LECTURE 7

Paxos and Consensus

Availability of P/B-based RSM

- When is RSM unavailable to serve requests?

- Replica is down but viewservice yet to detect

- How to …
  - … make RSM tolerant to network partitions?
  - … ensure that operations don't block even if some machines are unavailable?

Analogy

- US Senate needs to pass laws
- Senators are often on travel
  - Common case: Not all senators present
- How to pass laws successfully?

RSM via Consensus

- Key idea: Apply an update if majority of replicas commit to it
- If 2f+1 replicas, need f+1 to commit

- Why majority? Why not fewer or more?
- Remaining replicas cannot accept some other update

Context for Today's Lecture

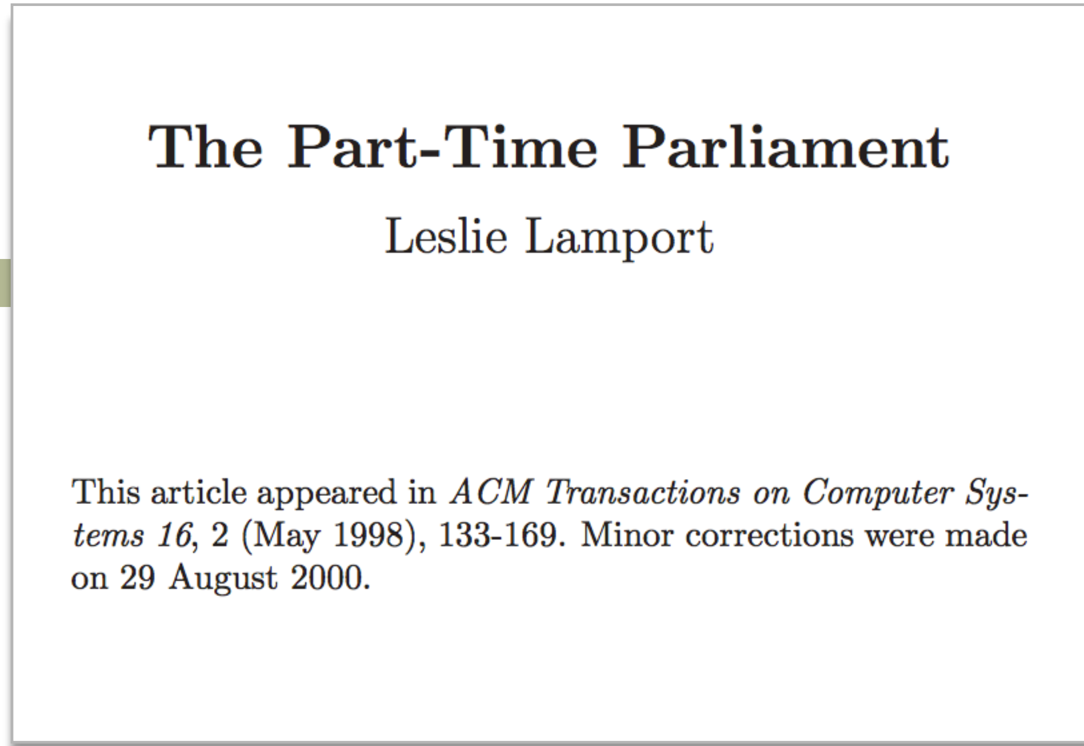
- Say all replicas are in sync with each other
- First: Among several concurrent new updates, how to pick next update to apply?
- Later: How to apply all updates in a consistent order at all replicas?

Strawman Approaches

- Every client proposes its value to all replicas
- Every replica accepts first proposal received
- Value accepted by majority is applied
- Why might this not work?

- Every client tags its proposal with seq number
- Every replica collects proposals and accepts lowest seq number proposal
- Why might this not work?

Paxos



The Part-Time Parliament

Leslie Lamport

This article appeared in *ACM Transactions on Computer Systems 16*, 2 (May 1998), 133-169. Minor corrections were made on 29 August 2000.

- Original paper submitted in 1990
  - Tells mythical story of Greek island of Paxos with "legislators" and "current law" passed through parliamentary voting protocol

- Widely used in industry today

Desirable Properties

- Safety
  - *"No bad things happen"*
  - System never reaches an undesirable state
- Liveness
  - *"Good things eventually happen"*
  - System makes progress eventually
- Tradeoff between consistency and latency

Desired Properties of Solution

- Safety:
  - Accept a value only if accepted by a majority
  - Accept a value only if proposed by some client
- Liveness:
  - If any values are proposed, one of them will eventually be accepted
  - If a value is accepted, all replicas will eventually discover that it was chosen

Roles of a Process

- Three conceptual roles
  - Proposers propose values
  - Acceptors accept values; chosen if majority accept
  - Learners learn the outcome (chosen value)

- In reality, a process can play any/all roles
- Roles in bank account example?
- Roles in US Senate example?

Paxos Overview

- Three phases within each round
- Prepare Phase:
  - Proposer sends a unique proposal number to all acceptors
  - Waits to get commitment from majority of acceptors
- Accept Phase:
  - Proposer sends proposed value to all acceptors
  - Waits to get proposal accepted by majority
- Learn Phase:
  - Learners discover value accepted by majority

