Replicated state machine and Paxos

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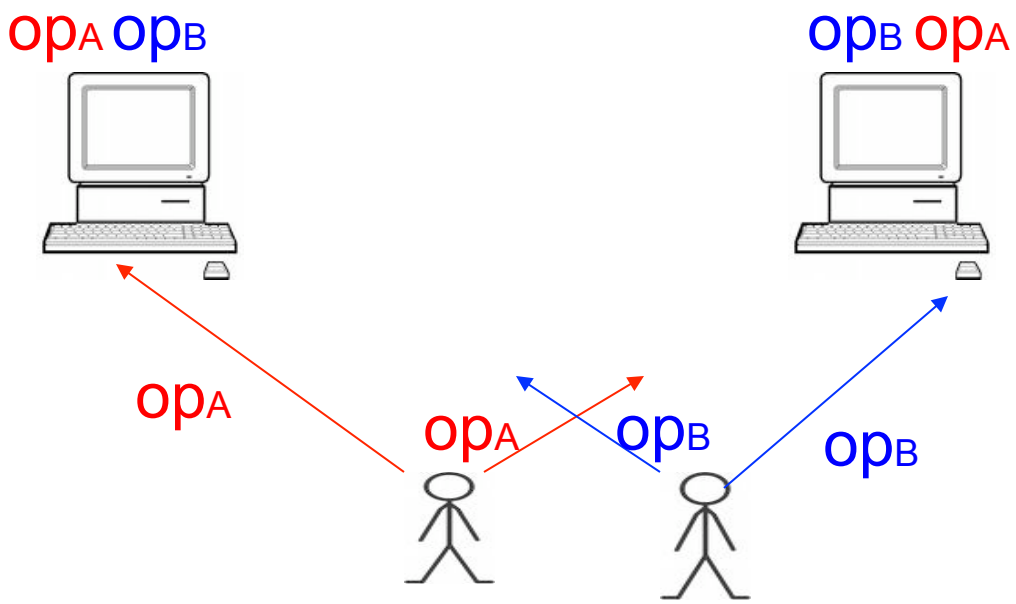
Fault tolerance => replication

- How to recover a single node from power failure?
  - Wait for reboot
    - Data is durable, but service is unavailable temporarily
  - Use multiple nodes to provide service
    - Another node takes over to provide service
    - How to make sure nodes respond in the same way?

Replicated state machine (RSM)

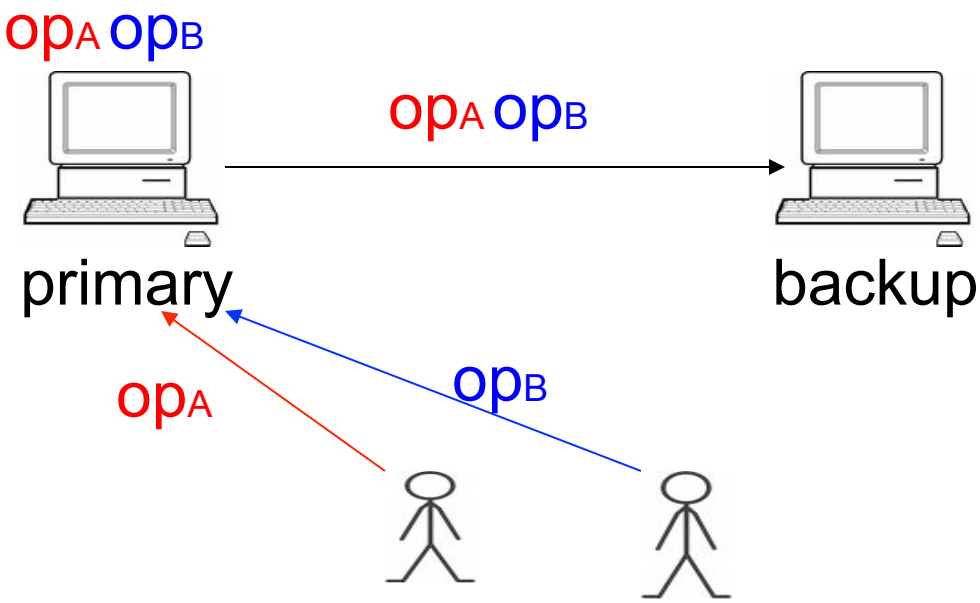
- RSM is a general replication method
  - Lab 8: apply RSM to lock service
- RSM Rules:
  - All replicas start in the same initial state
  - Every replica apply operations in the same order
  - All operations must be deterministic
- All replicas end up in the same state

