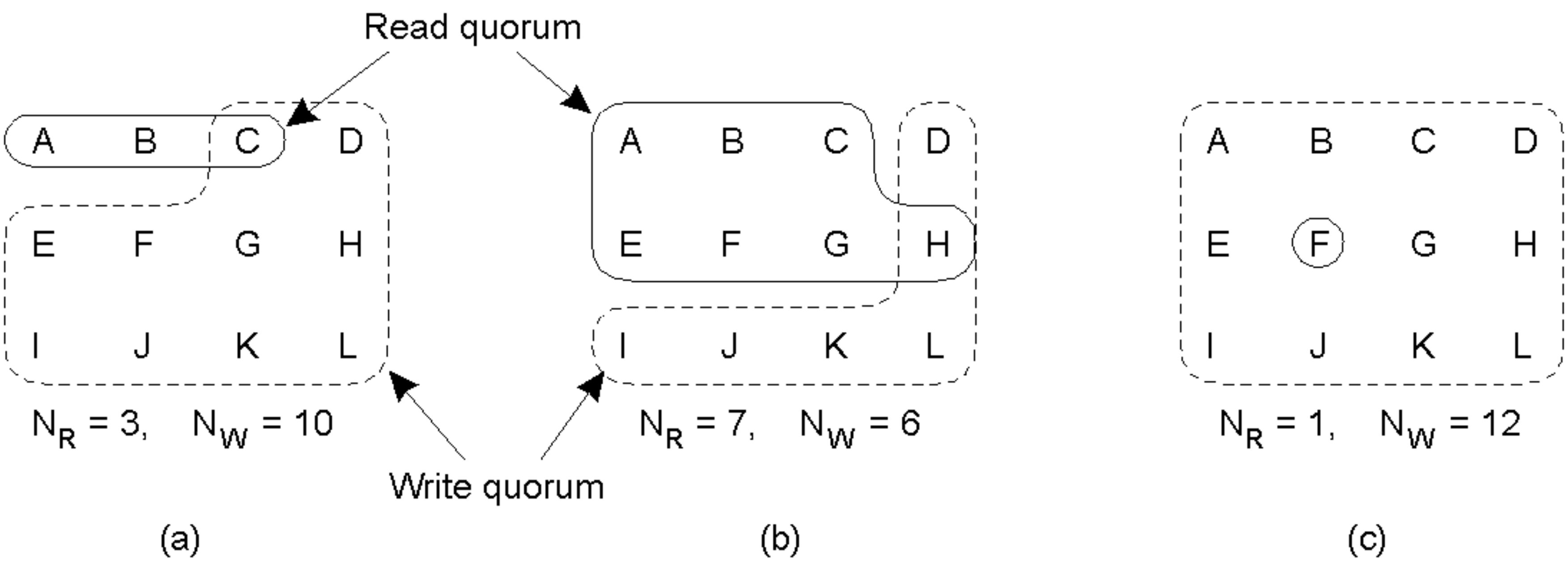
Quorum-Based Protocols (1)

- Use voting: clients request and acquire permission of multiple servers before reading/writing a replicated object
- Example distributed file system
  - File replicated on N servers
  - For an update a client must contact a majority of servers (half +1)
  - If agreement file changed and version number updated
  - For a read a client must contact at least half of servers+1 and ask them to send version numbers of the file
  - Choose the most recent version

Quorum-Based Protocols (2) -Gifford scheme

- A file with N replicas
- A read quorum (N_R servers) for reading the file
- A write quorum (N_W servers) for modifying the file
- $N_R + N_W > N$
- $N_W > N/2$

Quorum-Based Protocols (3)



a) A correct choice of read and write set

b) A choice that may lead to write-write conflicts

c) A correct choice, known as ROWA (read one, write all)

Pessimistic vs. optimistic replication (1)

- Pessimistic replication
  - Give the illusion of one replica (no divergence)
  - Block access to a replica unless it is up-to-date
  - Example: primary-copy algorithms
    - Elect a primary replica
    - After an update primary writes the change to secondary replicas
    - If primary crashes elect a new replica
  - Bad performance and availability

Pessimistic vs. optimistic replication (2)

- Optimistic replication
  - Allows replicas to diverge
    - Commit modifications immediately and propagate later
    - Observers can see different values on different sites
  - Eventual consistency
  - Mandatory for offline access
  - Better scaling

Eventual Consistency

- **Eventual delivery**: An update executed at some correct replica eventually executes at all correct replicas
- **Termination**: All update executions terminate
- **Convergence**: Correct replicas that have executed the same updates eventually reach equivalent state (and stay)
- Consensus moved to the background

Strong Eventual Consistency

- **Eventual delivery**: An update executed at some correct replica eventually executes at all correct replicas
- **Termination**: All update executions terminate
- **Strong convergence**: Correct replicas that have executed the same updates have equivalent states
- No consensus in background, no need to rollback

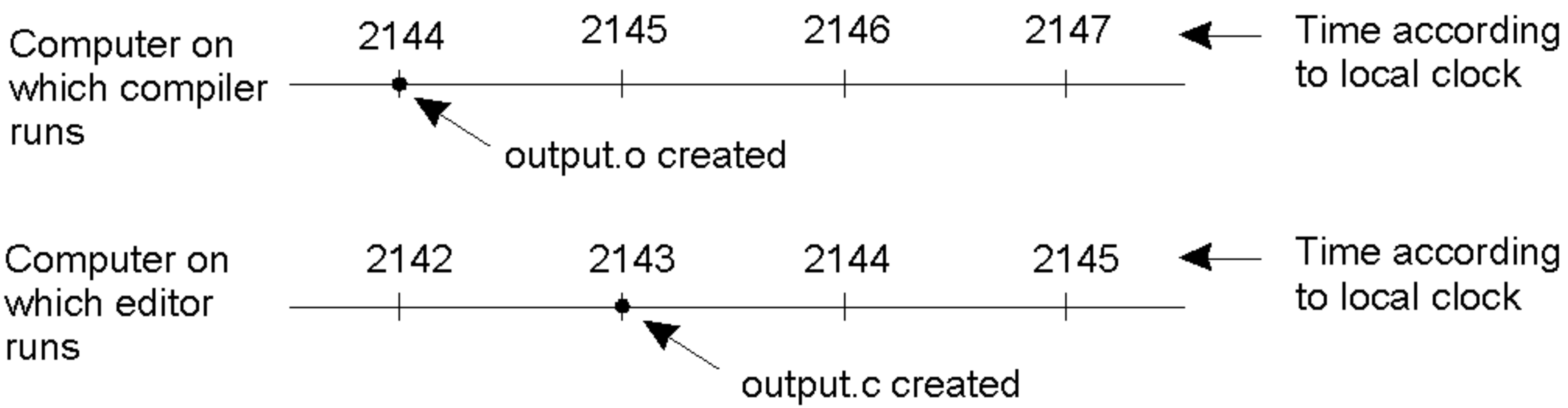
Pessimistic vs. optimistic replication (3)

- Basic principles of optimistic replication
  - N sites replicate an object
  - An object is modified by applying an operation
  - Local operations applied immediately
  - Operations broadcast to the other sites
  - Remote operations integrated and executed
  - System is correct if when it is idle all replicas are identical

Clock Synchronisation

- Time is unambiguous in a centralised system
- There is no global agreement on time in a distributed system
- Example
  - Program consisting of 100 files
  - Use of *make* to recompile only changed source files
  - If input.c has time 2151 and input.o has time 2150, then recompilation needed

Clock Synchronization



- make does not call the compiler

Logical clock

- Sufficient that all machines agree on the same time (not necessarily real time)
- Lamport 1978 – rather than agreeing on what time it is, sufficient to agree on the order in which events occur
- Previous example: if input.c is older or newer than input.o

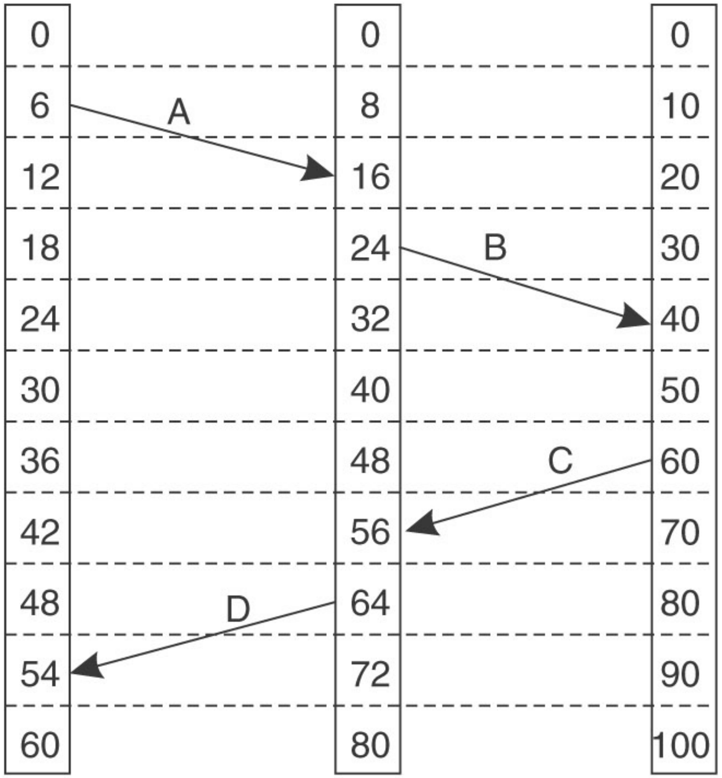
Lamport timestamps

- Happens-before relation
- $a \rightarrow b$ (*a* happens before *b*)
- Two situations:
  - If *a* and *b* are events in the same process and *a* occurs before *b*, then $a \rightarrow b$
  - If *a* is the event of a message being sent by one process and b is the event of the message being received by another process, then $a \rightarrow b$. A mesage cannot be received before or at the same time it is sent
- If $a \rightarrow b$ and $b \rightarrow c$ then $a \rightarrow c$
- If neither $a \rightarrow b$ nor $b \rightarrow a$ then *a is concurrent with b*

