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Lecture 13: Partial Synchrony and Paxos

CS 539 / ECE 526

Distributed Algorithms

What can we do about FLP?

- Consider easier problems
- Randomization
- Consider easier models (partial synchrony)

- Agreement, total order bcast, and replication possible in psync or async with randomization
  - Single-value broadcast still impossible

Partial Synchrony

- (Intuitively) The network is sometimes asynchronous and sometimes synchronous
  - Maintain safety during asynchronous periods
  - Achieve liveness during synchronous periods

Partial Synchrony

- (Formally) There exists an **unknown** Global Standardization Time (GST) after which the network becomes synchronous
  - Forever synchronous after GST???
    - Hope to capture “sufficiently long sync periods”
  - Unknown to whom?
    - Can be viewed as a game between protocol designer and the adversary

Psync Agreement Fault Bound

- Crash: $f < n/2$
  - Proof: Two groups $|P| \leq f$ and $|Q| \leq f$
  - Scenario I:
  - Scenario II:
  - Scenario III:

Psync Agreement Fault Bound

- Crash: $f < n/2$
  - Proof: Two groups $|P| \leq f$ and $|Q| \leq f$
  - Scenario I: P non-faulty & receive v, Q crash
    - P eventually commit v due to validity
  - Scenario II: Q non-faulty & receive v’, P crash
    - Q eventually commit v’ due to validity
  - Scenario III: Both non-faulty, P receive v, Q receive v’
    GST sufficiently large → Both think the other crashed
    - P commit v, Q commit v’

Paxos

- Lamport, submitted 1989, published 1998
- Partial synchronous
- Tolerate f < n/2 crash faults (best possible)
- First practical consensus protocol, likely the most widely known/used (before Bitcoin)

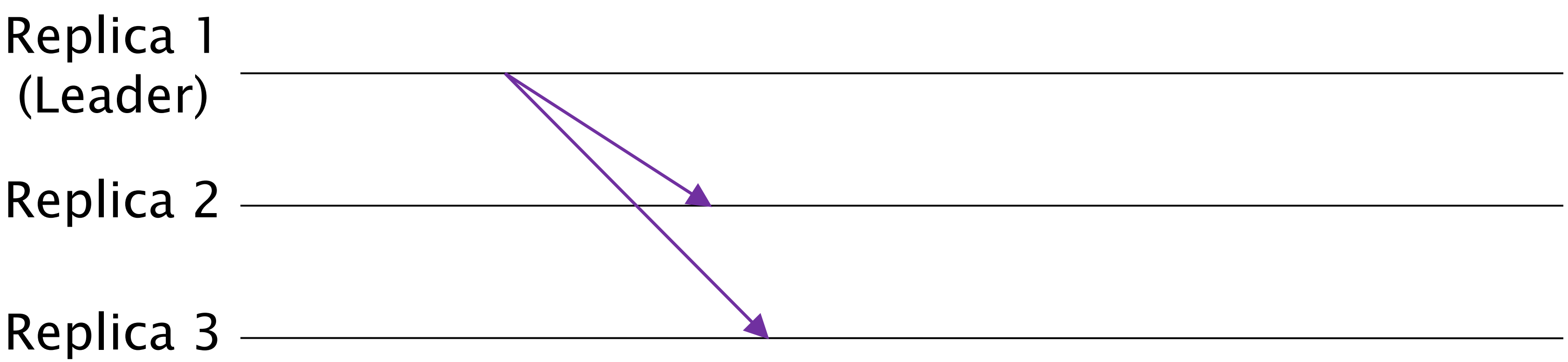
Paxos

- A (state machine) replication protocol
  - Agree on a sequence of values
    - We will again start with a single value
  - Values come from clients, validity is “external”

- Partial synchrony with alternating periods
  - Delay bound Δ holds during synchronous periods
  - Maintain safety during async, live during sync
    - We will use the unknown GST model

