Lecture 14: Practical Byzantine Fault Tolerance (PBFT)

CS 539 / ECE 526

Distributed Algorithms

Paxos Summary

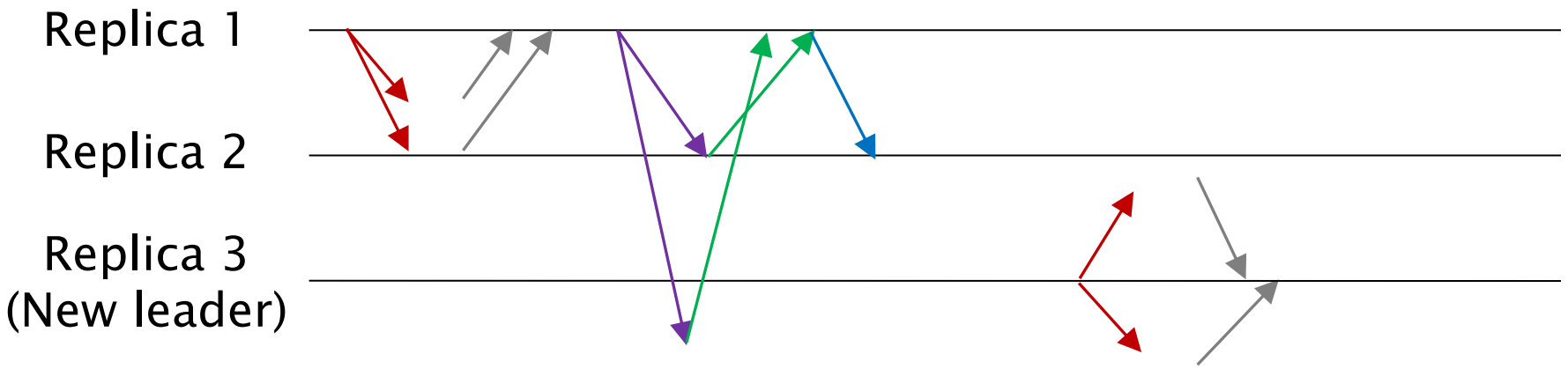
- Most widely known/used and first practical crash fault tolerant protocol
  - Replication, psync, f < n/2 crash
  - Leader-based, quorum intersection, lock ranking

PBFT

- Most widely known/used and first practical **Byzantine** fault tolerant protocol
  - Replication, psync, **f < n/3 Byzantine**
  - Leader-based, quorum intersection, lock ranking
  - Independently developed from Paxos by Castro and Liskov in 1999, but share many key concepts
- We will modify Paxos into PBFT
  - What obviously go wrong with Byzantine faults?