Paxos State

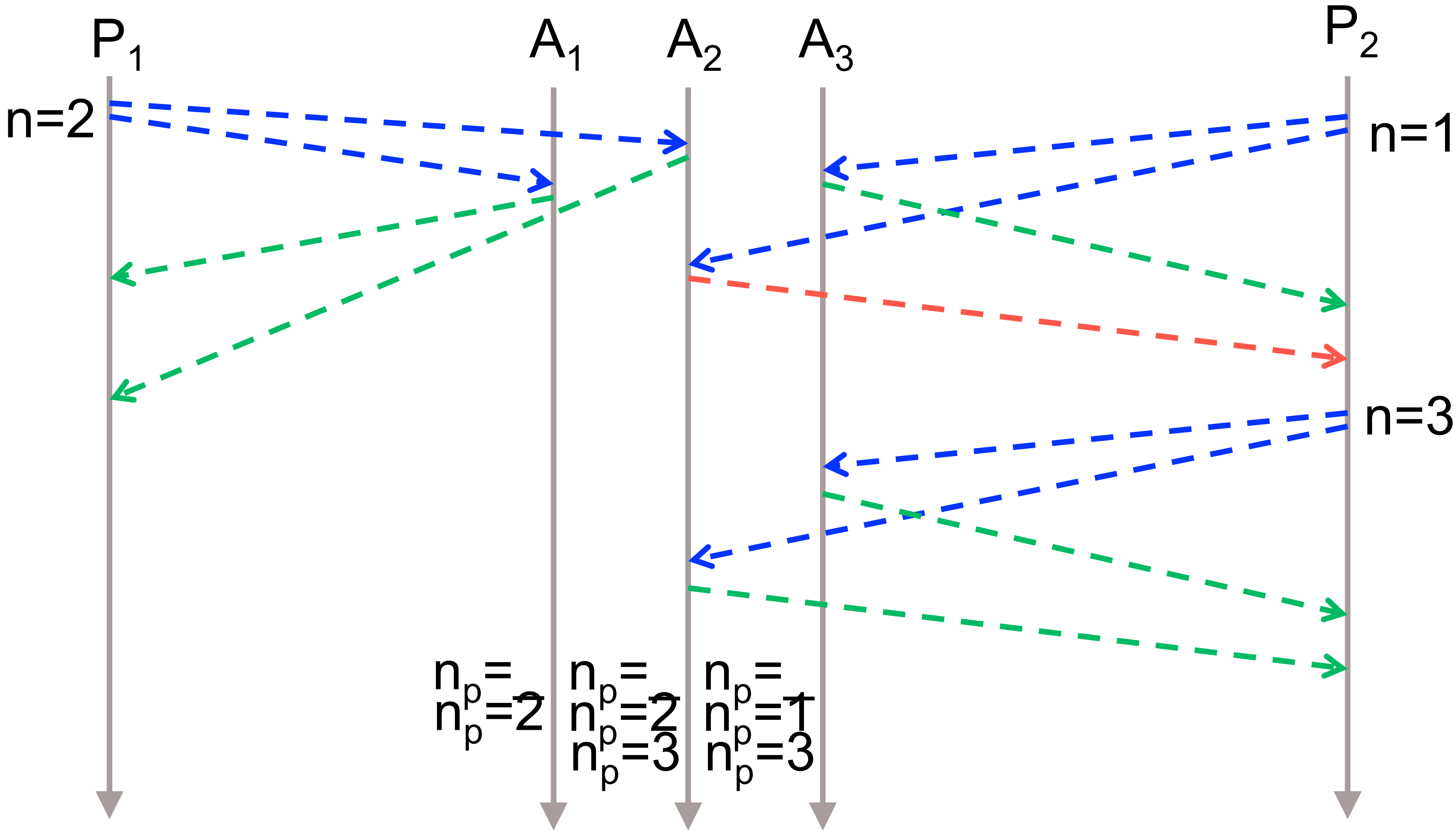
- Every acceptor maintains three values:
  - n_p → highest proposal number promised to accept
  - n_a → highest proposal number accepted
  - v_a → value accepted (operation)

- This state must persist across restarts
- Learners can re-discover accepted value (if any) from acceptors

Paxos Phase 1

- Proposer:
  - Choose unique proposal number n
  - Send <prepare, n> to all acceptors
- Acceptors:
  - If $n >= n_p$
    - $n_p = n$ ← promise not to accept any new proposals n' < n
    - If no prior proposal accepted
      - Reply < promise, n, Ø >
    - Else
      - Reply < promise, n, (n_a , v_a) >
  - Else
    - Reply < prepare-failed >

Prepare Phase



Paxos Phase 1

- Proposer: How to pick unique proposal number?
  - Choose unique proposal number n
  - Send <prepare, n> to all acceptors

    Why all? Why not majority?
- Acceptors:
  - If $n > n_p$
    - $n_p = n$ ← promise not to accept any new proposals n' < n
    - If no prior proposal accepted
      - Reply < promise, n, Ø >
    - Else
      - Reply < promise, n, (n_a, v_a) >
  - Else ← What else is worth including?
    - Reply < prepare-failed >

Paxos Phase 2

- Proposer:

  When would majority not promise?

  - Once received promises from majority of acceptors,
    - $v' = v_a$ returned with highest n_a, if exists, else own v
    - Send <accept, (n, v')> to acceptors