RSM



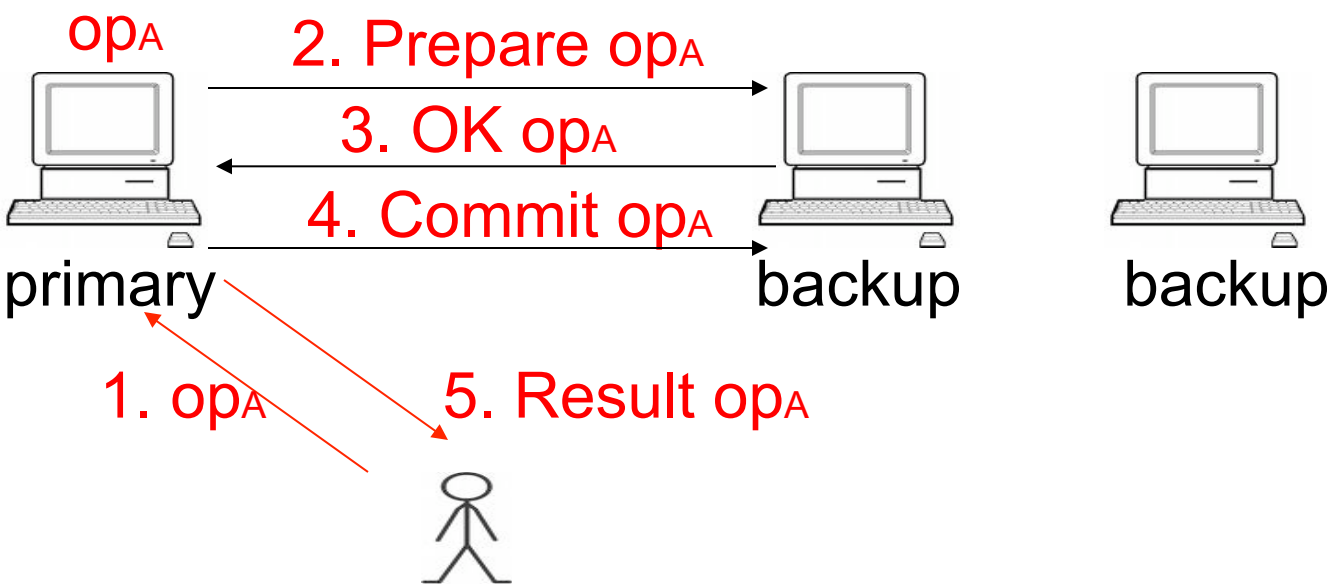
- How to maintain a single order in the face of concurrent client requests?

RSM using primary/backup



- Primary/backup: ensure a single order of ops:
  - Primary orders operations
  - Backups execute operations in order

When does primary respond?



- After majority of backups have commit to op
  - Run two-phase commit
  - Lab 8: no persistent state; can avoid messages 2 and 3

Caveats in Hypervisor RSM

- Hypervisor assumes failure detection is perfect
- What if the network between primary/backup fails?
  - Primary is still running
  - Backup becomes a new primary
  - Two primaries at the same time!
- Can timeouts detect failures correctly?
  - Pings from backup to primary are lost
  - Pings from backup to primary are delayed

Paxos: fault tolerant agreement

- Paxos lets all nodes agree on the same value despite node failures, network failures and delays
- Extremely useful:
  - e.g. Nodes agree that X is the primary
  - e.g. Nodes agree that Y is the last operation executed

Paxos: general approach

- One (or more) node decides to be the leader
- Leader proposes a value and solicits acceptance from others
- Leader announces result or try again

Paxos requirement

- Correctness (safety):
  - All nodes agree on the same value
  - The agreed value X has been proposed by some node
- Fault-tolerance:
  - If less than N/2 nodes fail, the rest nodes should reach agreement *eventually w.h.p*
  - Liveness is not *guaranteed*

Why is agreement hard?