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



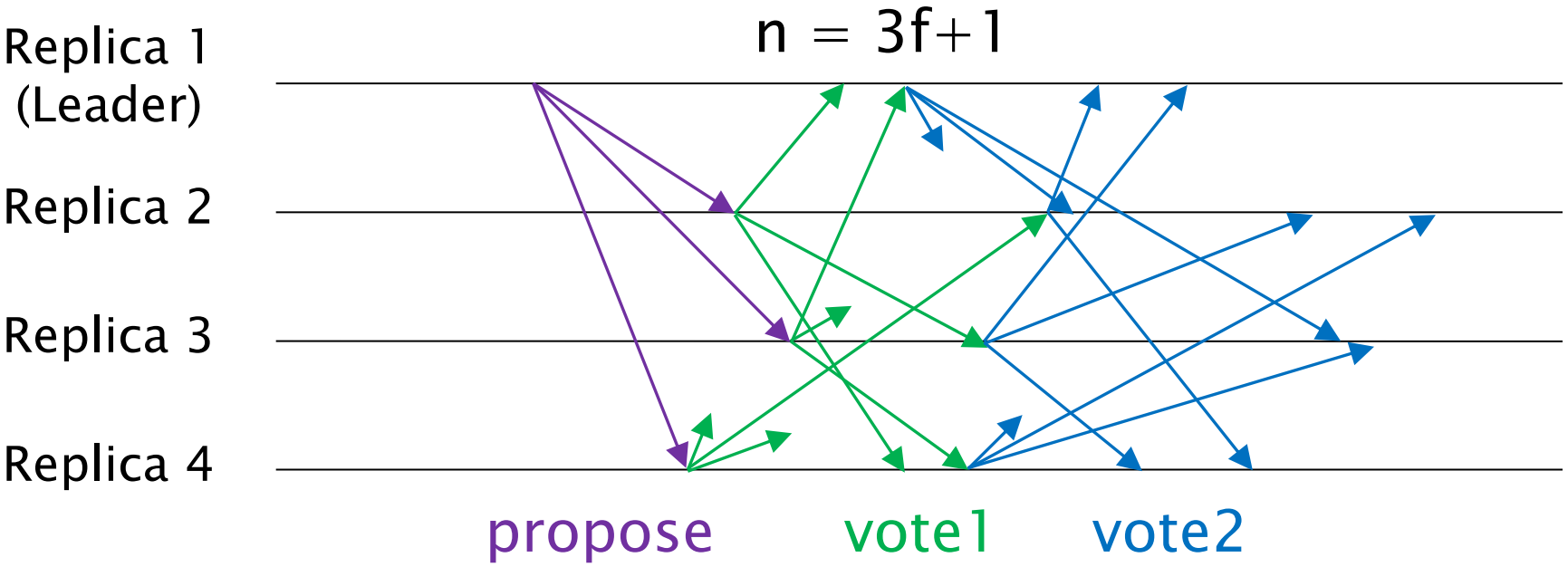
Challenges for Byzantine Paxos

- Leader may equivocate (e.g., double-propose)

- Byzantine nodes can make false "claims"
  - "Previous leader is not making progress."
  - "I am locked on value x with rank k."
  - "x is the highest locked value I have seen."

PBFT Steady State

- Leader (proposes, x, k), replicas (vote1, x, k)
- Upon n-f (vote1, x, k), lock (x, k) and send (vote2, x, k)
- Upon n-f (vote2, x, k), commit x



PBFT Steady State

- Two rounds of all-to-all voting
- When a replica locks, it has a *certificate*, i.e., 2f+1 signed (vote1, x, k) from distinct replicas

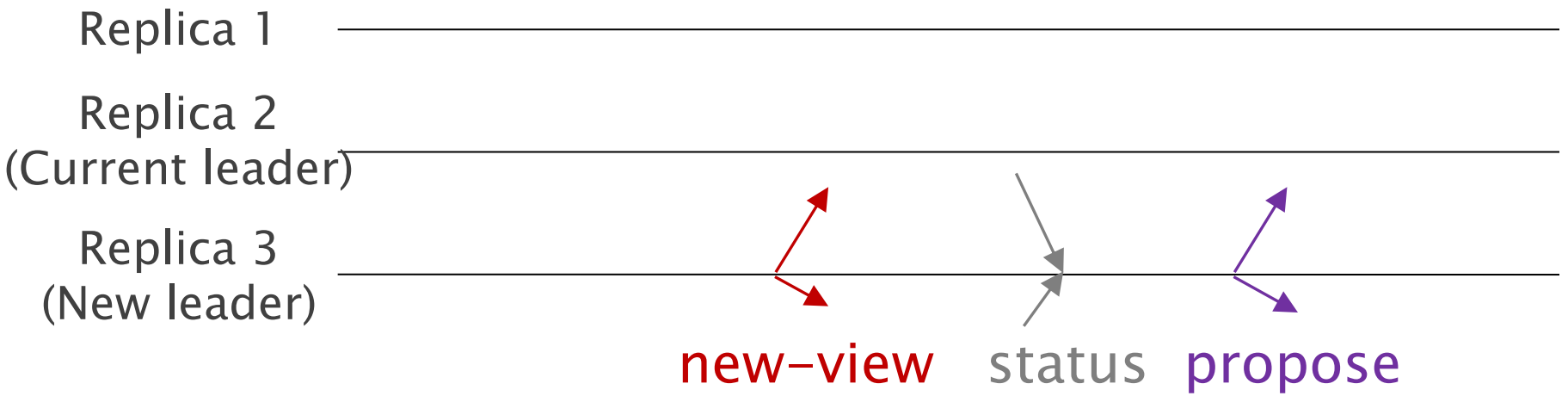
- Can still use all-leader-all voting
  - But no longer strictly better than all-to-all
  - Leader must forward certs, so fewer (linear) but longer (linear) msgs, still $O(n^2)$ bits in total
    - … unless using threshold sig, down to linear bits
    - All-to-all voting does not need sigs in steady state (important at the time, but less important today)