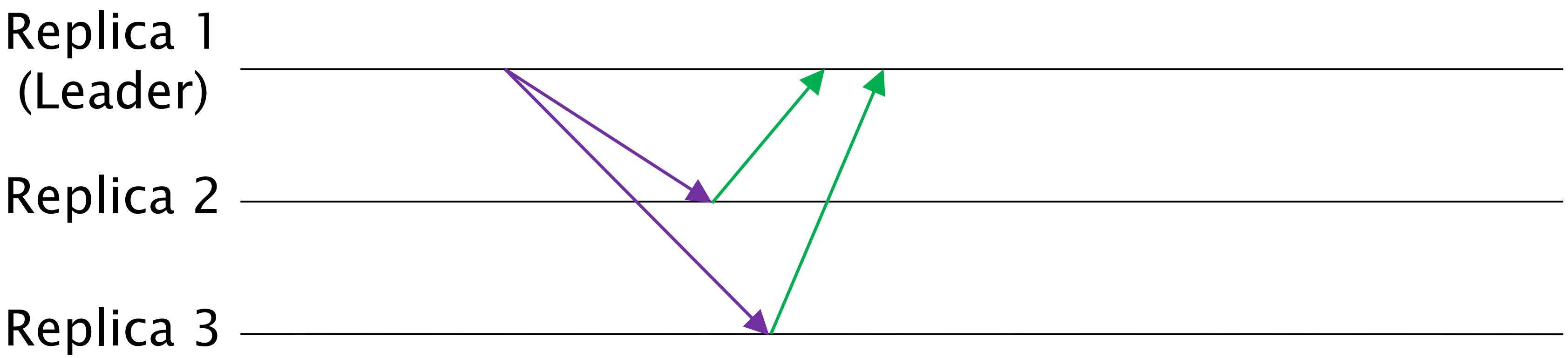
Paxos Protocol

- Leader sends (propose, x, k)
  - x is the proposed value
  - k is a rank/ballot/view/iteration number



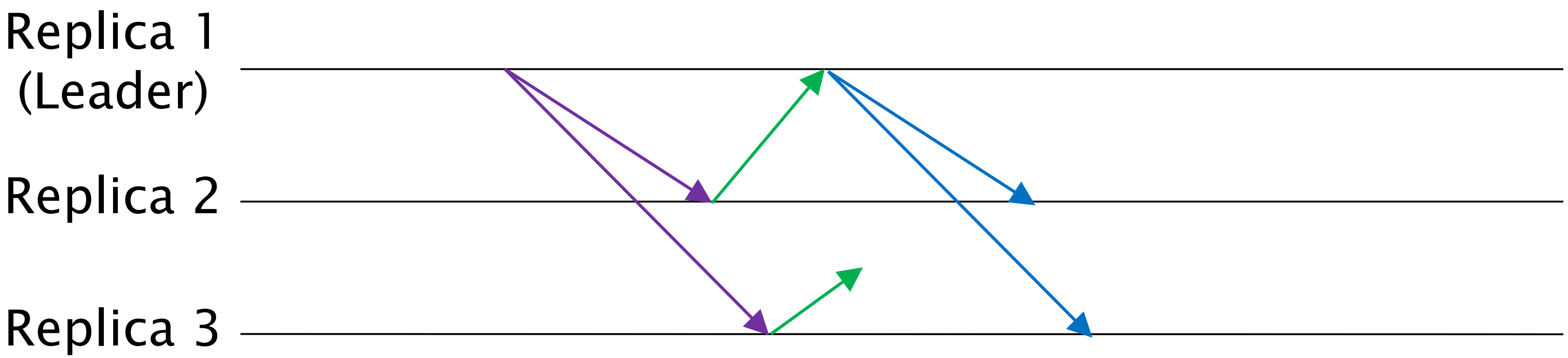
Paxos Protocol

- Leader sends (propose, x, k)
- Upon receiving the leader's proposal, others send (vote, x, k) back to the leader