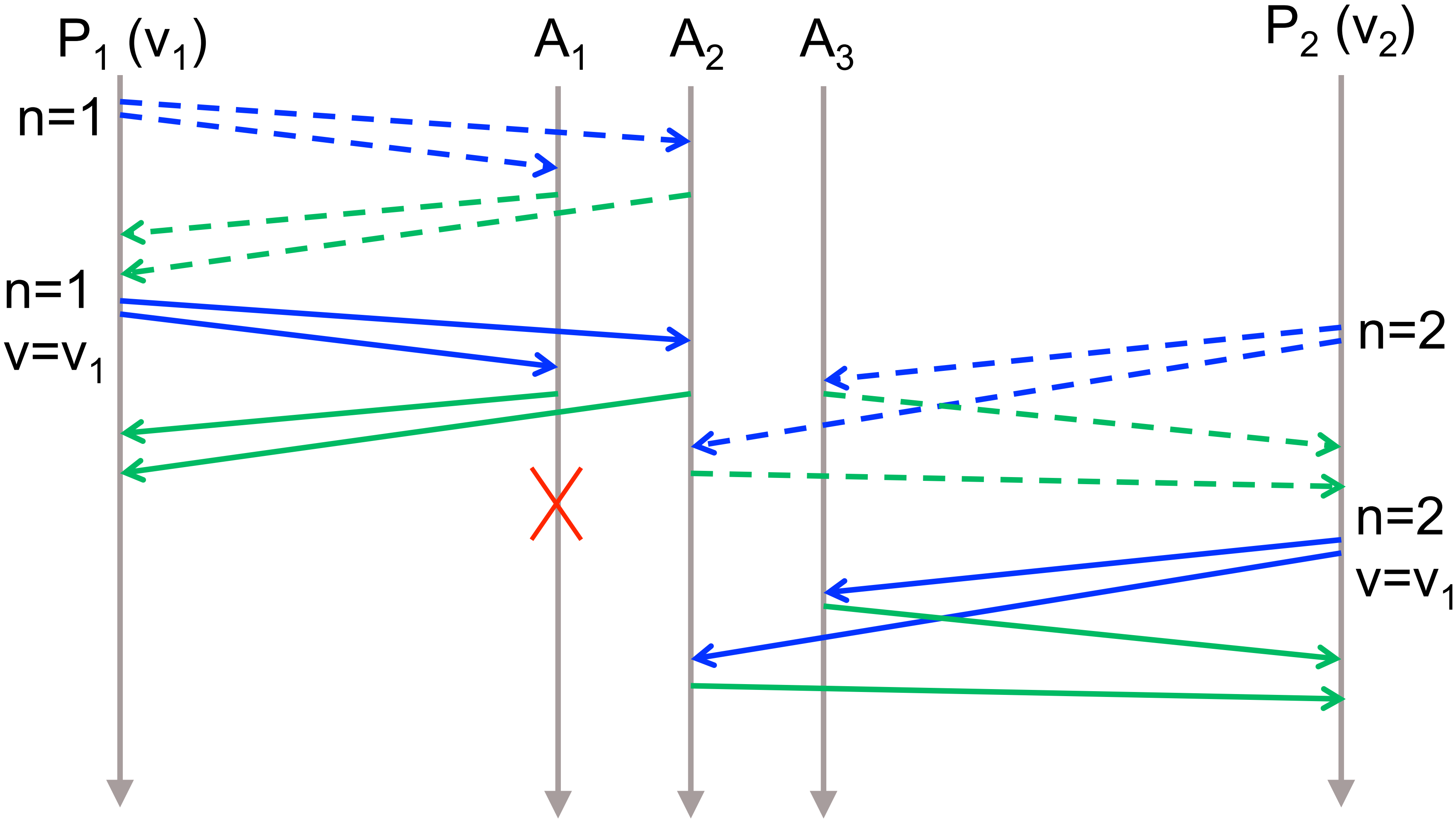
  Why not stop if v_a != v?

- Acceptors:
  - Upon receiving (n, v), if $n \geq n_p$,
    - Accept proposal and notify learner(s)