- What if >1 nodes become leaders simultaneously?
- What if there is a network partition?
- What if a leader crashes in the middle of solicitation?
- What if a leader crashes after deciding but before announcing results?
- What if the new leader proposes different values than already decided value?

Paxos setup

- Each node runs as a *proposer*, *acceptor* and *learner*
- Proposer (leader) proposes a value and solicit acceptence from acceptors
- Leader announces the chosen value to learners

Strawman

- Designate a single node X as acceptor (e.g. one with smallest id)
  - Each *proposer* sends its value to X
  - X decides on one of the values
  - X announces its decision to all *learners*
- Problem?
  - Failure of the single acceptor halts decision
  - Need multiple acceptors!

Strawman 2: multiple acceptors

- Each proposer (leader) propose to all acceptors
- Each acceptor accepts the first proposal it receives and rejects the rest
- If the leader receives positive replies from a majority of acceptors, it chooses its own value
  - There is at most 1 majority, hence only a single value is chosen
- Leader sends chosen value to all learners
- Problem:
  - What if multiple leaders propose simultaneously so there is no majority accepting?

Paxos solution

- Proposals are ordered by proposal #
- Each acceptor may accept multiple proposals
  - If a proposal with value v is chosen, all higher proposals have value v

Paxos state

- Acceptor maintains across reboots:
  - n_a, v_a: highest proposal # and its corresponding accepted value
  - n_p: highest proposal # seen
- Proposer maintains:
  - my_n: my proposal # in current Paxos
- Each round of Paxos has an instance #

Proposer

- PROPOSE(v)

  choose $my_n > np$

  send PREPARE(my_n) to all nodes

  if PREPARE_OK(n_a, v_a) from majority **then**

    v_a = v_a with highest n_a, or choose own v otherwise

    send ACCEPT (n_a, v_a) to all

    if ACCEPT_OK(n_a) from majority **then**

      send DECIDED(v_a) to all

Acceptor

- PREPARE(n)

  If n > n_p

  n_p= n

  reply <PREPARE_OK, n_a,v_a>

This node will not accept any proposal lower than n

- ACCEPT(n, v)