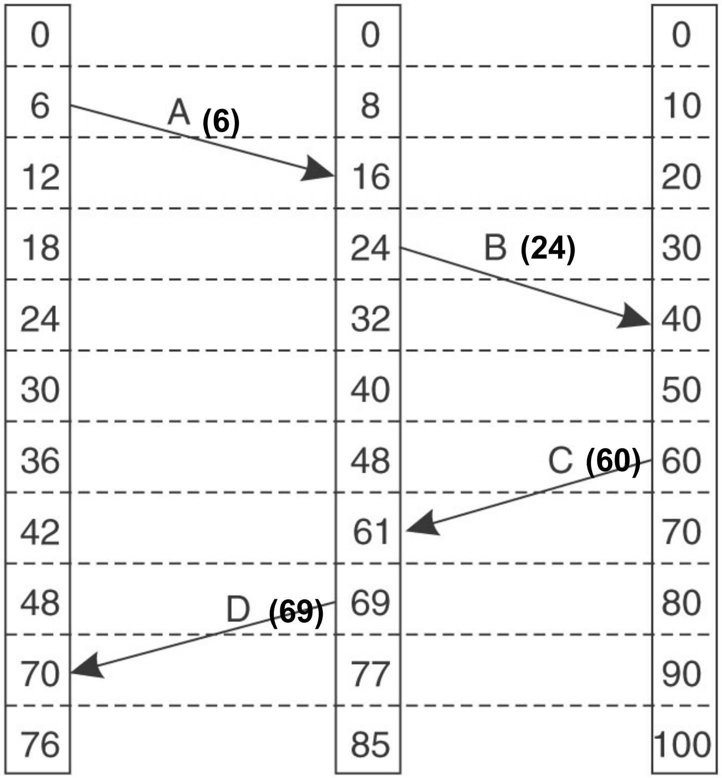
Lamport timestamps

- For every event *a* assign *C(a)* on which all processes agree
- If $a \rightarrow b$ then $C(a)<C(b)$
- Clock time must always increase
- Lamport solution
  - Each message carries the sending time
  - If receiver clock < time of the arrived message, then receiver forwards its clock to 1 + sending time

Lamport timestamps



(a)



(b)

Lamport timestamps

- If *a* happens before *b* in the same process then $C(a)<C(b)$
- If *a* and *b* represent the sending and receiving of a message, $C(a)<C(b)$
- For all distinctive events *a* and *b*, $C(a) \neq C(b)$
  - Attach the number of the process to the lower order of the time
  - If *a* generated by process 1 at time 40 and *b* generated by process 2 at time 40, then $C(a)=40.1$ and $C(a)=40.2$

Vector timestamps

- Lamport timestamps limits
  - if *C(a)<C(b)* does not imply that *a→b*
  - *a || b* does not imply *C(a)=C(b)*
- Example: posting articles and reactions to posted articles
- Lamport timestamps do not capture causality
- Vector timestamps capture causality
  - If VT(a)<VT(b), then a causally precedes b
  - Each process P_i maintains V_i
    - $V_i[i]$ = the no. of events that occured so far at P_i
    - If $V_i[j]=k$ then P_i knows that k events occurred at P_j

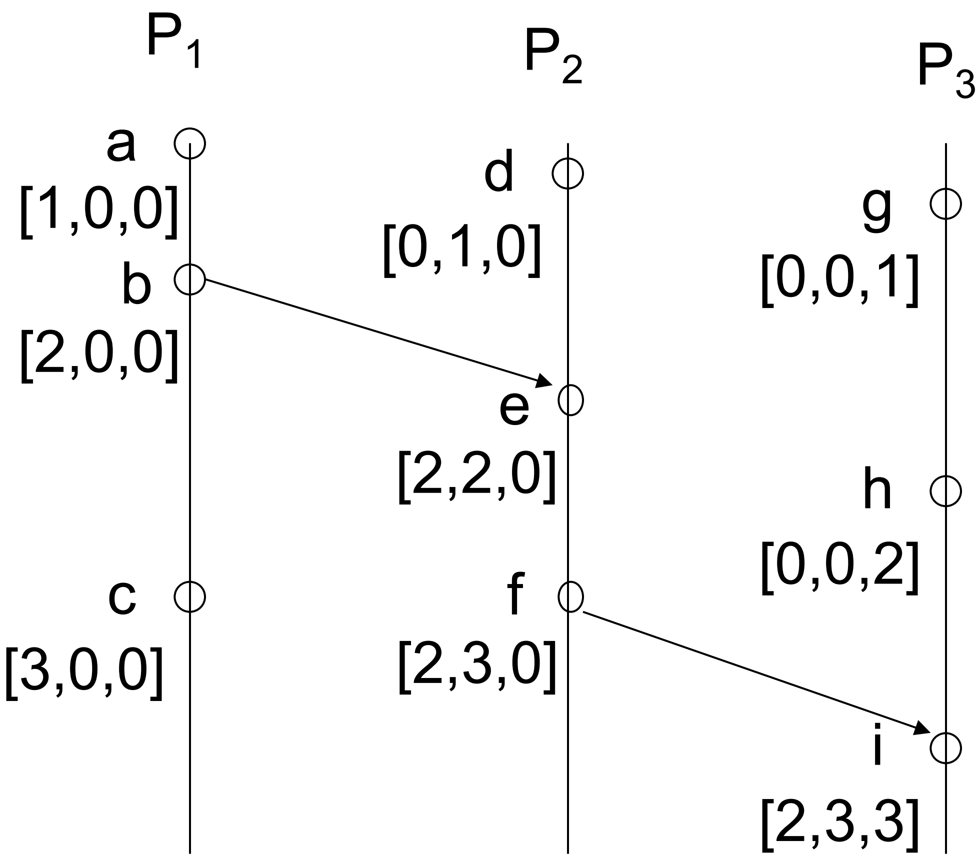
Vector timestamps

- Comparison of two vectors
  - V=W iff $\forall$ i V[i]=W[i]
  - V<W iff forall i V[i]≤W[i] and $\exists$i V[i]<W[i]
  - [1,2,0] < [3,2,1]
  - [0,1,1] $\nless$ [1,0,1]