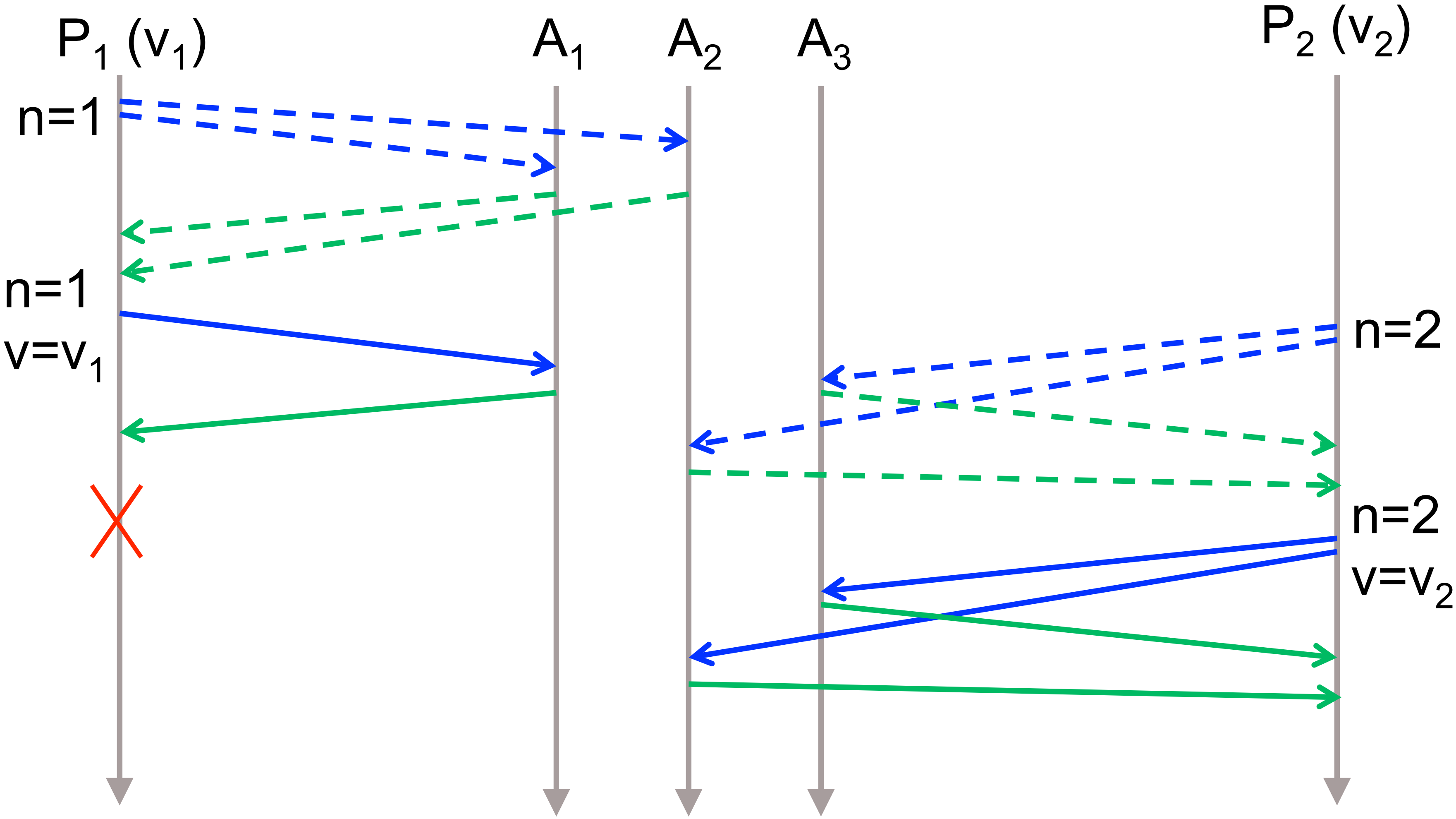
      $n_a = n_p = n$

      $v_a = v$

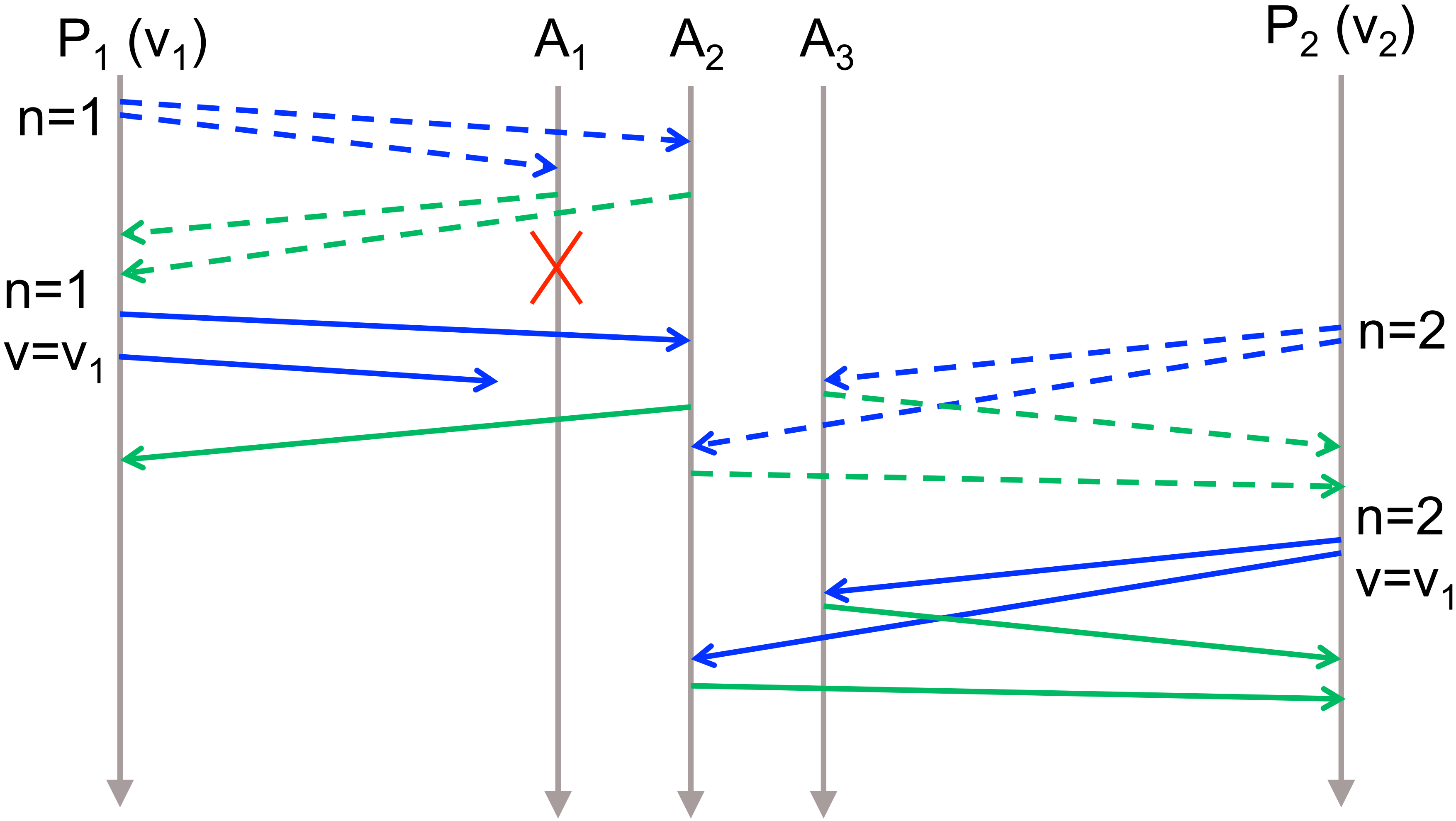
Accept Phase



Accept Phase



Accept Phase



Paxos: Sample Execution

- Acceptor1: P1 A1-X P2
- Acceptor2: P1 A1-X P2 P3
- Acceptor3: P1 A1-X P3

Paxos: Sample Execution

- Acceptor1: P1 A1-X P3 A3-X
- Acceptor2: P1 P2 A1-X P3 A2-Y A3-X
- Acceptor3: P2 A2-Y