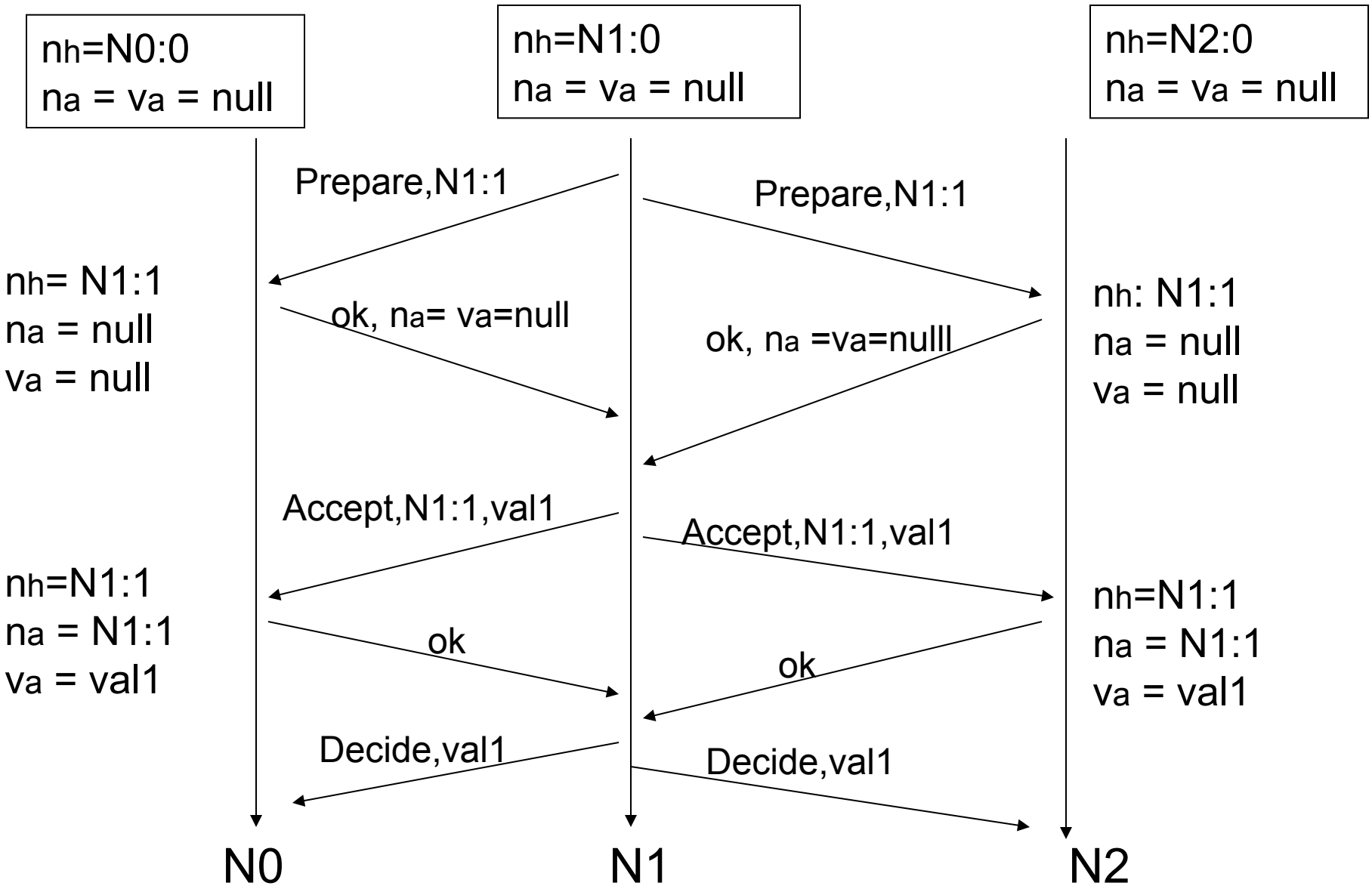
  If n >= n_p

  n_a = n

  v_a = v

  reply with <ACCEPT_OK>

Paxos operation: 3 phase example



Paxos properties

- When is the value V chosen?
  1. When leader receives a majority prepare-ok and proposes V
  2. When a majority nodes accept V
  3. When the leader receives a majority accept-ok for value V

Understanding Paxos

- What if more than one leader is active?
- Suppose two leaders use different proposal number, N0:10, N1:11
- Can both leaders see a majority of prepare-ok?