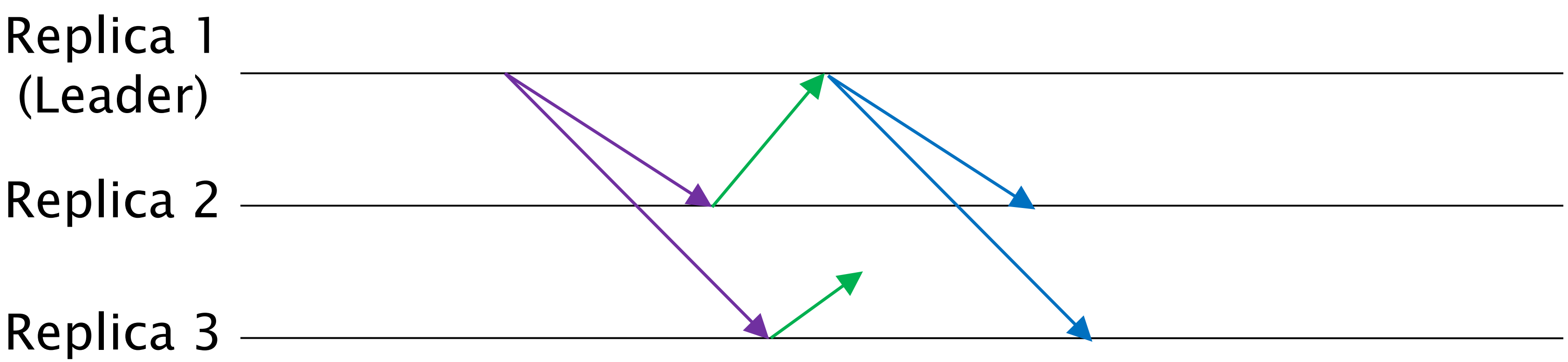
Paxos Protocol

- Leader (propose, x, k); Others (vote, x, k)
- Leader waits for n-f votes, sends (success, x, k)
- Upon receiving (success, x, k), others commit x



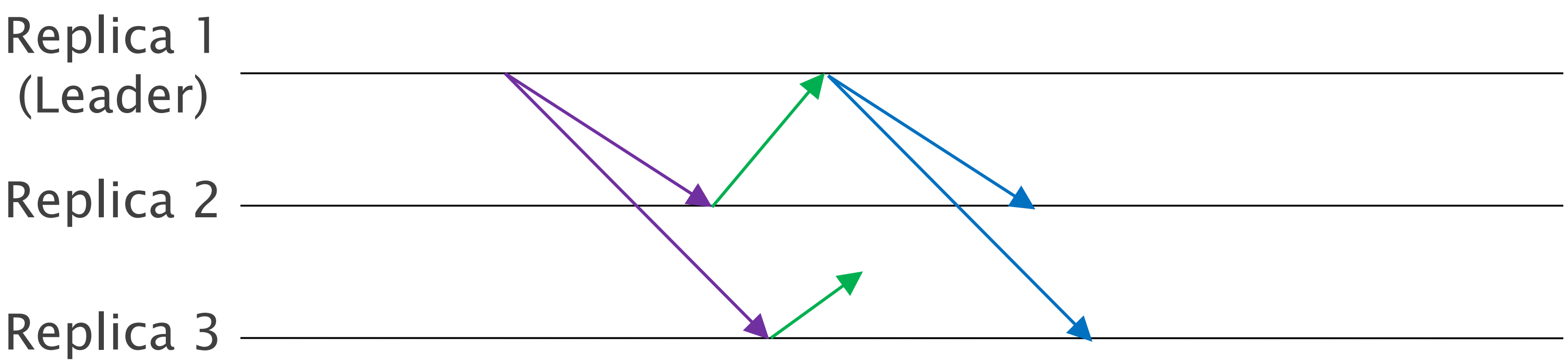
Paxos Protocol

- Leader (propose, x, k); Others (vote, x, k)
- Leader: (success, x, k); Others: commit x
- After a time-out, repeat under the next leader with k incremented