PBFT Safety and Liveness

- Safety within view: quorum intersection
  - Two quorums of 2f+1 intersect at f+1 → there cannot be two proposals both certified
- Safety across views: hard part (later)
- Liveness: honest leader during synchrony

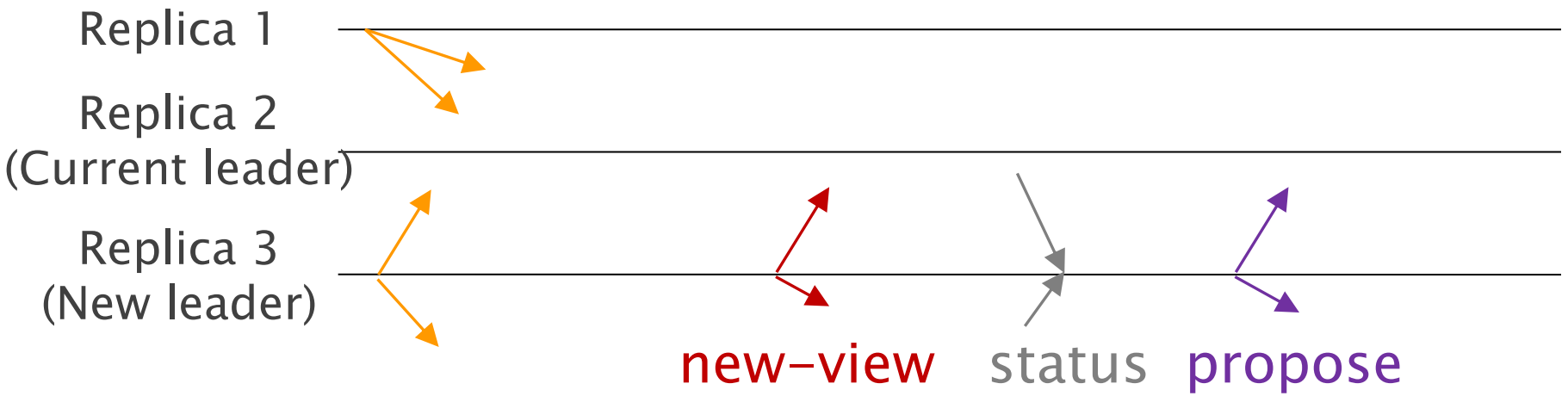
PBFT View Change

- Every "claim" needs to be "backed up" by signed msgs from sufficiently many replicas
  - New leader cannot step up at will
  - Replica reported locks need certificates
  - Leader's claimed highest lock needs proof