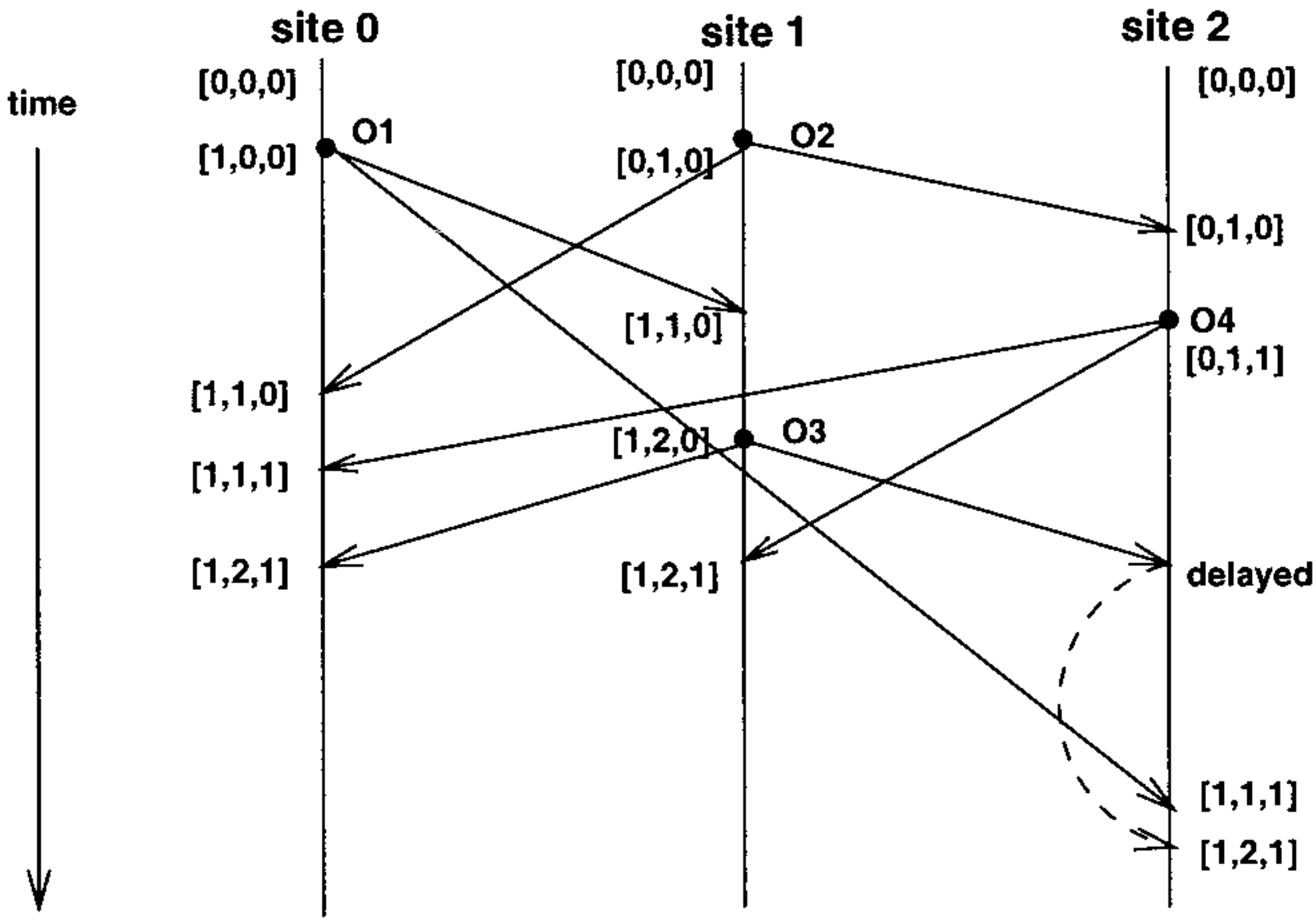
Vector timestamps – computation rules

- Process P_i
  - Initialisation: $\forall k\ V_i[k]=0$
  - Local event: $V_i[i]= V_i[i]+1$
  - Sending message m : $V_i[i]= V_i[i]+1$, then send (m,V_i)
  - Receiving message (m,V_j):
    - $\forall\ k\ V_i[k]=\max(V_i[k], V_j[k])$
    - $V_i[i]=V_i[i]+1$

Vector timestamps – example



State vector



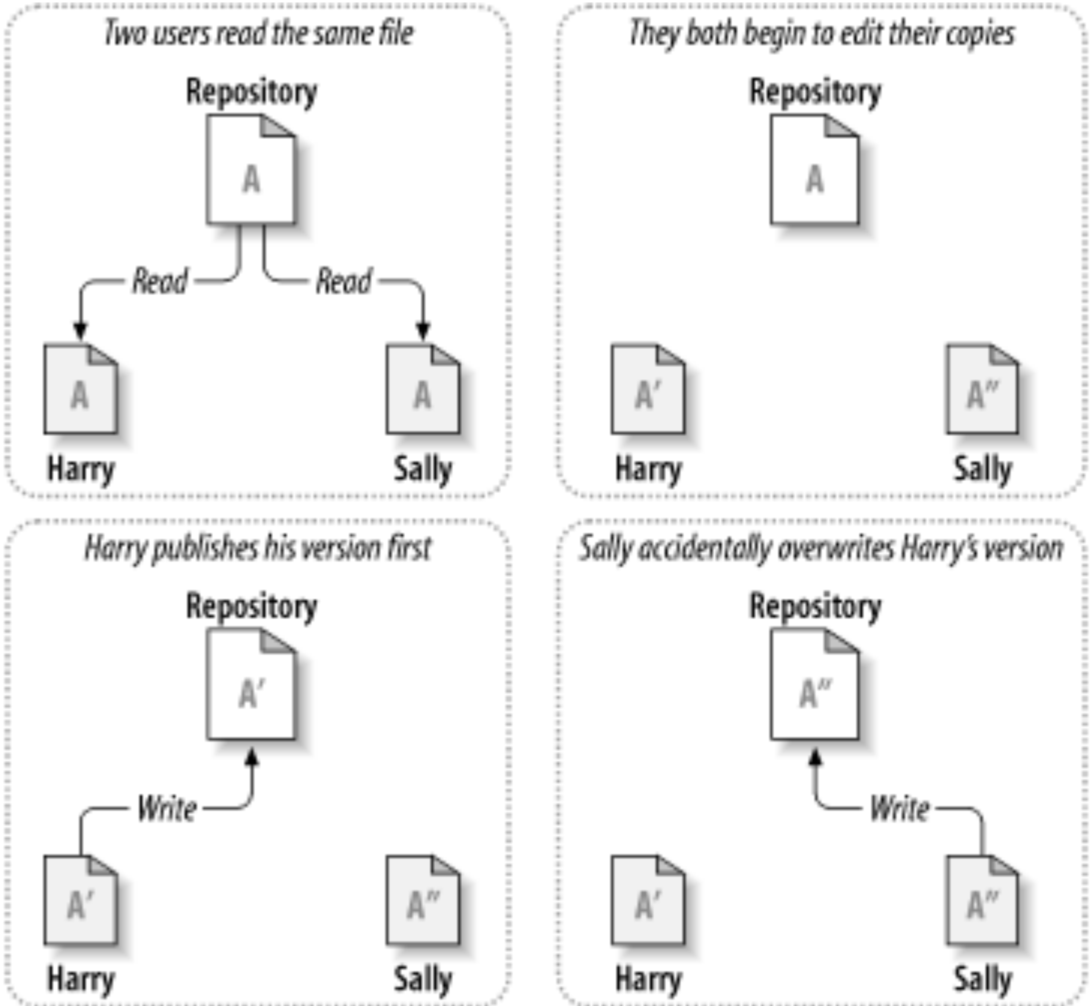
State vector based timestamping scheme

- State vector SV^k at site k
  - Initially $SV^k[i]=0$, $\forall i \in \{0,\ldots,N-1\}$
  - Updating rule 1: after executing a local operation, $SV^k[k]=SV^k[k]+1$
  - After executing a local operation and updating SV^k, the local operation is timestamped with SV^k and broadcast to all remote sites
  - Updating rule 2: after executing a remote operation O with SV_O, $SV^k[i]=\max(SV^k[i], SV_O[i])$, $\forall i \in \{0,\ldots,N-1\}$

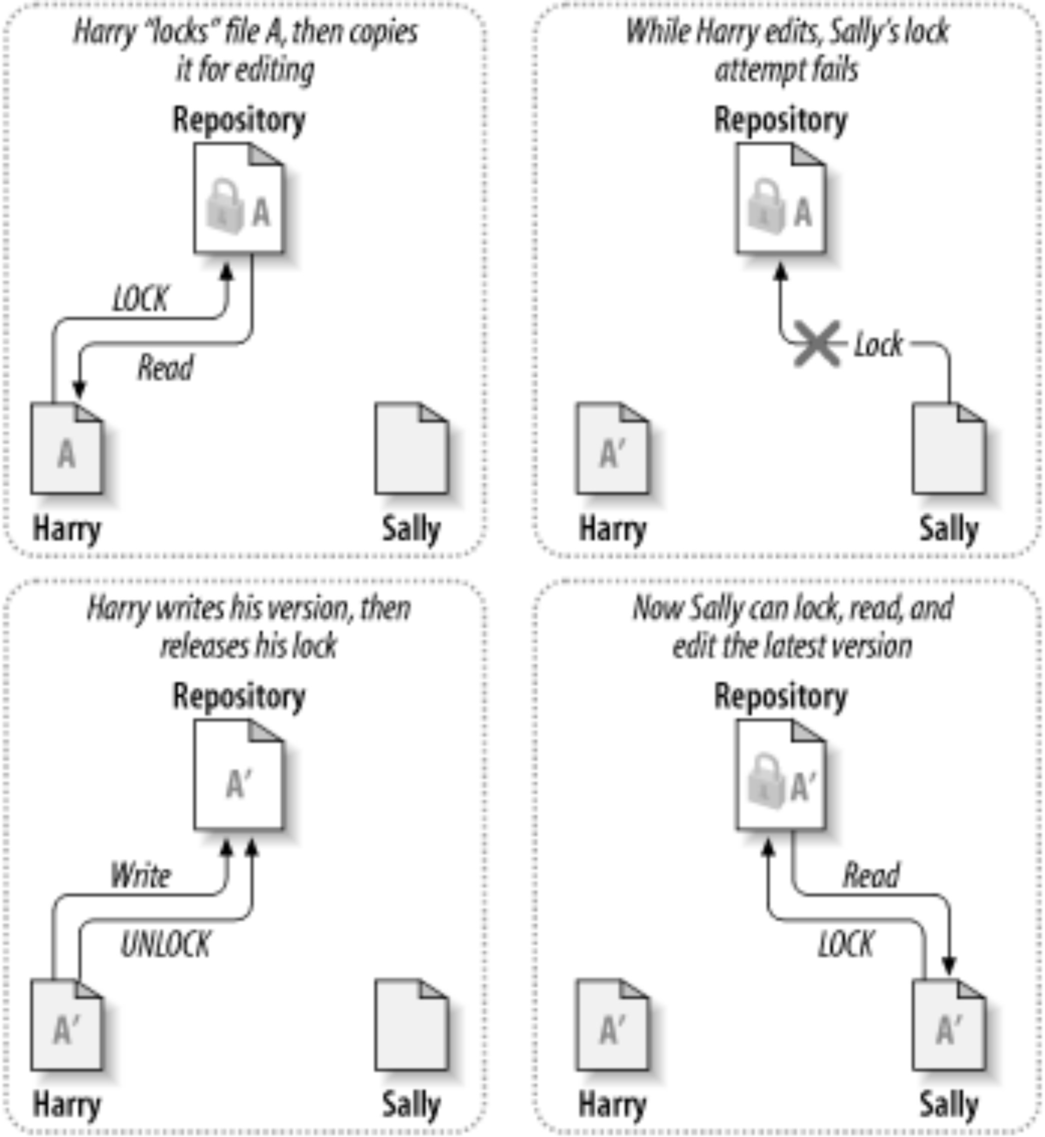
State vector: causality preservation

- O_i generated at site i and timestamped by SV_{Oi}
- O_i not allowed to be executed at site k ($k \neq i$) until:
  - $SV_{Oi}[i]=SV^k[i]+1$
  - $SV_{Oi}[j] \leq SV^k[j]$, $\forall j \in \{0,\ldots,N-1\}$, $j \neq i$