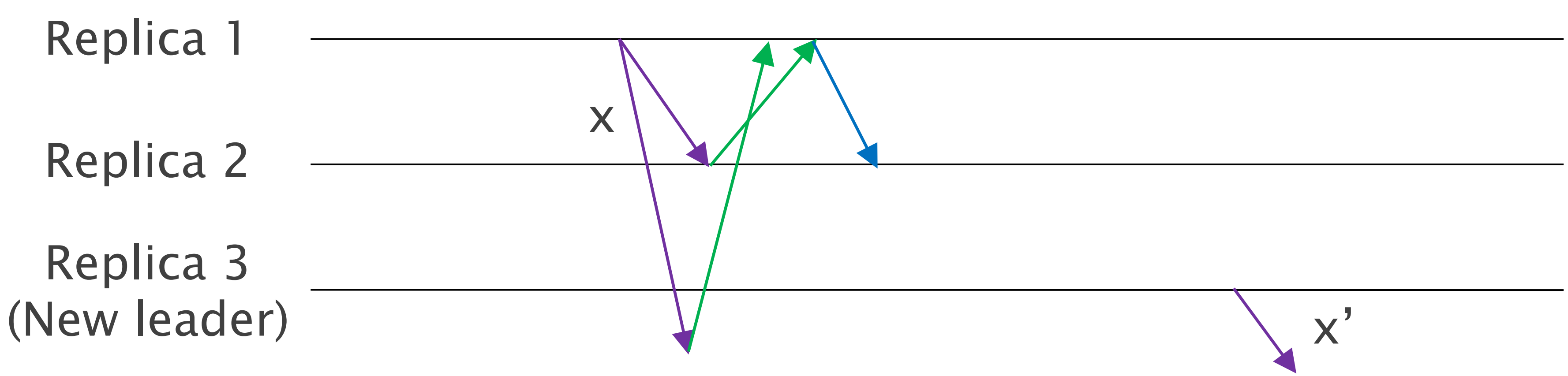
Paxos Liveness

- Rotating leaders tolerate faulty leaders
- Non-faulty leader after GST gives liveness



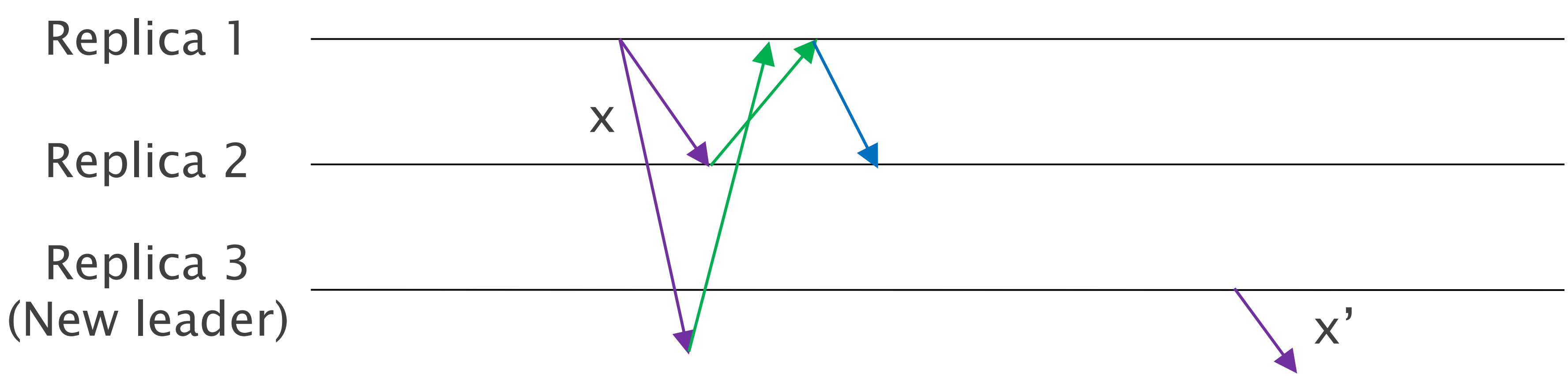
Paxos Safety

- Safety under one leader is obvious
  - Because leader is benign
- Safety across leaders is the challenge