Paxos: Sample Execution

- Acceptor1: P1 A1-X
- Acceptor2: P1 A1-X P2
- Acceptor3: P2

Paxos: Sample Execution

- Acceptor1: P1 A1-X
- Acceptor2: P1 A1-X P2 A2-X
- Acceptor3: P2 A2-X

Paxos: Sample Execution

- Acceptor1: P1
- Acceptor2: P1 A1-X P2
- Acceptor3: P2

Paxos: Sample Execution

- Acceptor1: P1
- Acceptor2: P1 A1-X P2 A2-X
- Acceptor3: P2 A2-X

Paxos: Sample Execution

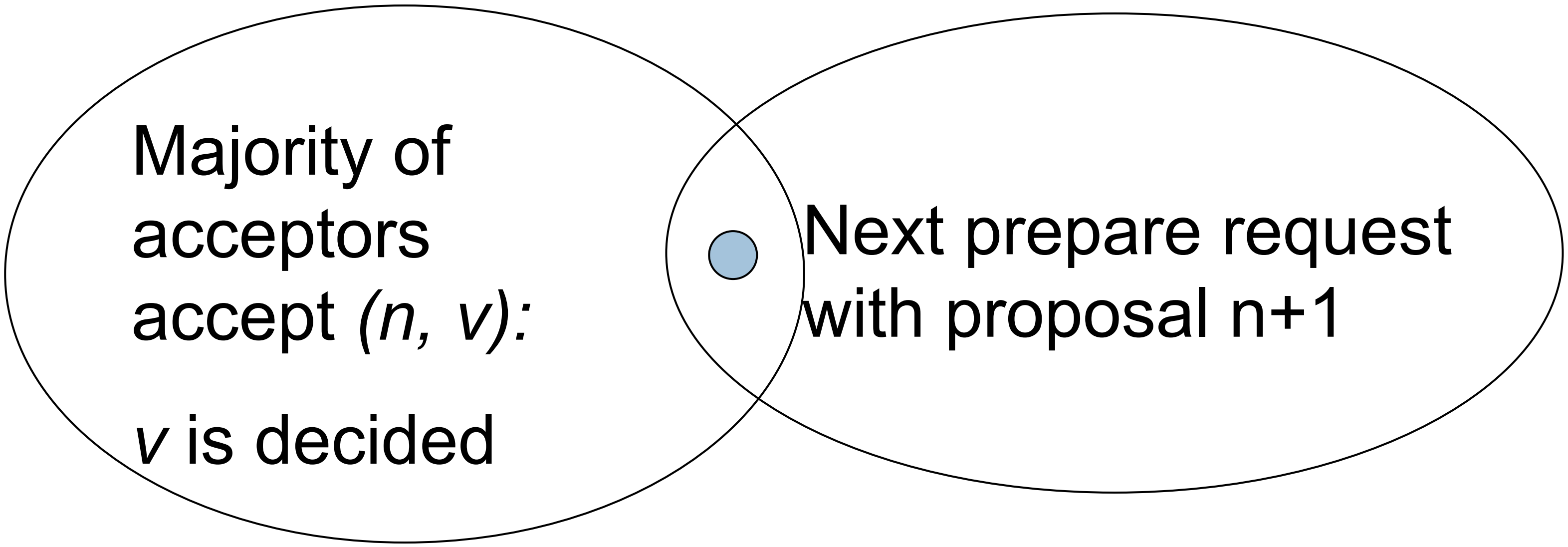
- Acceptor1: P1 A1-X
- Acceptor2: P1 P2
- Acceptor3: P2

Paxos: Sample Execution

- Acceptor1: P1 A1-X
- Acceptor2: P1 P2 A2-Y
- Acceptor3: P2 A2-Y

Paxos is safe

- Intuition: Once proposal with value v accepted, then every higher-numbered proposal issued by any proposer has value v



Desired Properties of Solution

- Safety:
  - Accept a value only if accepted by a majority
  - Accept a value only if proposed by some client
- Liveness:
  - If any values are proposed, one of them will eventually be accepted
  - If a value is accepted, all replicas will eventually discover that it was chosen

Race condition leads to liveness problem

Process 0 | **Process 1**

Completes phase 1 with proposal n0

Starts and completes phase 1 with proposal n1 > n0

Performs phase 2, acceptors reject

Retries and completes phase 1 with proposal n2 > n1

Performs phase 2, acceptors reject

… can go on indefinitely …

Paxos: Race condition

- Acceptor1: P1 A1-X P3
- Acceptor2: P1 P2 A1-X P3 A2-Y P4
- Acceptor3: P2 A2-Y P4

How to fix this?

Fixes to liveness problem

- When proposal fails, back off for a random period of time before retrying

- Pre-determined ordering of proposers
  - Negative response from acceptor includes ID of proposer to whom the acceptor has committed
  - Back off period chosen based on ordering

- Note co-operative nature of protocol

Why two phases?

- Liveness problem is partly due to two phases
  - Between one proposer's Prepare and Accept phases, n_p updated by another proposer

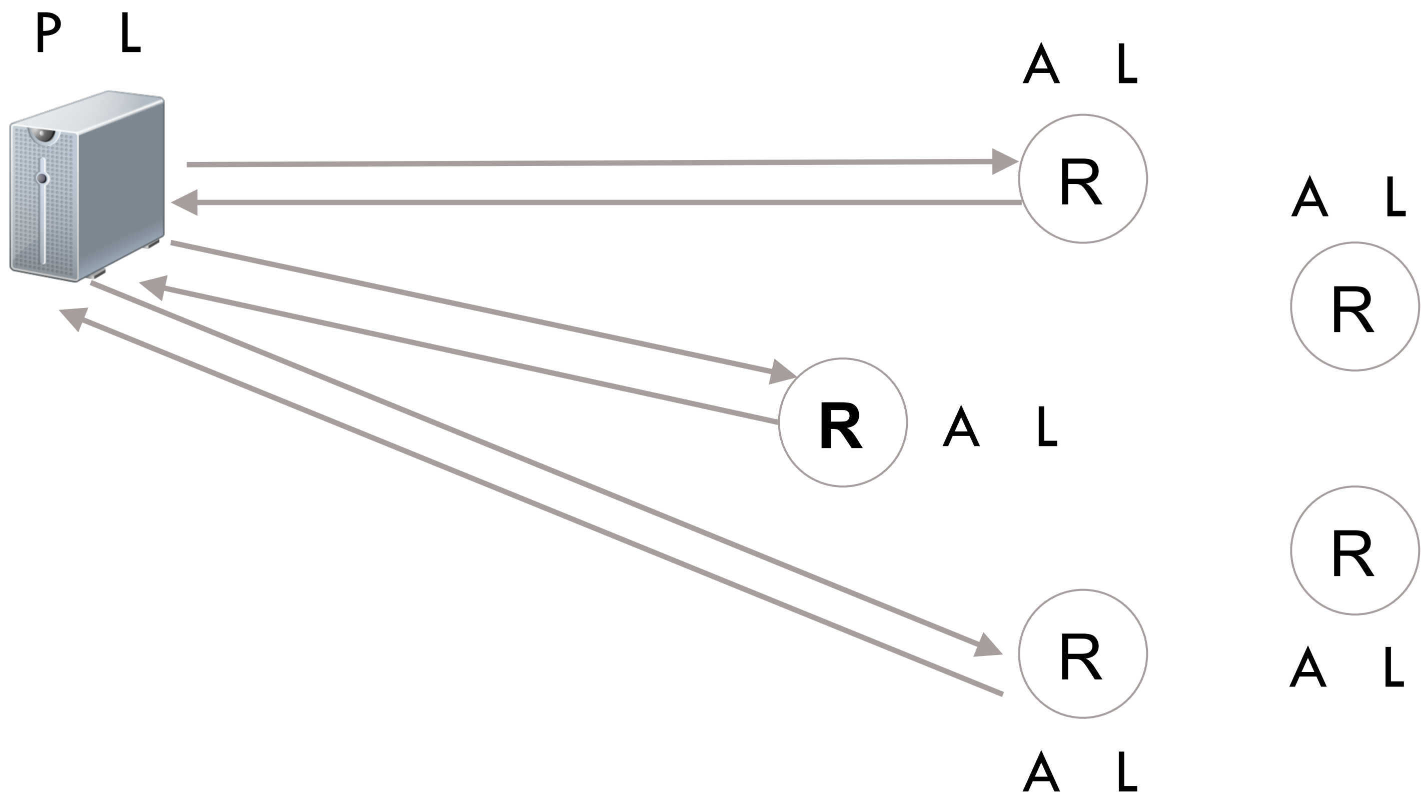
- Alternate design:
  - Proposer sends propose messages to all acceptors
  - Retry with higher proposal no. if majority don't accept