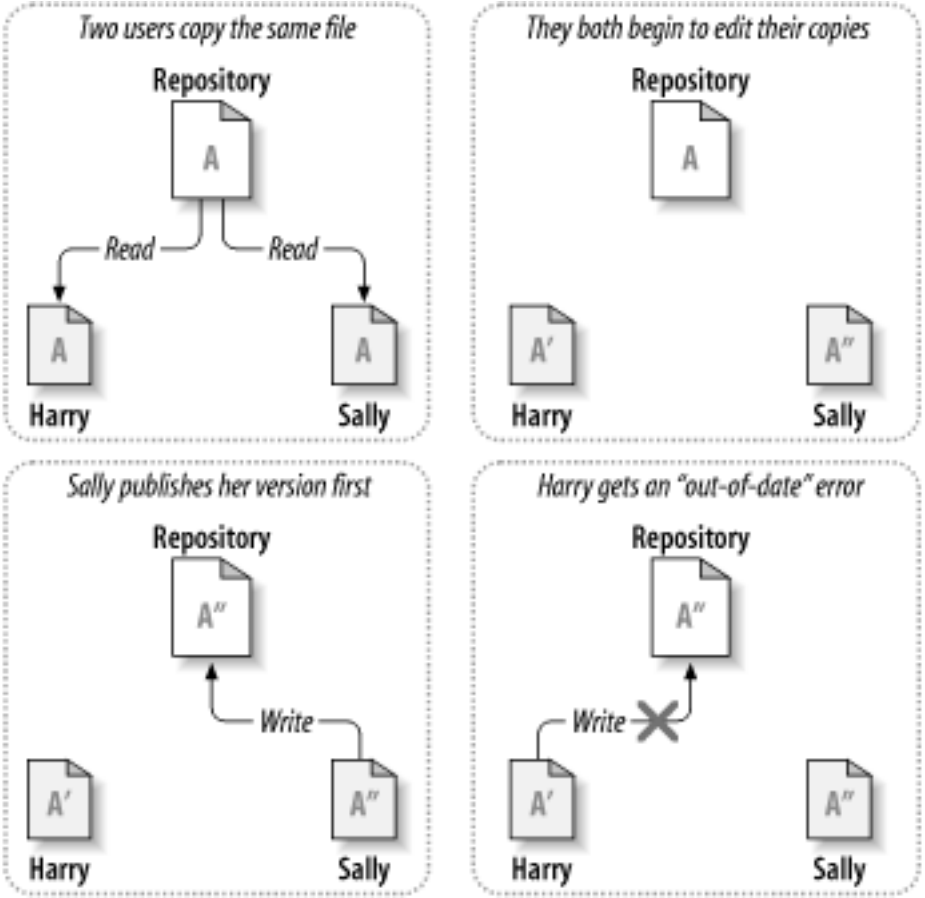
Version control systems: CVS, Subversion



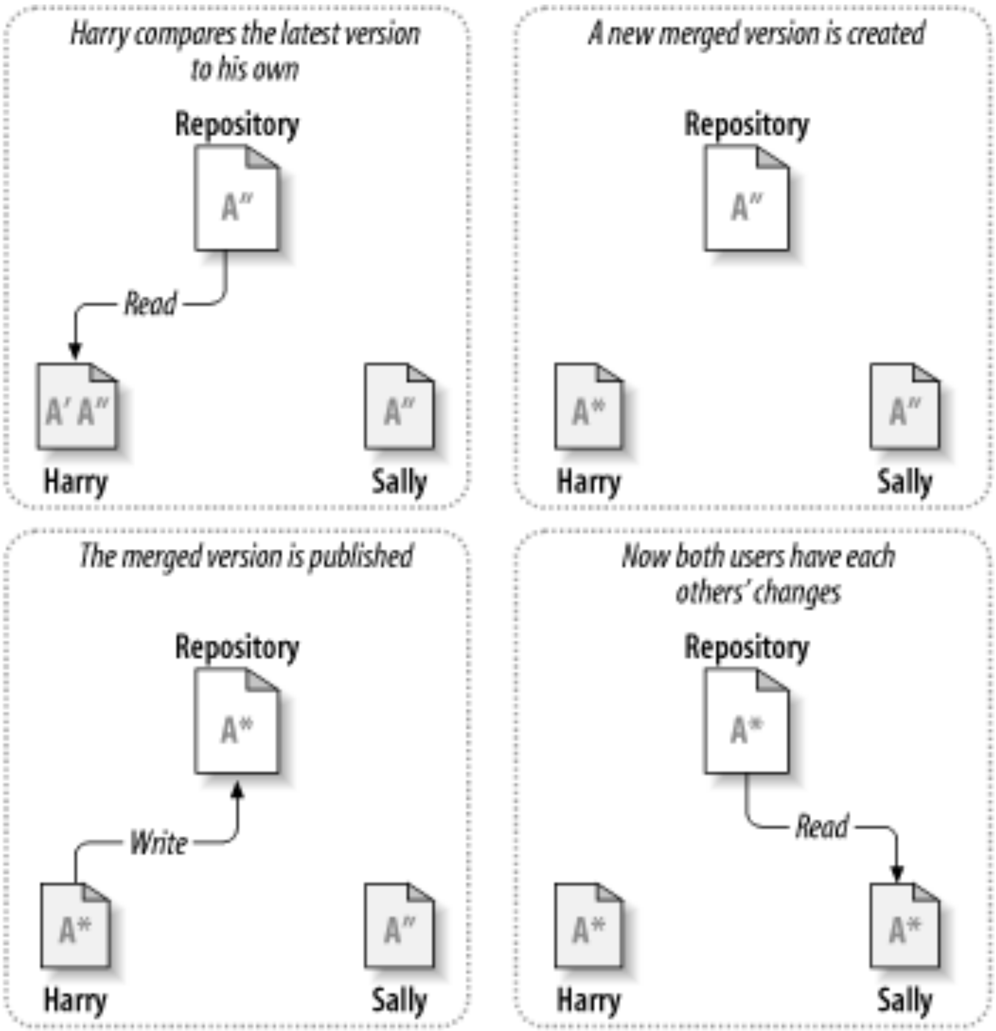
Lock-modify-unlock solution



Copy-modify-merge solution



Copy-modify-merge solution

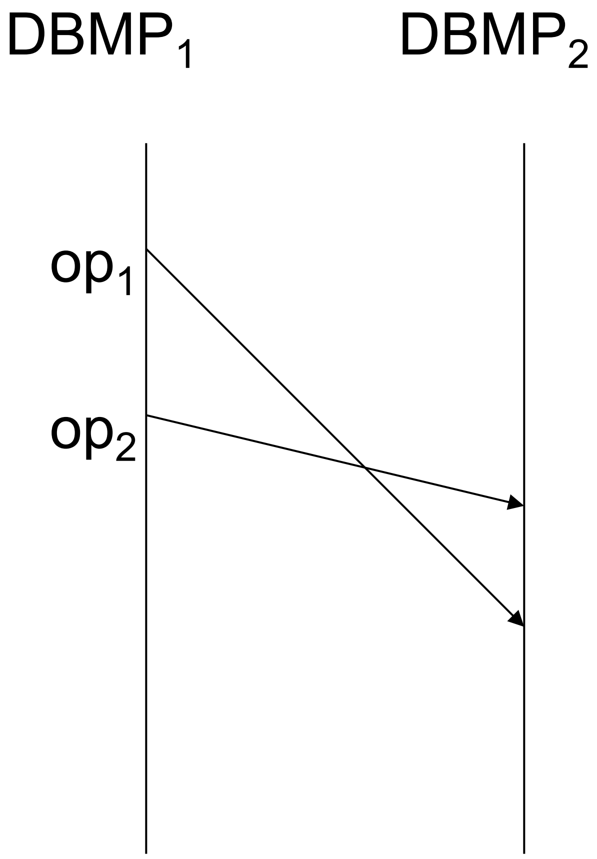


Duplicated databases (Thomas Write Rule 1975) (*)