Understanding Paxos

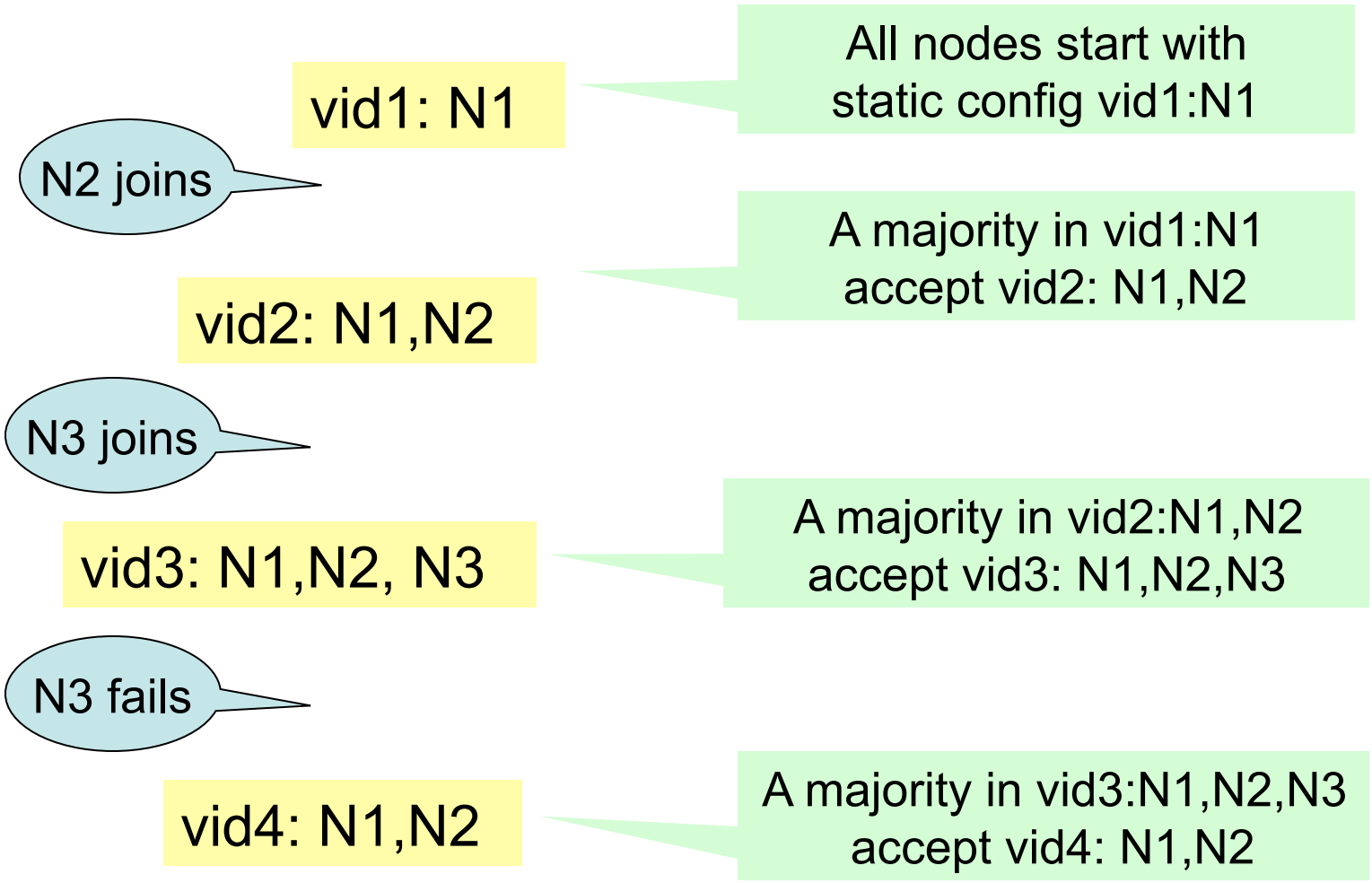
- What if leader fails while sending accept?
- What if a node fails after receiving accept?
  - If it doesn't restart …
  - If it reboots …
- What if a node fails after sending prepare-ok?
  - If it reboots …