- Problem?
  - Once a value is accepted by majority, we don't want another value accepted by a majority

Paxos: Three Phases

- Prepare Phase:
  - Proposer gets commitment from majority of acceptors
- Accept Phase:
  - Proposer sends proposed value to all acceptors
  - Waits to get proposal accepted by majority
- Learn Phase:
  - Learners discover value accepted by majority

Paxos in Action



Paxos Phase 3

- Goal: For all learners to discover if any value was accepted by majority

- Potential approaches:
  - Proposer who has proposal accepted by majority of acceptors informs all learners
  - Acceptor broadcasts to all learners whenever it accepts any value
  - Acceptors notify distinguished learner, which informs others

Paxos Phase 3

- Learners mimic proposers
- Discover value accepted by each acceptor in response to prepare messages

Paxos: Sample Execution

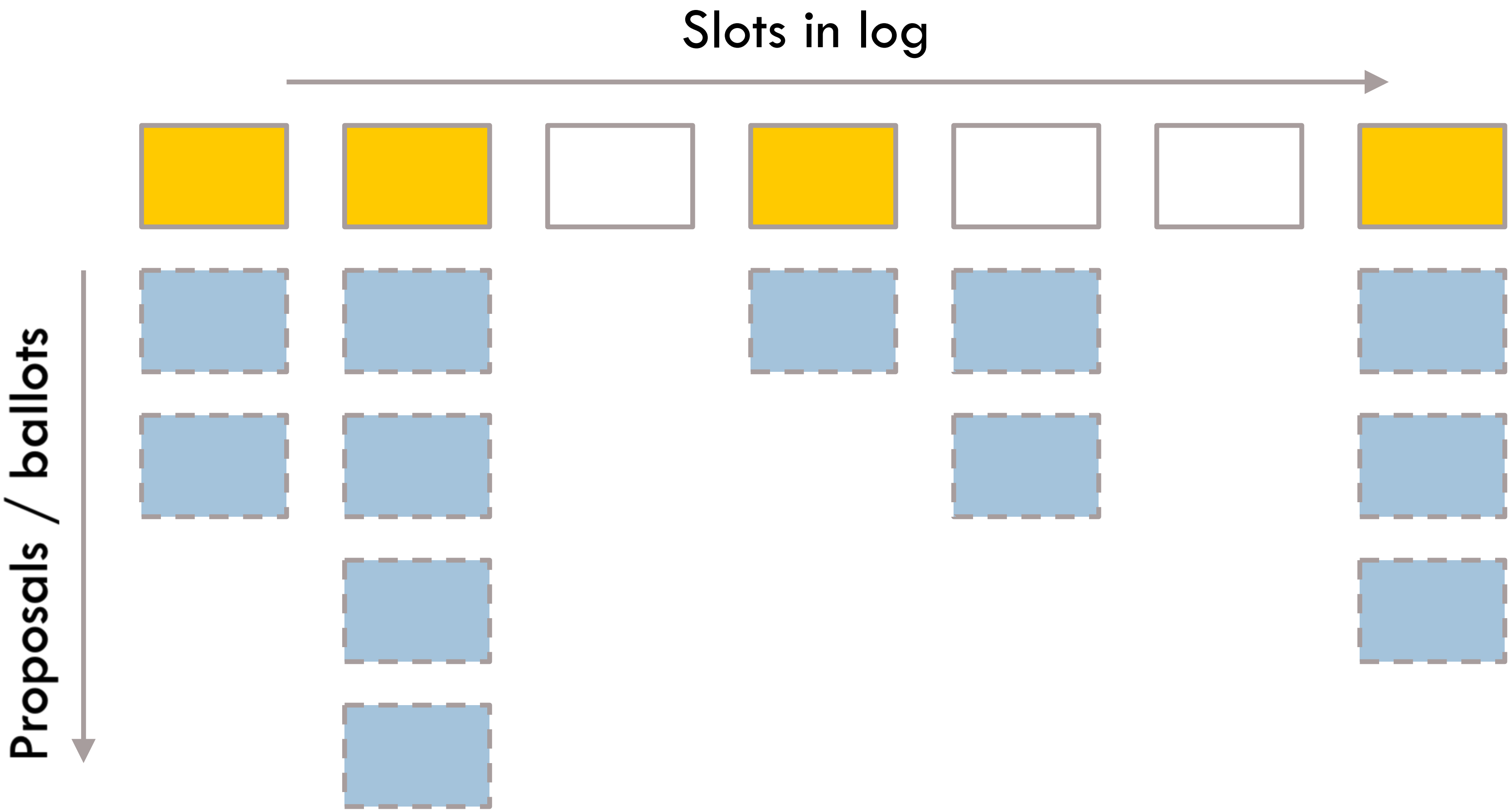
- Acceptor1: P1 A1-X P2
- Acceptor2: P1 A1-X P2 P3
- Acceptor3: P1 A1-X P3