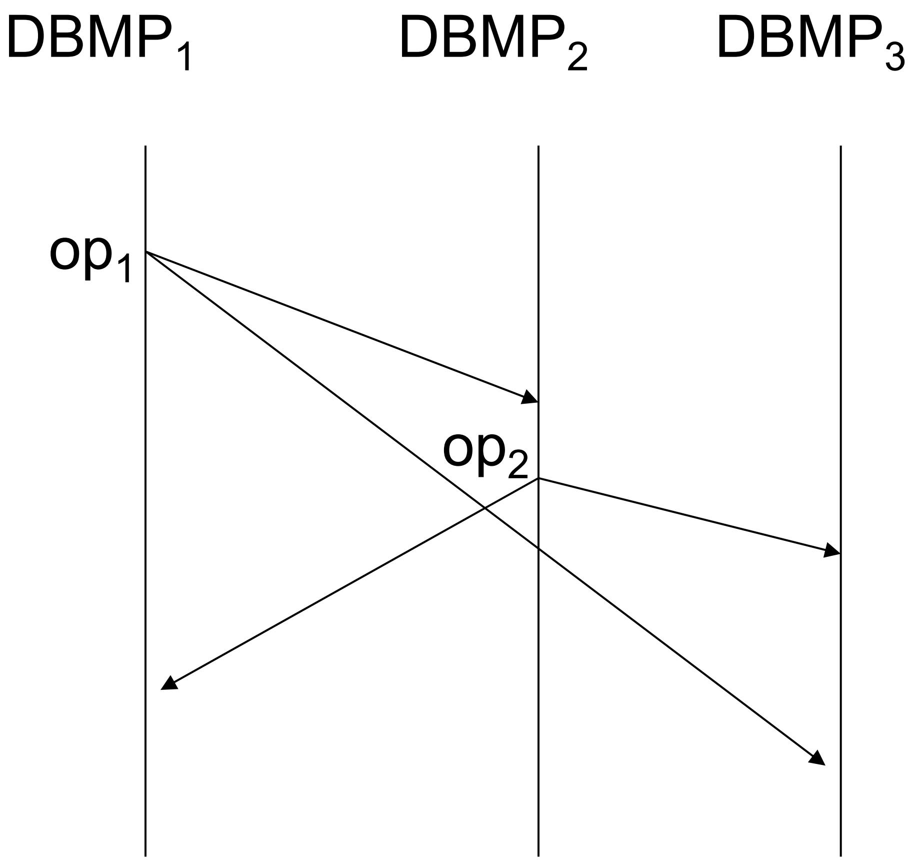
- Model
  - A set of indepedent DBMPs
  - Each DBMP has its own copy of the database
  - DBMPs communicate via messages
  - Communications are subject to failures
  - Messages between two sites are delivered in the same order they were sent
  - No use of global timestamps
- The system is correct if it eventually converges

(*) P. Johnson and R. Thomas. RFC677 : The maintenance of duplicate databases, 1975.

Duplicated databases (Thomas Write Rule 1975)



Not possible

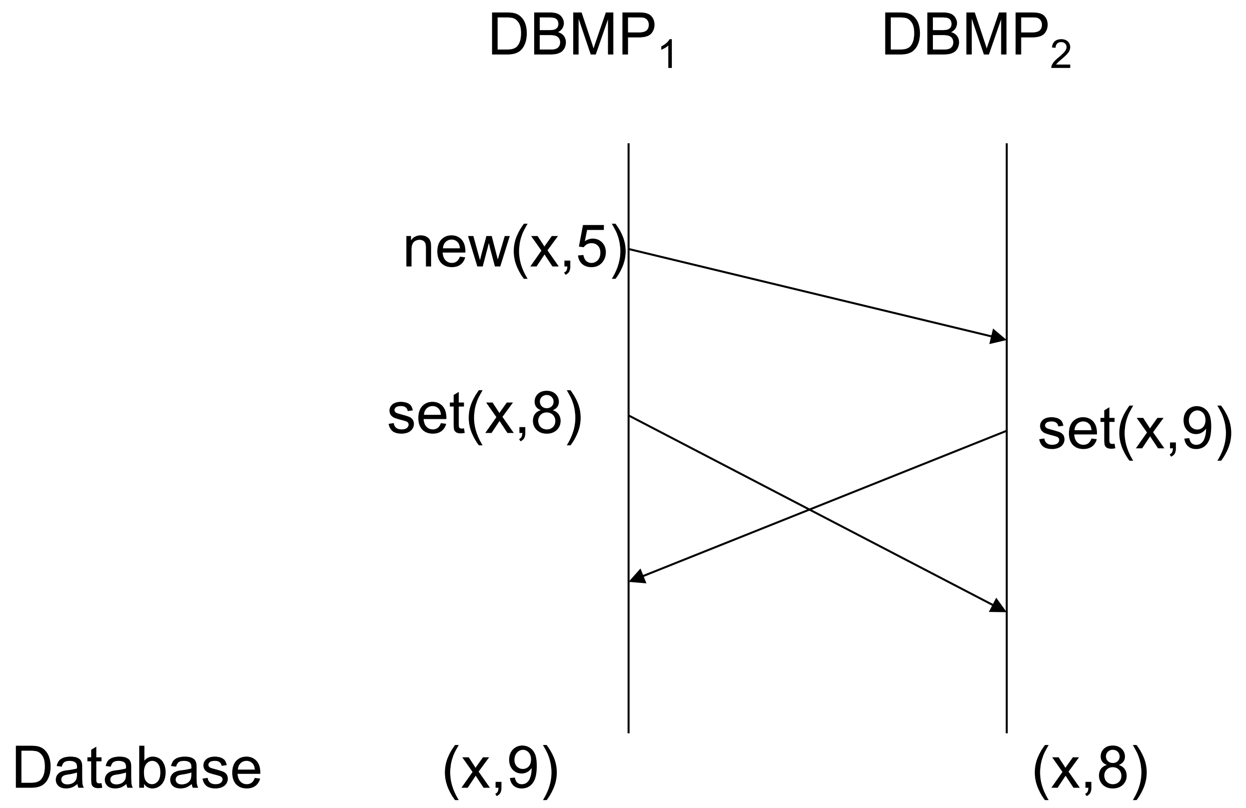


Possible

Duplicated databases (Thomas Write Rule 1975)

- The database = collection of (selector,value) pairs
- Operations:
  - Selection:
    - get(selector) returns the current associated value
  - Assignment:
    - set(selector, new_value) replaces associated value with new_value
  - Creation:
    - new(selector, initial_value) adds (selector, initial_value) entry
  - Deletion:
    - delete(selector, value) deletes existing (selector, value) pair

Duplicated databases (Thomas Write Rule 1975)



- How to guarantee that copies are consistent?

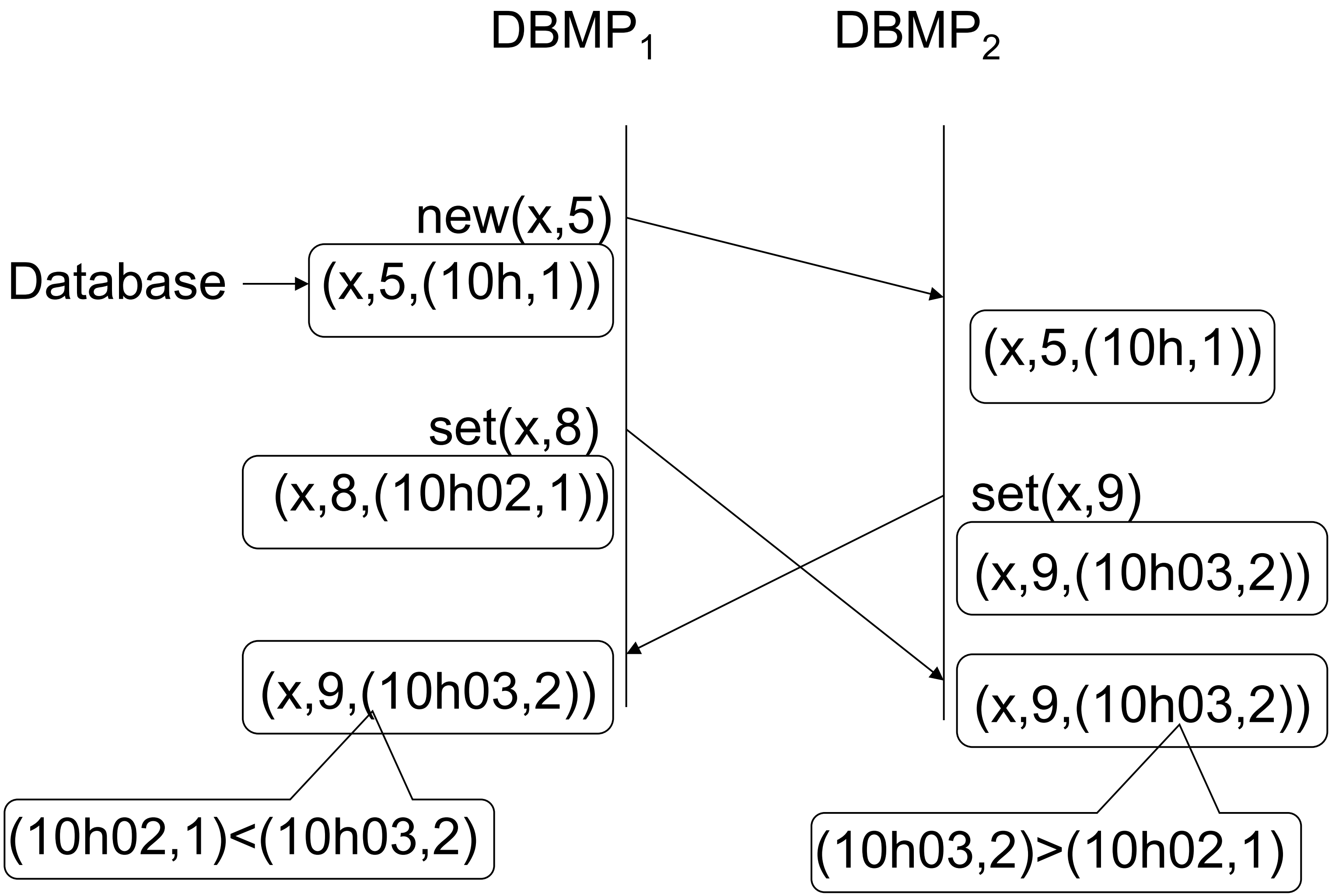
Thomas Timestamps

- In the face of concurrent modifications to an entry, how to select the « most recent » change?
- Thomas timestamps before Lamport timestamps !
- A timestamp is a pair (T,D)
  - T is a network time standard (time-of-day)
  - D is a DBMP identifier
- Timestamps comparison
  - (T1,D1)>(T2,D2) iff (T1>T2) or (T1=T2 and D1>D2)
- If D1=D2 and T1=T2, then the same operation