Using Paxos for RSM

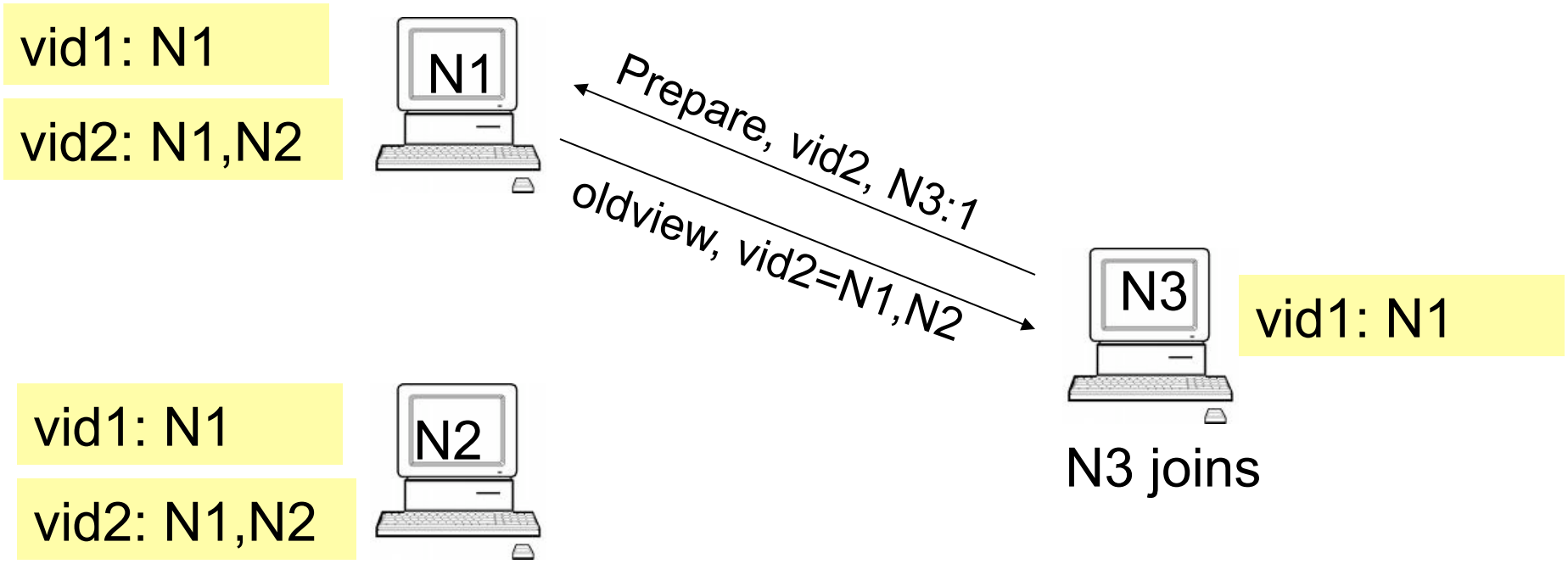
- Fault-tolerant RSM requires consistent replica membership
  - Membership: <primary, backups>
  - RSM goes through a series of membership changes

  <vid-0, primary, backups><vid-1, primary, backups> ..
- Use Paxos to agree on the <primary, backups> for a particular vid
  - vid == paxos instance #

Lab8: Using Paxos for RSM



Lab7: Using Paxos for RSM



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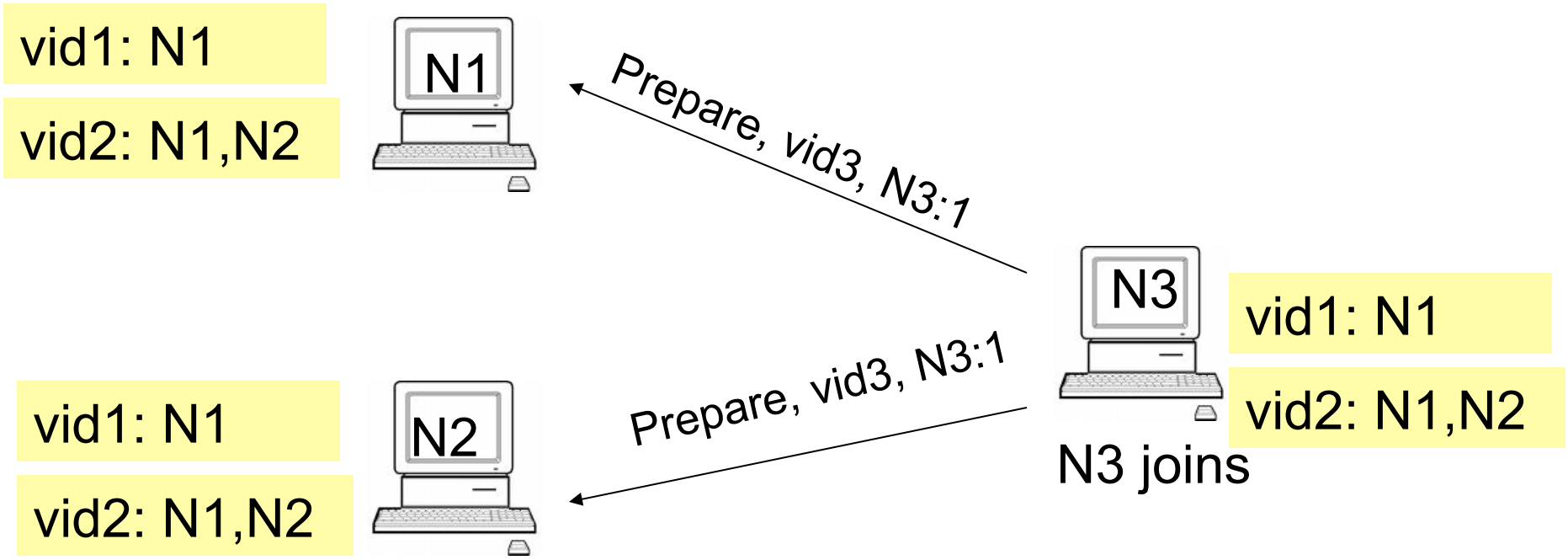