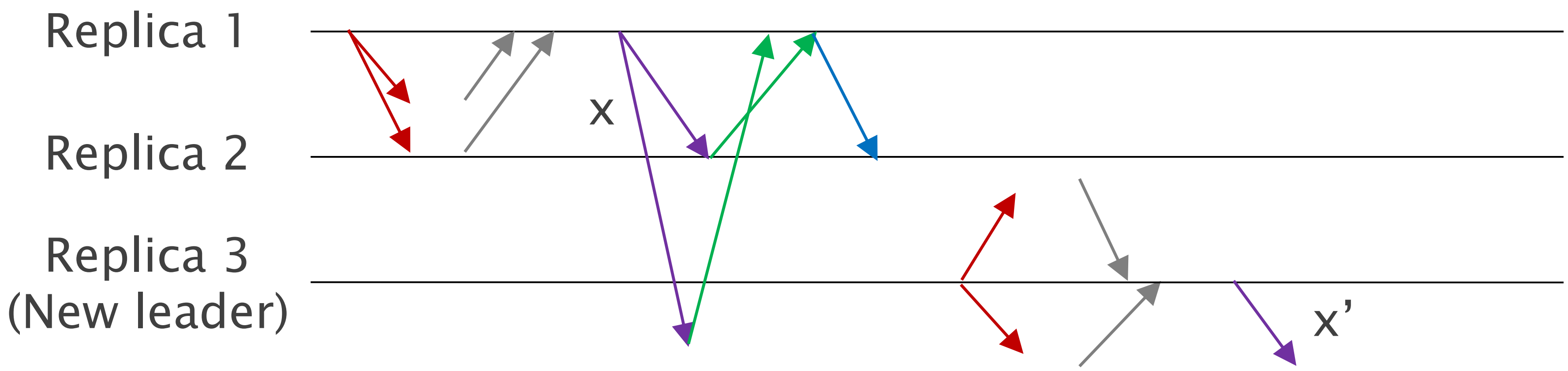
Safety Across Leaders

- New leader must find out what happened
- If one replica commits x, we want <u>many</u> replicas to "recommend" x to new leaders
  - Naturally, recommend the value one has voted



Paxos Protocol

- Leader (replica k % n) sends (new-view, k)
- Others reply with (status, k, x_{lck}, k_{lck})
- Leader (propose, x, k)
- Others (vote, x, k) **and lock (x, k)**
- Leader (success, x, k); Others commit x



Safety Across Views

- One replica commits x

→ n-f replicas voted and locked x

→ Each future leader collects locks from n-f replicas, at least one is locked on x

  → Due to quorum intersection

→ Each future leader re-proposes x

→ No other value can ever be proposed, voted or committed

Any issues in this proof?

Safety Across Views

- One replica commits x

→ n-f replicas voted and locked x

→ Each future leader collects locks from n-f replicas, at least one is locked on x

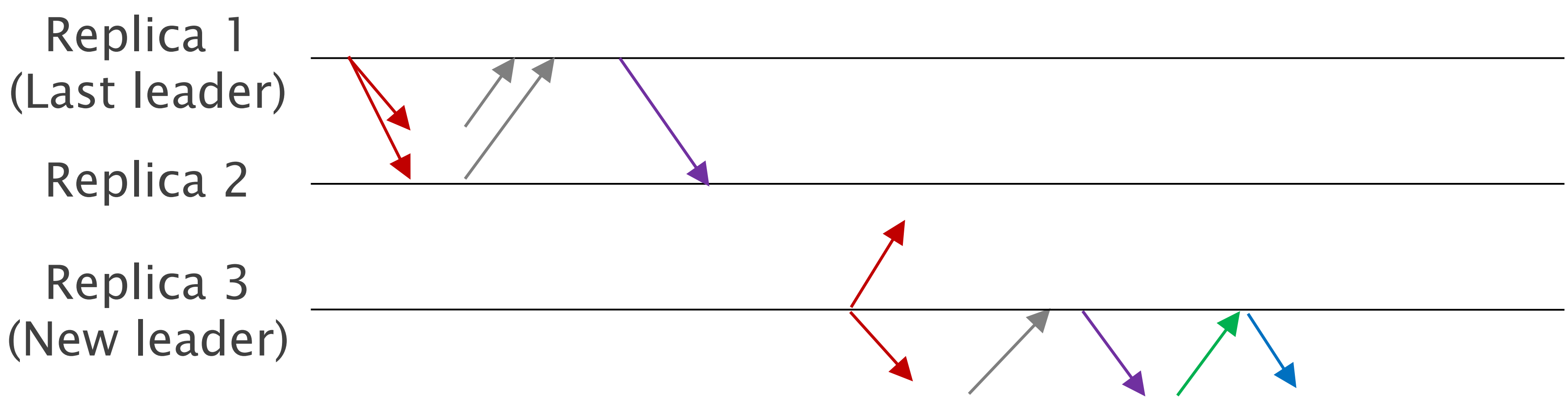
→ Due to quorum intersection

→ Each future leader re-proposes x

What if some other replica reports a different locked value?