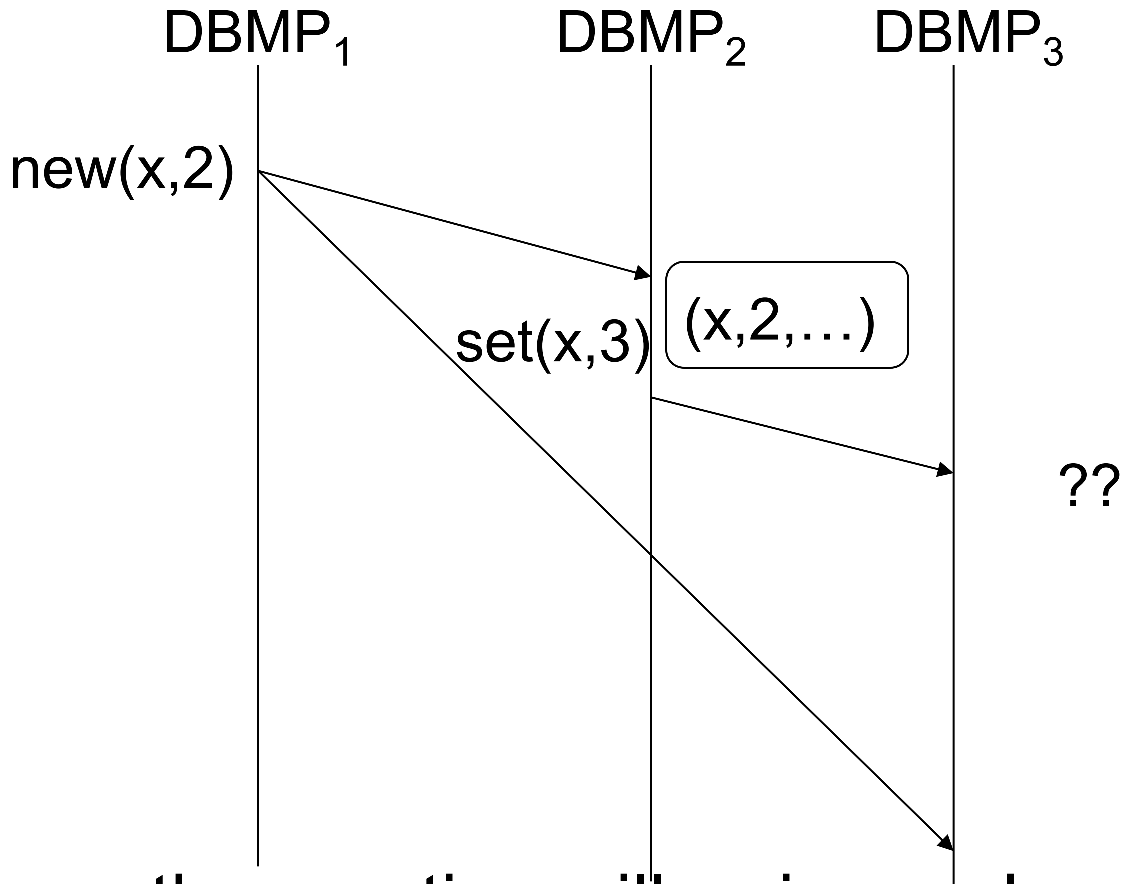
Database entry

- E::=(S,V,T)
  - S is the selector
  - V is the value
  - T is the timestamp = (Time, DBMP id) of the last change to the entry