RSM with Paxos

- Log of updates at every replica
  - Replicas execute updates in order in log

- Use Paxos to come to consensus about each slot of the log

RSM with Paxos



RSM with Paxos

- Example: updates from MapReduce workers submitted to replicated Master

- Whenever an update is submitted:
  - Attempt to get update accepted to a particular slot in replicated log
  - If unsuccessful, retry proposing to higher slot

- Challenge: Must guess slot at end of log

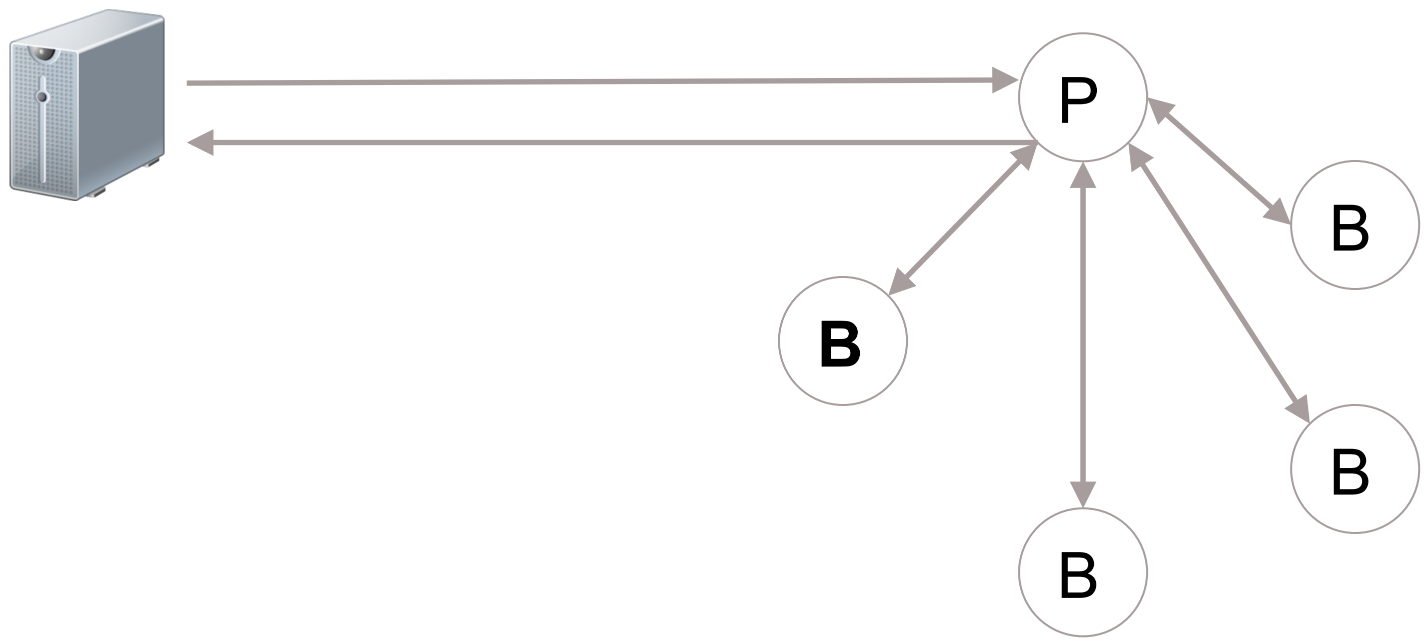
RSM with Paxos

- e1: an operation is accepted to i^{th} slot in log
- e2: i^{th} operation is executed at all replicas

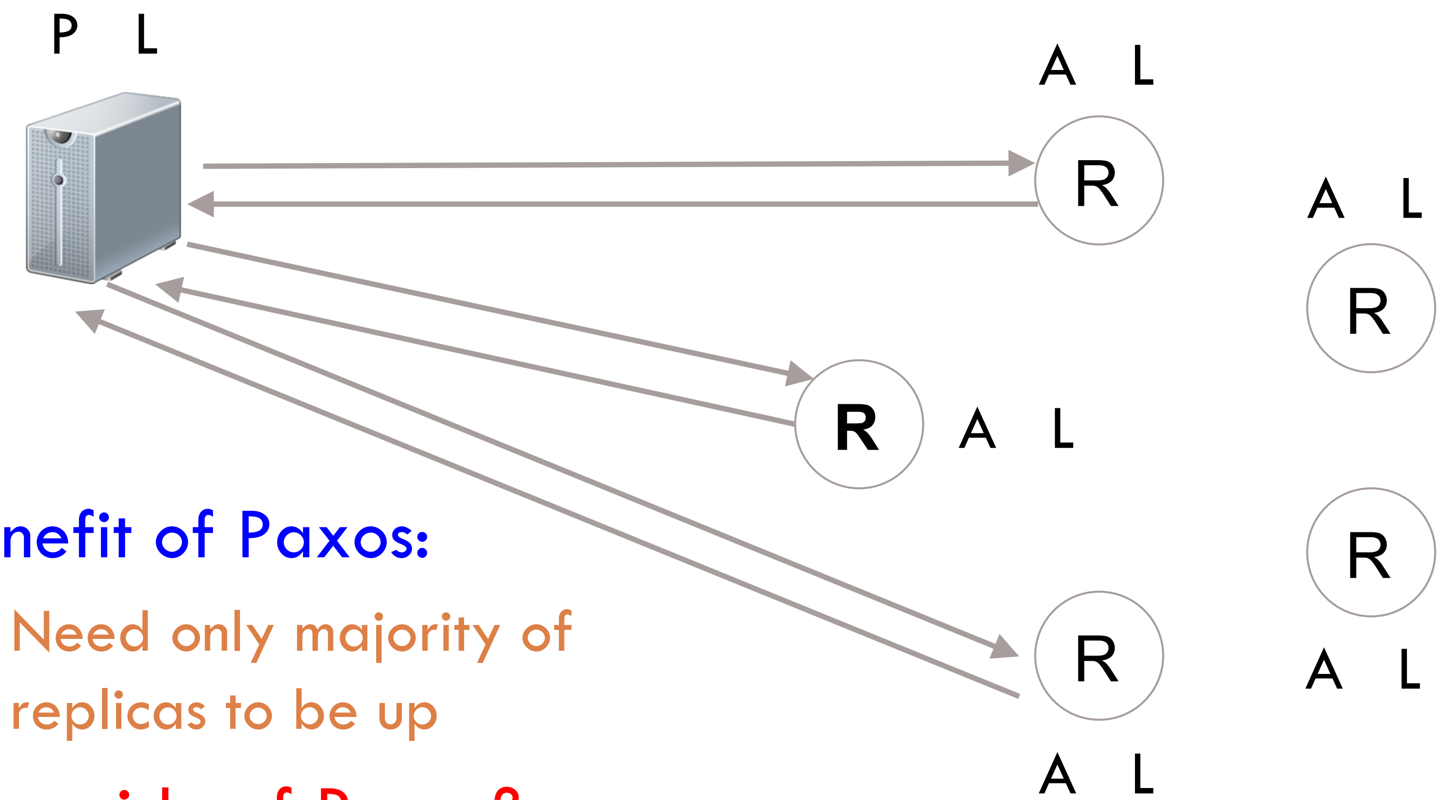
- Arbitrarily large delay between events e1 and e2