Paxos Locks

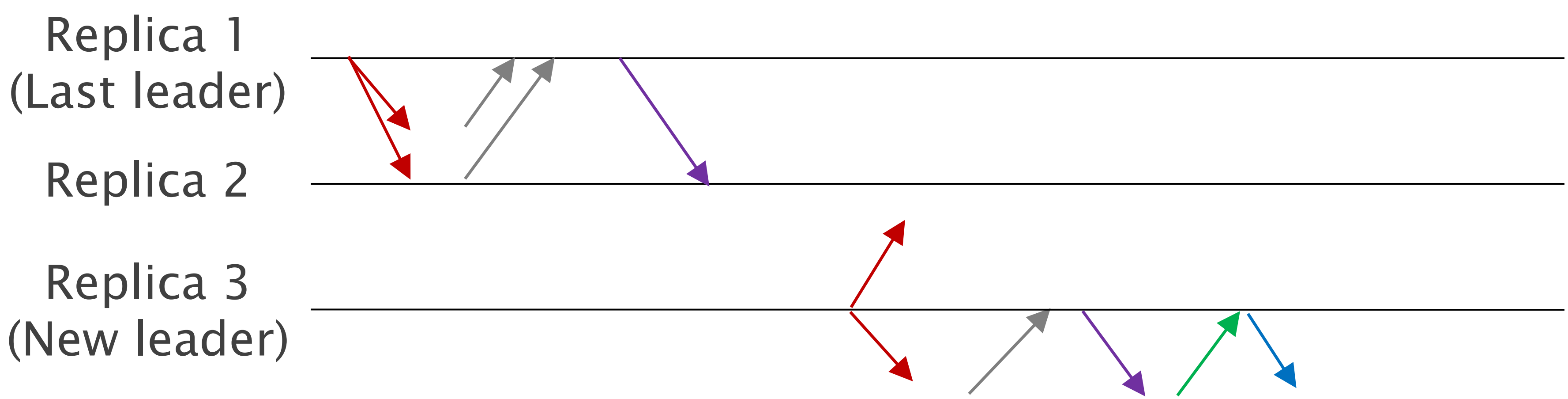
- Can replicas lock on different values?
  - and one of the value is committed?
- Need a tie-breaking mechanism on locks that favors the committed value (if any)



Paxos Protocol

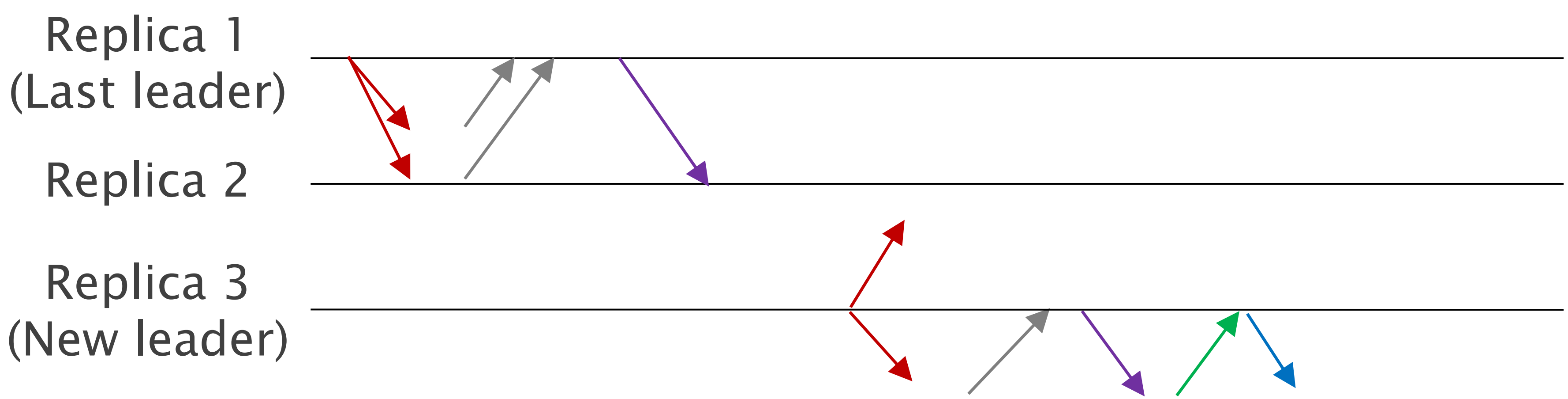
- Leader (replica k % n) sends (new-view, k)
- Others reply with (status, k, x_{lck}, k_{lck})
- Leader (propose, x, k)