Thomas write rule = last writer wins

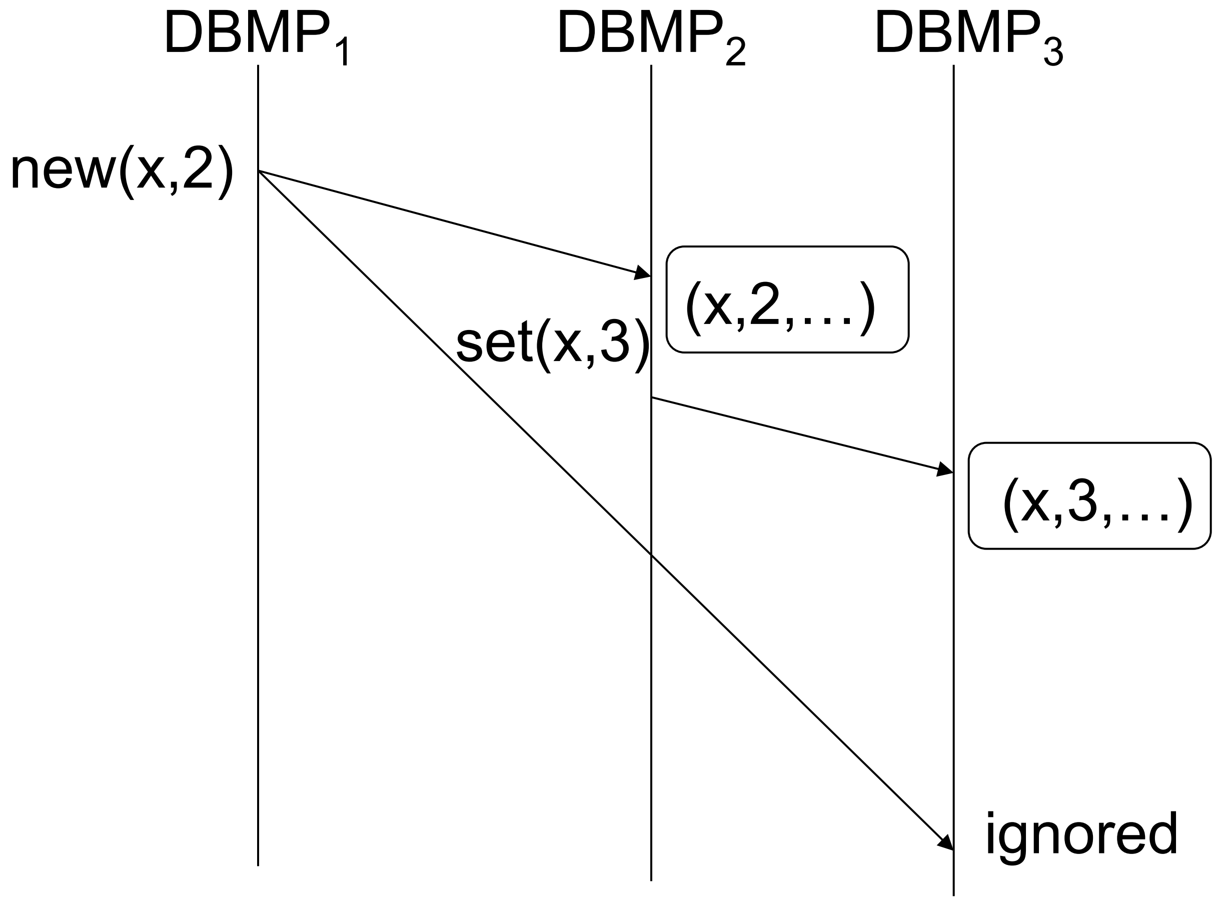


Creation/update

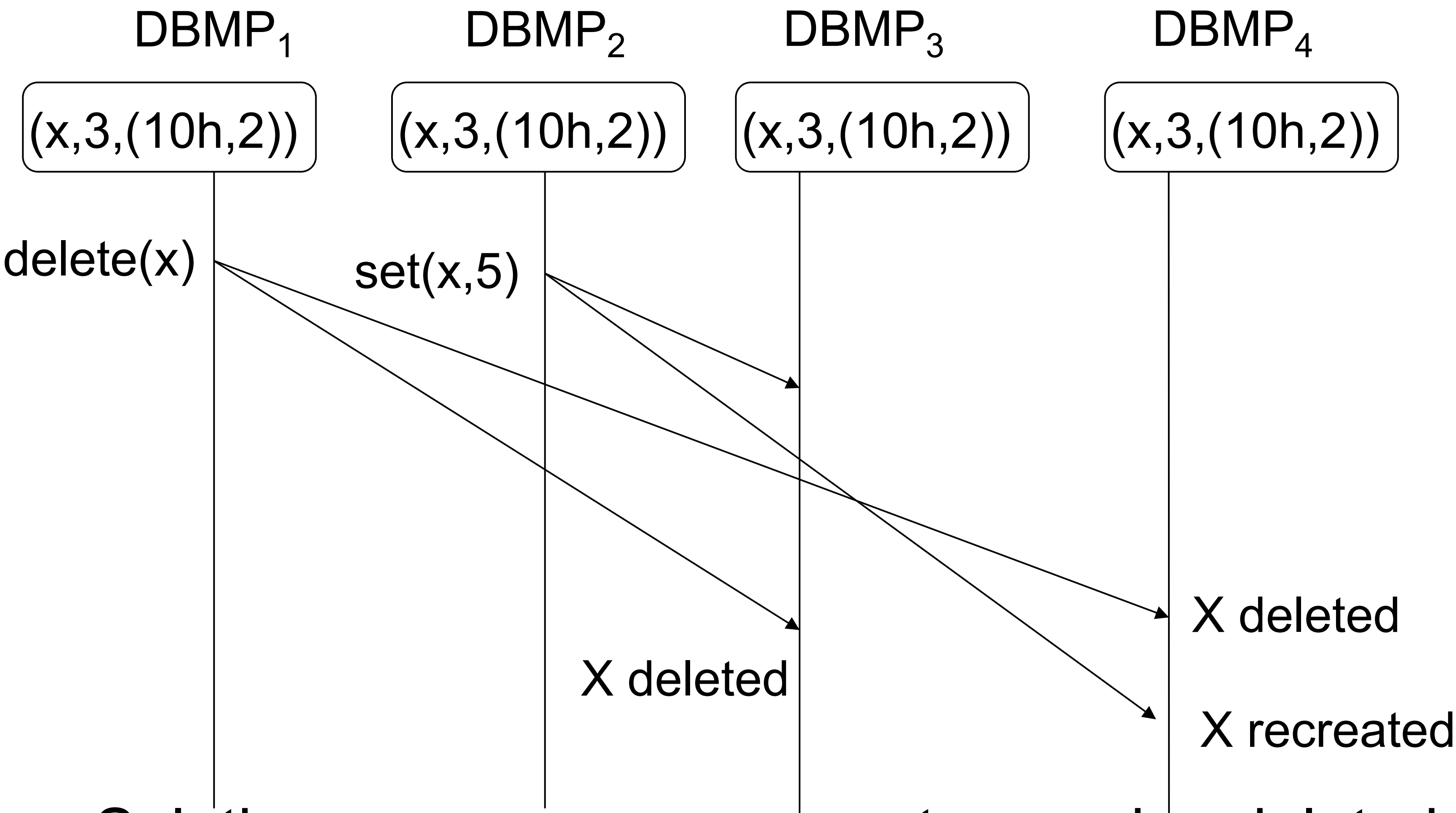


- Assume the creation will arrive and create the entry right away
- Creation operation ignored at arrival

Creation/update



Deletion

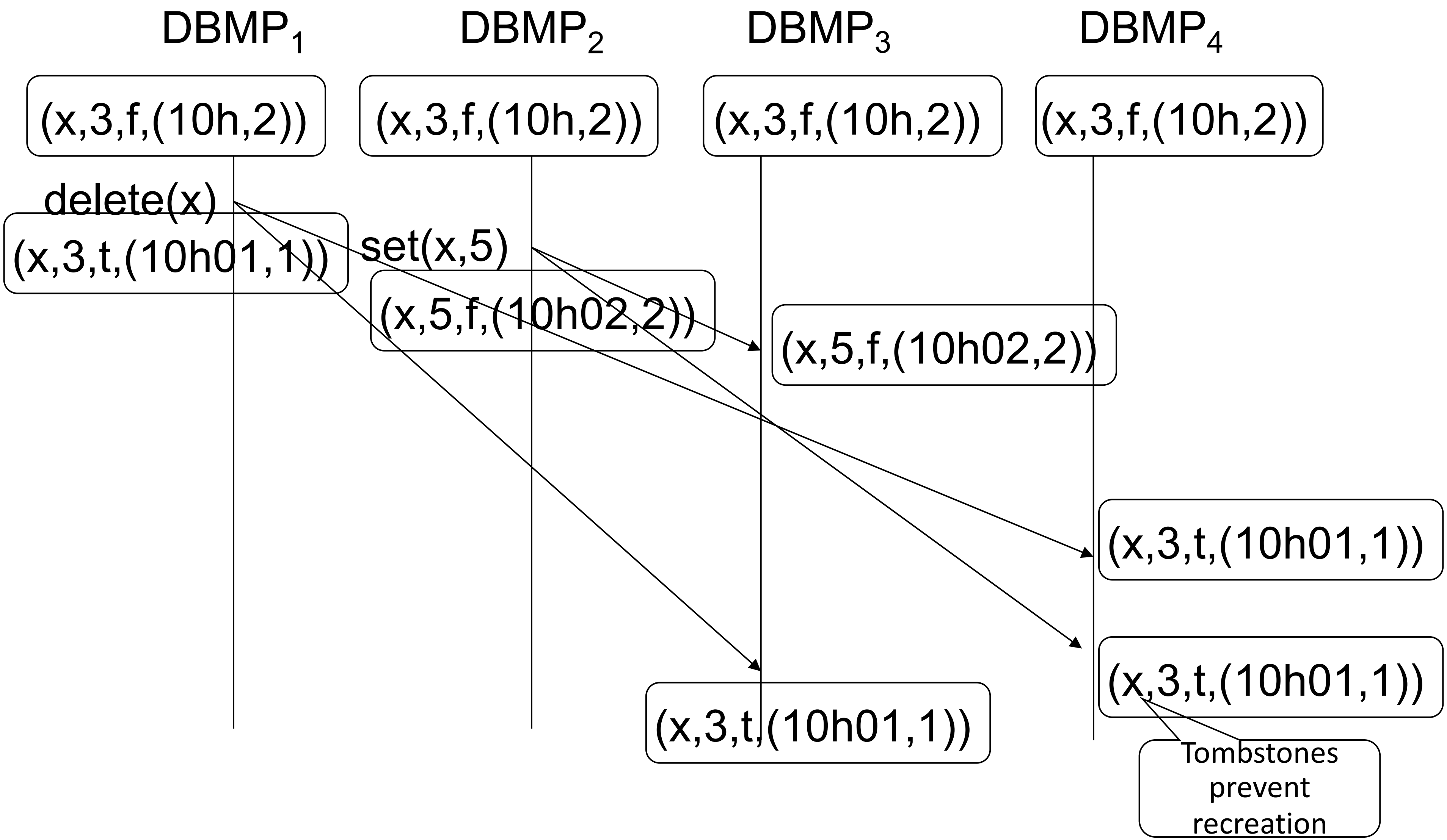


- Solution: never remove an entry, mark « deleted » flag

Tombstones

- E::=(S,V,F,T)
  - S is the selector
  - V is the value
  - F is the deleted/not-deleted flag
  - T is the timestamp = (Time, DBMP id) of the last change to the entry
- F=t if deleted
- F=f if not-deleted

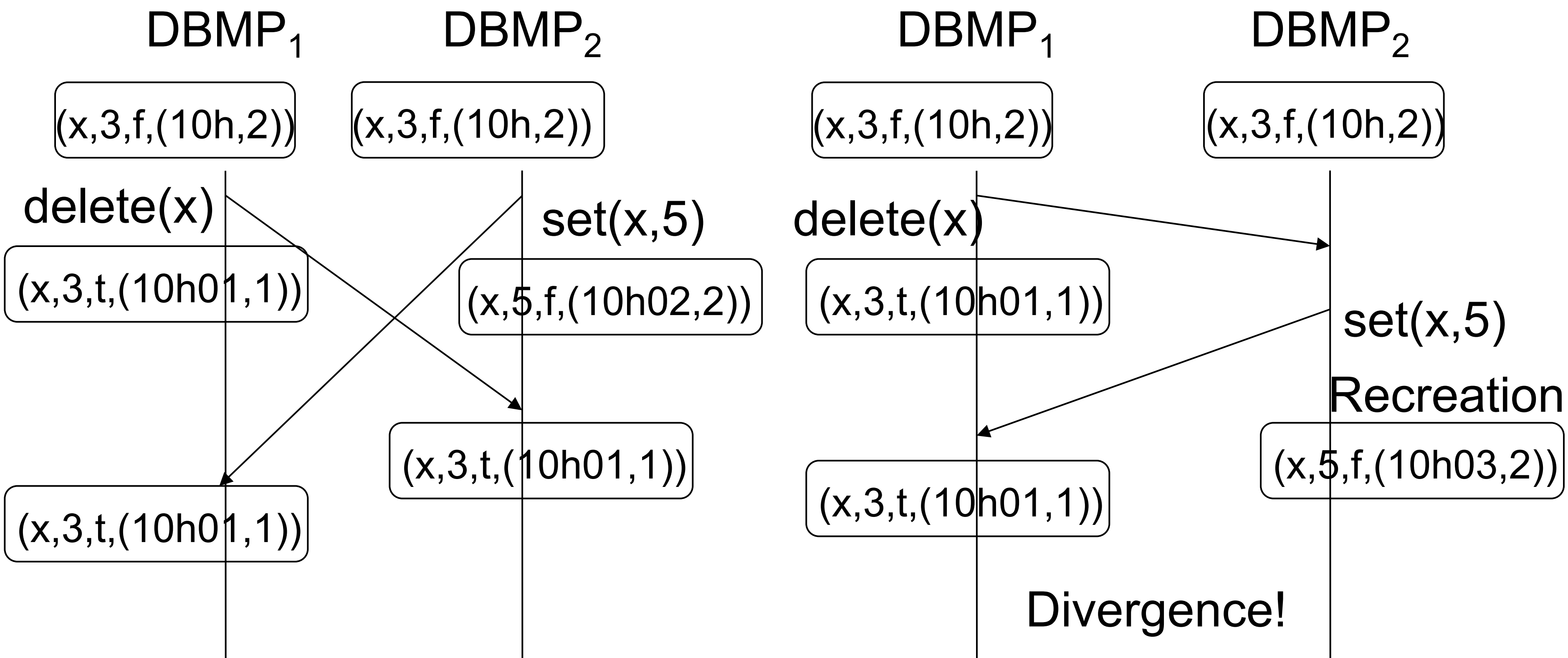
Tombstones



DBMP1
DBMP2
DBMP3
DBMP4
(x,3,f,(10h,2))
(x,3,f,(10h,2))
(x,3,f,(10h,2))
(x,3,f,(10h,2))
delete(x)
(x,3,t,(10h01,1))
set(x,5)
(x,5,f,(10h02,2))
(x,5,f,(10h02,2))
(x,3,t,(10h01,1))
(x,3,t,(10h01,1))
(x,3,t,(10h01,1))
Tombstones prevent recreation