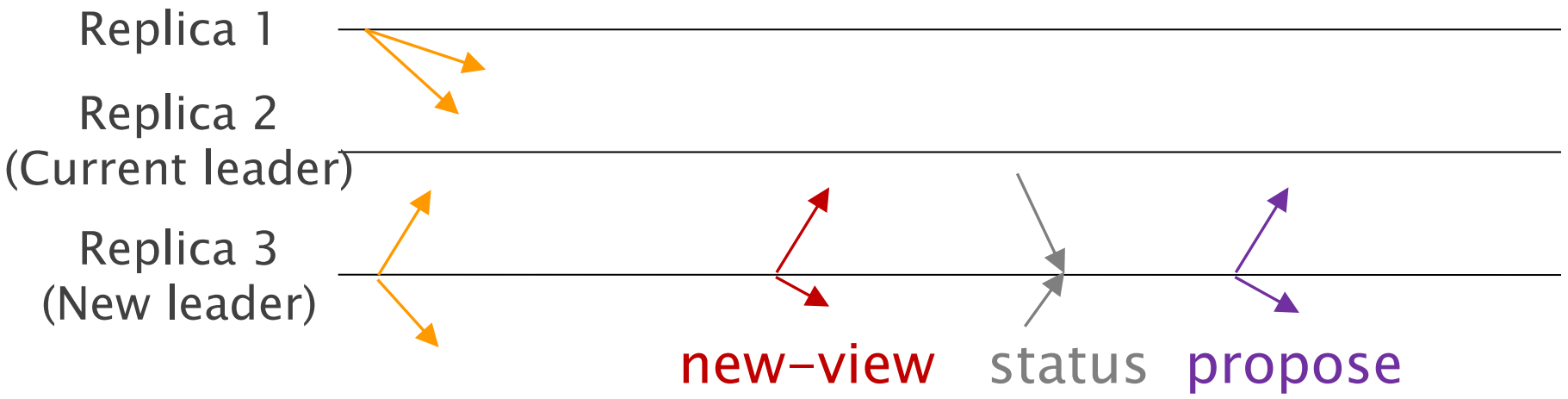
PBFT View Change

- If suspecting leader k-1, send (blame, k-1) to all
- New leader sends (new-view, k, {(blames, k-1)})
- Replicas send (status, k, x_{lck}, k_{lck}, {(vote1, x_{lck}, k_{lck})}) to leader k
- Leader sends (propose, x, k, {(status, k, …, {vote1, …})}) where (x, k) is the **highest locked value** among 2f+1 status msgs



PBFT View Change

- Blame and status can be sent together
- new-view and propose can then also be merged
- But it may aid understanding to treat them separately



Safety Across Views

- One replica commits x in view k

→ 2f+1 replicas voted and locked (x, k)

→ f+1 of them are honest

→ Leader k+1 presents 2f+1 status (locks), must include one (x, k), which is highest

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

→ Leader k+2 presents (status) locks, at least one (x, k), still highest, re-proposes x

→ ……

PBFT Efficiency

- Steady state: 3 rounds, $O(n^2)$ communication
- View change: 2 (4) rounds
- View change communication?
  - n-to-n blames of size O(1)
  - 1-to-n new-view of size O(n)
  - n-to-1 status of size O(n) (since they contain certs)
  - 1-to-n propose of size $O(n^2)$ (contains n status)

  - Total: $O(n^2)$ msgs and $O(n^3)$ bits

PBFT Original Notation

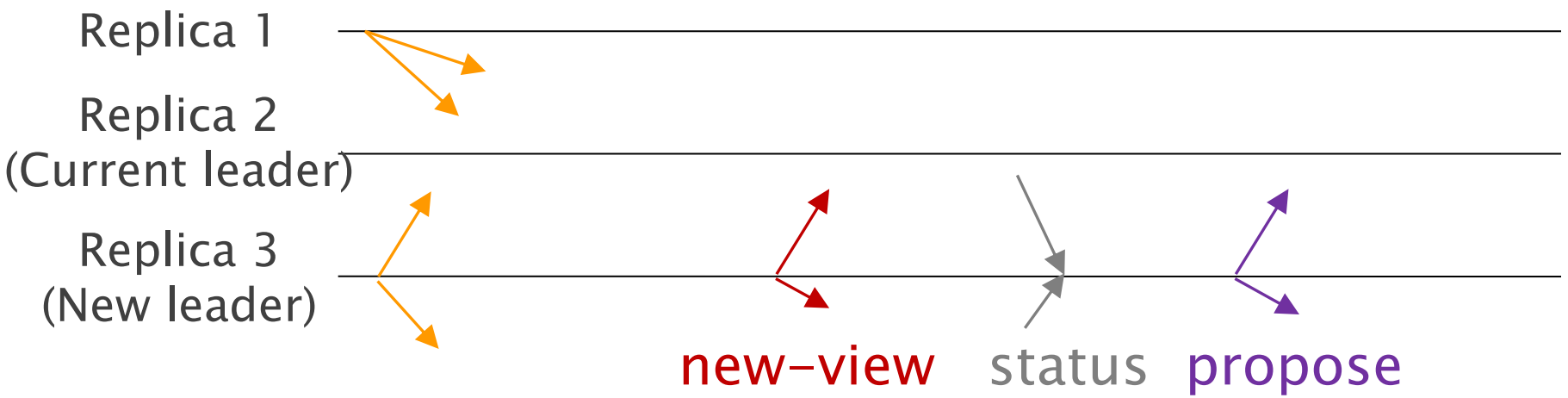
- Original notation FYI:
  - blame + status = view-change
  - new-view + propose = preprepare
  - vote1 = prepare
  - vote2 = commit