- Others (vote, x, k) and lock (x, k)
- Leader (success, x, k); Others commit x



Paxos Protocol

- Leader (replica k % n) sends (new-view, k)
- Others reply with (status, k, x_{lck}, k_{lck})
- Leader (propose, x, k) where x is the **highest locked value** among the f+1 status
- Others (vote, x, k) and lock (x, k)
- Leader (success, x, k); Others commit x



Single-slot Paxos Full Protocol

- Upon detecting a lack of progress, replica (k % n) sends (new-view, k)
- Upon receiving (new-view, k), a replica enters view k and replies with (status, k, x_{lck}, k_{lck})
- Upon receiving n-f status, leader sends (propose, x, k) where x is the highest locked value. If none has locked, the leader can choose x freely.
- Upon receiving (propose, x, k), a replica sends (vote, k) and locks (x, k) if it has not entered a higher view
- Upon receiving n-f (vote, k), leader sends (success, x)
- Upon receiving (success, x), a replica commits x

Safety Across Views

- One replica commits x in view k

→ n-f replicas voted and locked (x, k)

→ Leader k+1 collects locks from n-f replicas, at least one (x, k), **which is the highest**

→ Leader k+1 re-proposes x. No other value can be voted or locked in view k+1

→ Leader k+2 collects locks from n-f replicas, at least one (x, k), **still the highest**

→ Leader k+2 re-proposes x. No other value can be voted or locked in view k+2

→ ……

Paxos Locks

- Tie-breaking favors lock from the latest view
- Why?

- Lock protects a potential commit
- Value x committed → no other higher lock ever in all subsequent views
- Hence, favoring a higher lock is always safe
  - Safe to "unlock" x if there is a higher lock on x'

Quiz

- What will go wrong if … ?
  - vote for leader k even after quitting view k
  - leader waits for only f status
  - leader does not repropose highest lock
  - the network is async
- When does Paxos become univalent?
- If n > 2f+1, can we wait for less than n-f msgs?

Multi-slot Paxos

- All messages are tagged with a slot number s (position in the ledger)
  - (propose/vote/success, s, x, k)

- Steady state vs. view-change
  - Repeat propose + vote + success for each slot in steady state
  - Upon lack of progress, do view-change using new-view + status

Multi-slot Paxos

- During view-change, exchange information on what slots have been committed
  - New leader sends (new-view, k, s*) where s* is its last committed slot (or any format to convey this)
  - For slots committed by the follower but not the leader, send success msg to the leader
  - For slots committed by the leader but not the follower, request success msg from the leader
  - For slots committed by neither but locked by the follower, send (status, k, x_{lck}, k_{lck}, s) for all such s
- Leader updates its ledger, send requested success msgs, re-propose for locked slots, and propose new values for “fresh” slots

Multi-slot Paxos Efficiency

- During steady state (non-faulty leader and synchrony), 3 rounds and 3n msgs per decision
  - Isn't there a f+1 round lower bound?
- View-change: 2 rounds and possibly many msgs

Paxos Summary

- Most widely known/used and first practical crash fault tolerant protocol
  - Replication, partial synchrony, $f < n/2$ crash
  - Leader-based, quorum intersection, lock ranking

- Original notation FYI:
  - new-view = prepare
  - status = promise
  - propose = accept
  - vote = accepted