Tombstones

- DBMP1 cannot distinguish in which of the two cases DBMP2 is

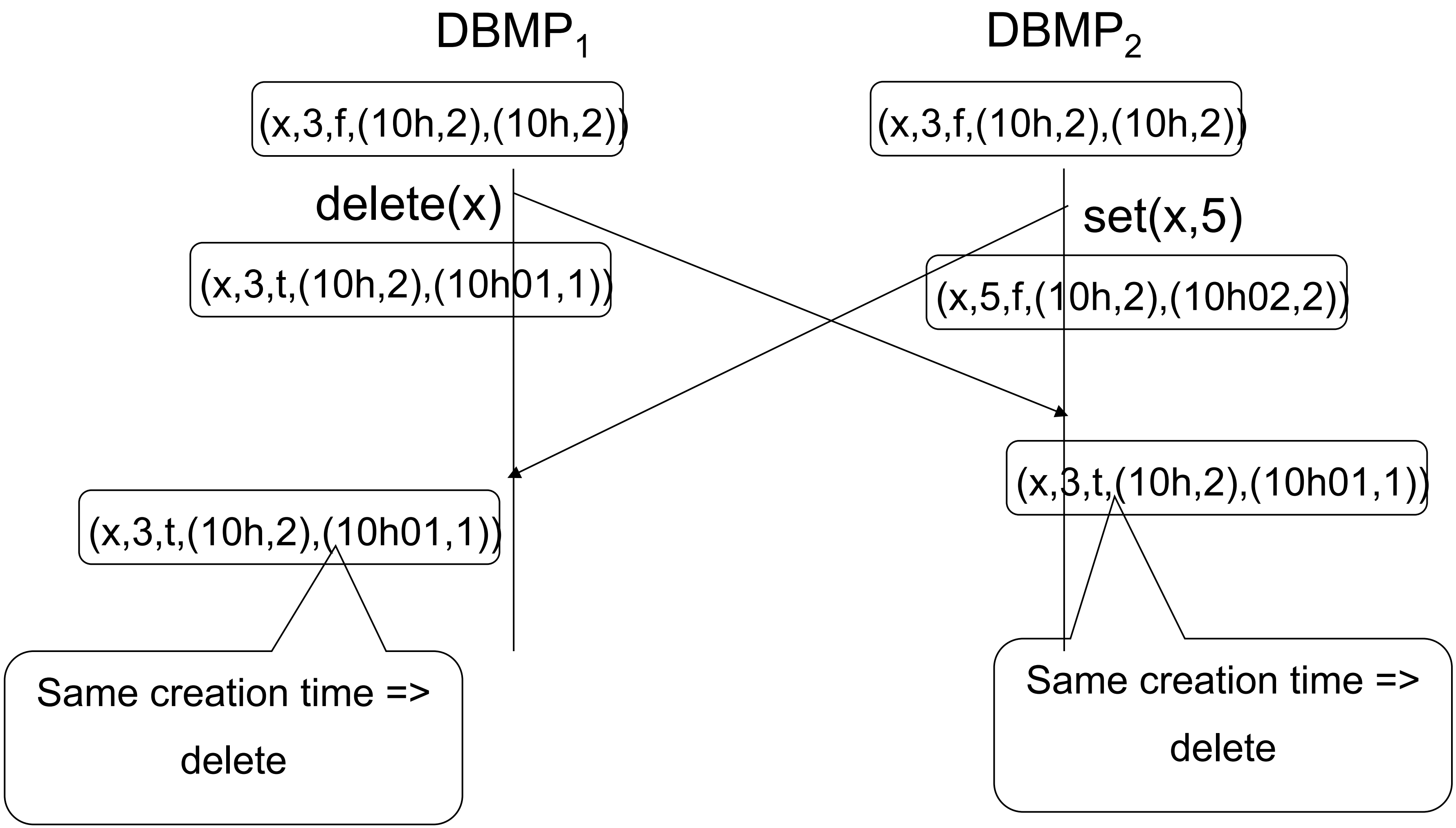


- Solution: Associate to an entry the creation timestamp

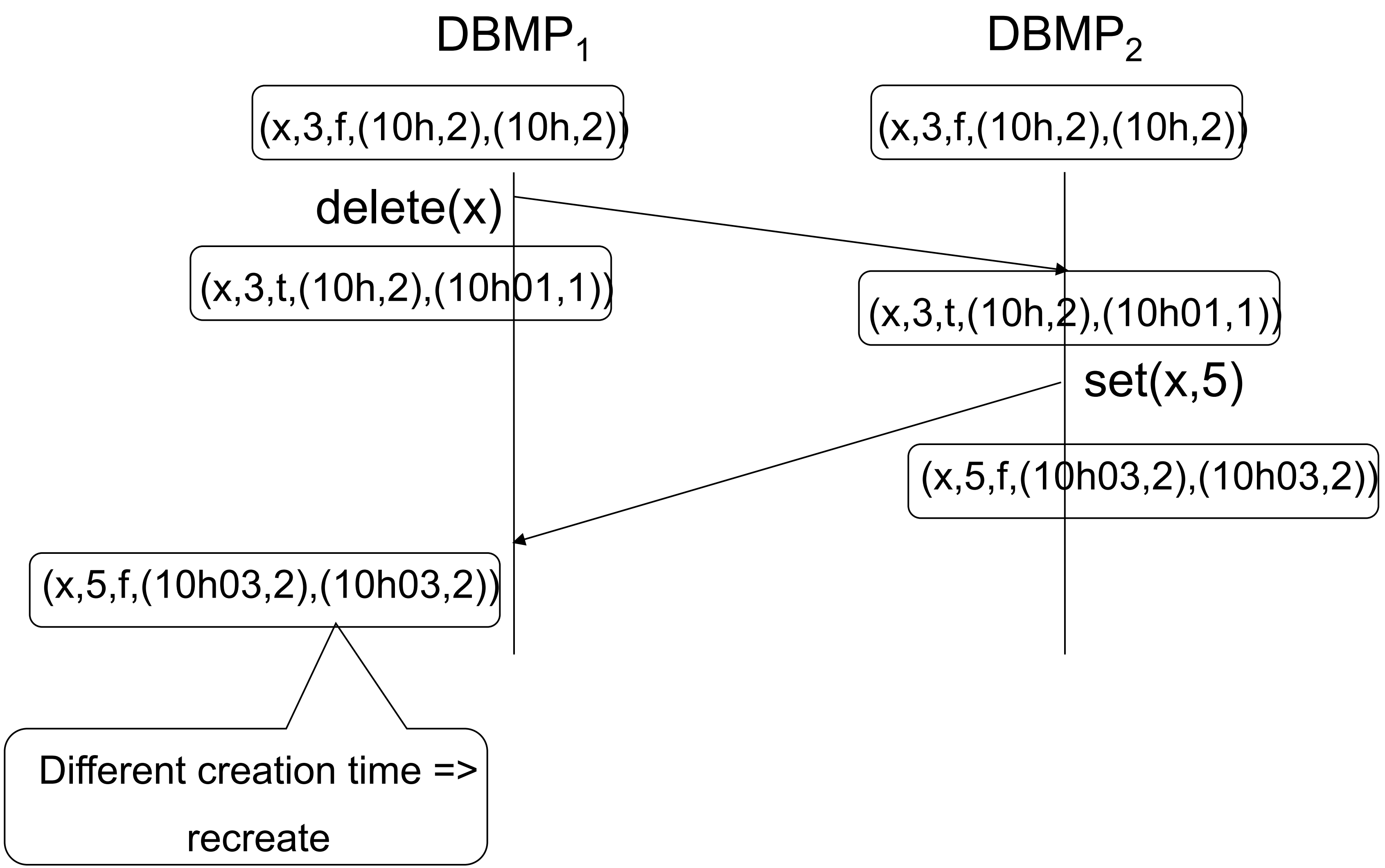
Tombstones

- E::=(S,V,F,CT,T)
  - S is the selector
  - V is the value
  - F is the deleted/not-deleted flag
  - CT is the timestamp for creation
  - T is the timestamp = (Time, DBMP id) of the last change to the entry
- If F=f and CT=T, then creation
- If F=f and CT<T, then assignment
- If F=t, then deletion

Tombstones


DBMP1
DBMP2
(x,3,f,(10h,2),(10h,2))
(x,3,f,(10h,2),(10h,2))
delete(x)
set(x,5)
(x,3,t,(10h,2),(10h01,1))
(x,5,f,(10h,2),(10h02,2))
(x,3,t,(10h,2),(10h01,1))
(x,3,t,(10h,2),(10h01,1))
Same creation time =>
delete
Same creation time =>
delete

Tombstones


$DBMP_1$
$DBMP_2$
(x,3,f,(10h,2),(10h,2))
(x,3,f,(10h,2),(10h,2))
delete(x)
(x,3,t,(10h,2),(10h01,1))
(x,3,t,(10h,2),(10h01,1))
set(x,5)
(x,5,f,(10h03,2),(10h03,2))
(x,5,f,(10h03,2),(10h03,2))
Different creation time => recreate