PBFT Summary

- Most widely known/used and first practical Byzantine fault tolerant protocol
  - Replication, psync, $f < n/3$ Byzantine
  - Leader-based, quorum intersection, lock ranking
  - $O(n^2)$ steady state, $O(n^3)$ view change
- We skipped many subtle details (e.g., multi-slot is quite tricky)
- Many improvements, active research area
  - Most significant: Linear View Change [Kwon, 2014]

Linear View Change (LVC)

- If suspecting leader k-1, send (blame, k-1) to all
- New leader sends (new-view, k, {(blames, k-1)})
- Others send leader (status, k, x_{lck}, k_{lck}, {(vote1,x_{lck},k_{lck})})
- Leader sends (propose, x, k, {(vote1, x_{lck}, k_{lck})}) where (x, k) is the **highest locked value** among 2f+1 status
  - Leader is not using 2f+1 signed status to back up its proposal
  - Why is this safe?



Linear View Change (LVC)

- If suspecting leader k-1, send (blame, k-1) to all
- New leader sends (new-view, k, {(blames, k-1)})
- Others send leader (status, k, x_{lck}, k_{lck}, {(vote1,x_{lck},k_{lck})})
- Leader sends (propose, x, k, {(vote1, x_{lck}, k_{lck})}) where (x, k) is the **highest locked value** among 2f+1 status
  - Leader is not using 2f+1 signed status to back up its proposal
  - Why is this safe? Safe if others do not blindly believe the leader
- A replica refuses to vote if it has a higher lock than the certificate in the leader's propose msg!

Safety Across Views with LVC

- One replica commits x in view k

→ 2f+1 replicas voted and locked (x, k)

→ f+1 of them are honest

→ If leader k+1 proposes x' ≠ x, it cannot show a certificate as high as (x, k)

→ At most 2f votes for x' in view k+1, not a cert

→ If leader k+2 proposes x'' ≠ x, it cannot show a certificate as high as (x, k)

→ ……

LVC Efficiency

- View change: 2 (4) rounds
- View change communication?
  - n-to-n blames of size O(1)
  - 1-to-n new-view of size O(n)
  - n-to-1 status of size O(n) (contain cert)
  - 1-to-n propose of size O(n) (contains cert)
  - Total view change communication in bits: $O(n^2)$
- Why is it called **Linear** View Change then?
  - With threshold signatures, cert is O(1)
  - With static view-change schedule (e.g., every epoch), can skip blame and new-view in some cases

PBFT Summary

- Most widely known/used and first practical **Byzantine** fault tolerant protocol
  - Replication, psync, $f < n/3$ Byzantine
  - Leader-based, quorum intersection, lock ranking
- Steady state: 3 rounds, $O(n^2)$ communication
  - 5 rounds, O(n) communication with all-leader-all voting and threshold signature
- View change: 2 rounds, $O(n^3)$ communication
  - $O(n^2)$ communication with Tendermint view change
  - O(n) communication further adding threshold sig and static view-change schedule