- Consequence: Local state at any replica differs from state of replicated log

Comparing with P/B Replication

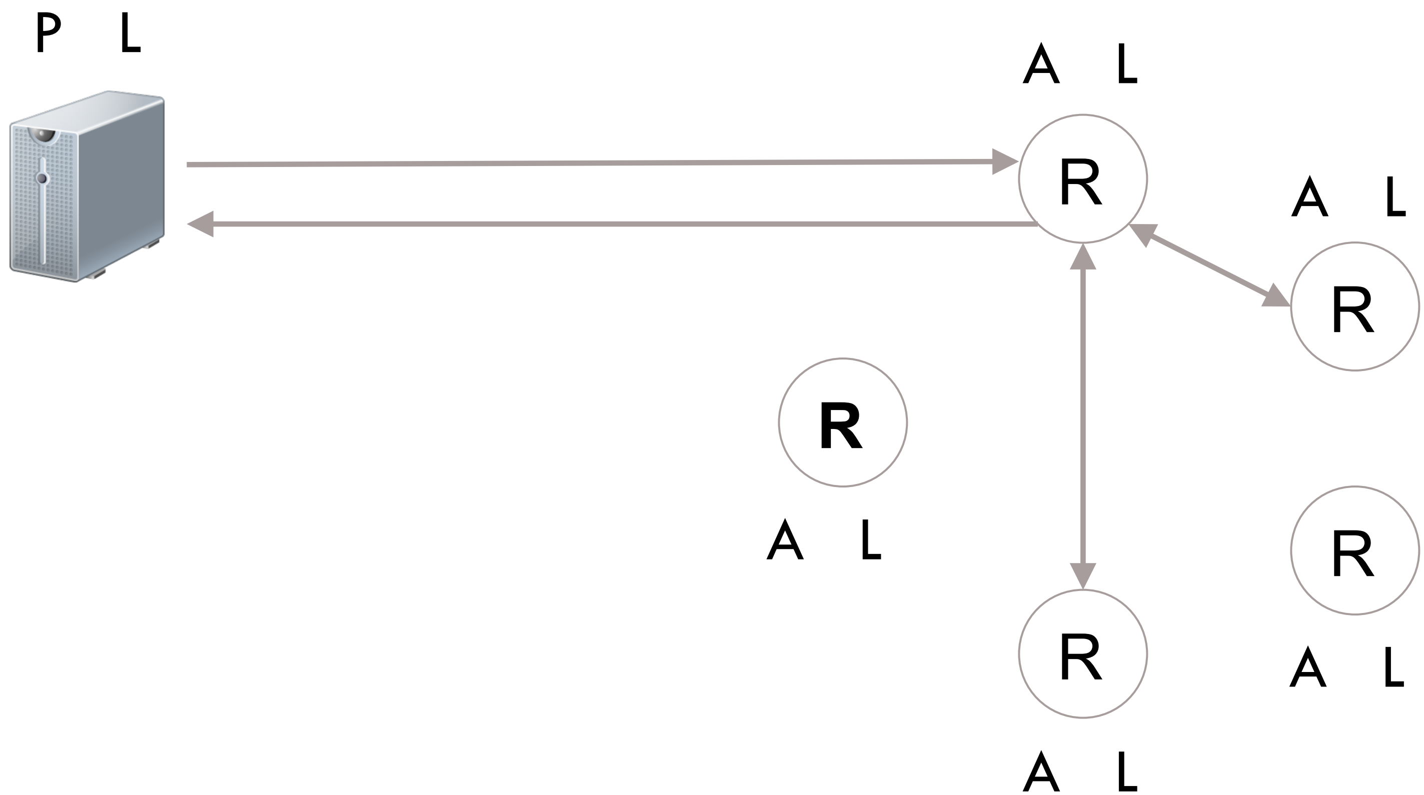


Comparing with P/B Replication



- Benefit of Paxos:
  - Need only majority of replicas to be up
- Downside of Paxos?
  - Need two rounds of inter-replica communication

Leader-based Paxos



Leader-based Paxos

- Pick one of the acceptors as the leader
- All clients submit proposals to leader
- Leader can directly skip to Accept phase because no contention
- Learn phase executed asynchronously

- How to pick a leader?
  - Paxos!
- Drawbacks compared to leaderless Paxos?
  - Leader may be far from client