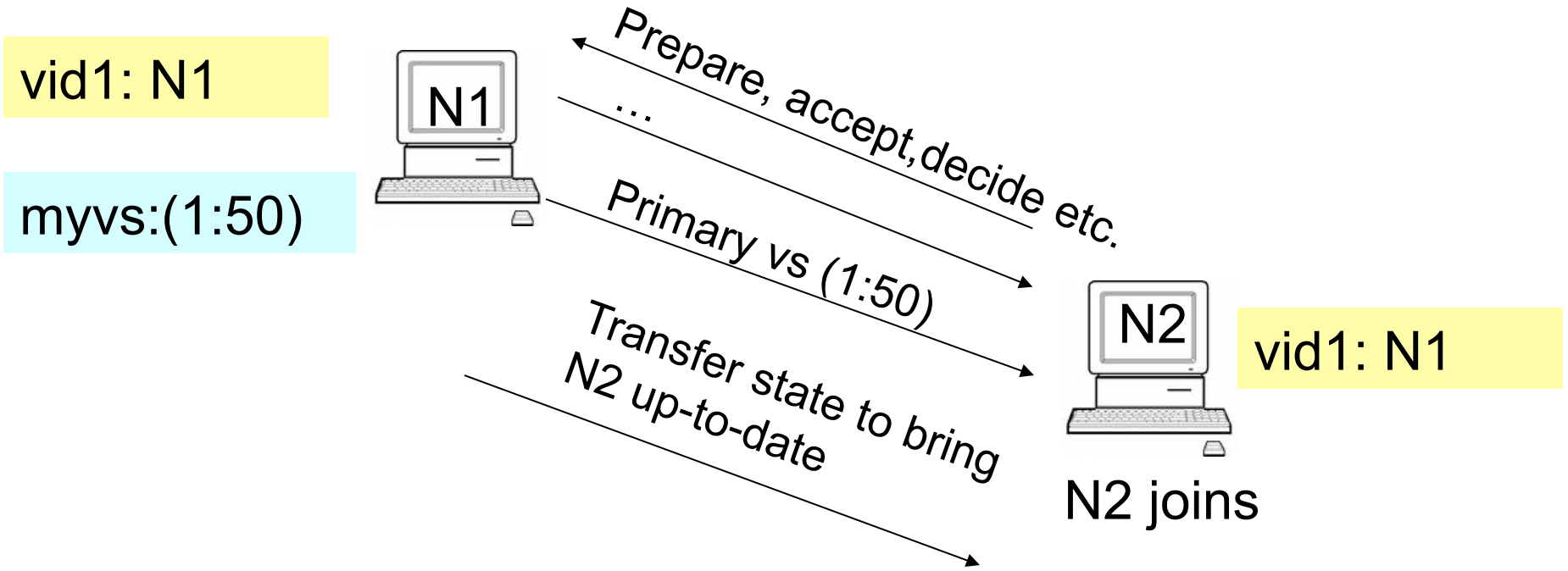
Lab8: re-configurable RSM

- Use RSM to replicate lock_server
- Primary in each view assigns a viewstamp to each client requests
  - Viewstamp is a tuple (vid:seqno)
  - (0:0)(0:1)(0:2)(0:3)(1:0)(1:1)(1:2)(2:0)(2:1)
- All replicas execute client requests in viewstamp order

Lab8: Viewstamp replication

- To execute an op with viewstamp (vs), a replica must have executed all ops < vs
- A newly joined replica need to transfer state to ensure its state reflect executions of all ops < vs

Lab8: Using Paxos for RSM



- Primary in new view is last primary, if alive
- Otherwise, backup lowest ID
- Resume responding to client after backups and primary are in sync