CS 582: Distributed Systems

Multi-Paxos and Byzantine Fault Tolerance

Dr. Zafar Ayyub Qazi

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Acknowledgments: Slides use some material from John Ousterhout (Stanford University) and Barbara Liskov (MIT)

Agenda

- Wrap-up discussion of Multi-Paxos
- Byzantine Fault Tolerance

Specific learning outcomes

By the end of today's lecture, you should be able to:

- ❑ Explain how configuration changes are implemented in Multi-Paxos
- ❑ Analyze the safety properties of Multi-Paxos
- ❑ Evaluate the performance characteristics and trade-offs of Multi-Paxos
- ❑ Define Byzantine faults and identify scenarios where Byzantine fault tolerance is critical
- ❑ Examine the behavior of Paxos and Raft under Byzantine faults
- ❑ Describe the core components and workflow of the PBFT algorithm
- ❑ Assess the effectiveness of PBFT in maintaining consensus under Byzantine conditions

It’s OK if you did not completely understand Multi-Paxos in the class

Multi-Paxos is complex

There is lot going on

Recap: Paxos Summary

- Basic Paxos:
  - Prepare phase
  - Accept phase
- Multi-Paxos:
  - Choosing log entries
  - Leader election
  - Eliminating most Prepare requests
  - Full information propagation
- Client protocol
- Configuration changes

Example on the board

Recap: Multi-Paxos Key ideas

- Choosing log entries
  - Run Basic Paxos on firstUnchosenIndex
- Pick a leader [to improve efficiency]
  - Pick a leader so only one server acts as a proposer
- Eliminating Prepares [to also improve efficiency]
  - Make proposal numbers refer to entire log, not just one entry
  - Also, return noMoreAccepted; no proposals accepted for any log entry beyond current one
  - Once a leader receives noMoreAccepted from majority of acceptors, no need for Prepare RPCs.

Recap: Multi-Paxos Key ideas

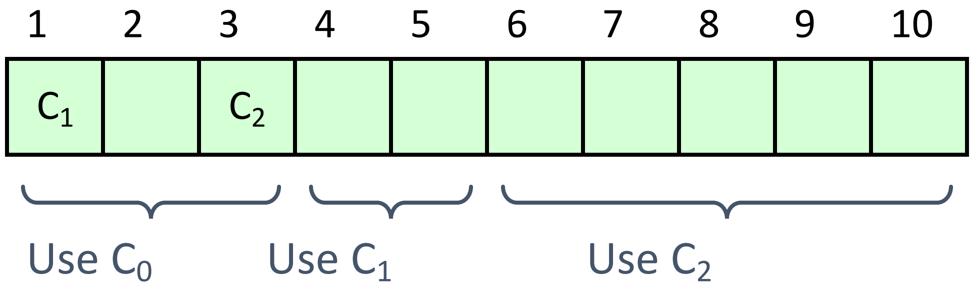
- Full Replication
  - Retry Accepts in background
  - Track chosen entries
    - **Mark entries** that are known to be chosen:
      - acceptedProposal[i] = ∞
    - Each server maintains **firstUnchosenIndex**
  - Proposer tells acceptors about chosen entries
  - Acceptor returns its firstUnchosenIndex in Accept replies
    - If proposer's firstUnchosenIndex > firstUnchosenIndex from response, then proposer sends Success RPC (in background)

Recap: Multi-Paxos Key ideas

- Success(index, v): notifies acceptor of chosen entry:
  - acceptedValue[index] = v
  - acceptedProposal[index] = ∞
  - return its new firstUnchosenIndex
  - Proposer sends additional Success RPCs, if needed

Recap: Configuration Changes

- Paxos solution: use the log to manage configuration changes:
  - Configuration is stored as a log entry
  - Replicated just like any other log entry
  - Configuration for choosing entry i determined by entry i-**α**.
    Suppose **α** = 3:



- Notes:
  - **α** limits concurrency: can't choose entry i+**α** until entry i chosen
  - Issue no-op commands if needed to complete change quickly

Discussion: Multi-Paxos Analysis

- Safety?

- Performance?

So far, we have assumed fail-stop failures when dealing with consensus

Consensus with Fail-stop failures

- Failure-Stop failures: Nodes fail by crashing
  - A machine is either working correctly or it is doing nothing
- Paxos/Raft can ensure safety and solve the state machine replication problem as long as at least a majority of nodes are up
  - With $N = 2f + 1$ replicas can tolerate upto f simulatenous fail-stop failures
  - Ensure replicas execute operations in the same order
- Remember FLP proof still applies: can't sure both safety and liveness in an asynchronous system
  - Raft/Paxos provide liveness when at least a majority of nodes can communicate with reasonable timeliness

Byzantine Faults

- Nodes fail arbitrarily, and may
  - Perform incorrect computation
  - Send different and wrong messages
  - Not send message at all
  - Lie about the input value
  - Collude with other failed nodes
  - And more …

Why care about Byzantine faults?

- Can be caused by
  - Malicious attack → increasing
  - Software errors → commonplace
- Example applications
  - Aircraft flight control systems (e.g., Boeing)
  - Blockchain platforms (e.g., Zilliqa, Hyperledger)
  - Byzantine-tolerant Distributed File System

Mini-case study: Boeing 737 Max

- Launched at the end of 2017
  - Had more efficient engines than 737 aircrafts
  - Introduced a new software system for automatic maneuvering of the plane (called MCAS)

- Multiple crashes
  - Lion Air Flight 610 – Oct 2018
    - Killing all 189 people on board
  - Ethiopian Airlines Flight 302 – March 2019
    - Killing all 157 people on board

Mini-case study: Boeing 737 Max (cont'd)

"Shortly after Flight 610 left Jakarta on Oct. 29, the sensor began sending bad information to the jet's computer, triggering the automated feature and driving down the plane's nose, according to the investigators' report …"

Washington Post

Indonesian investigators said Oct. 29 that Boeing 737 Max's design, regulatory lapses and pilot training were at fault for last year's fatal Lion Air crash. (Reuters)

By Ainur Rohmah, Ian Duncan, Michael Laris and Shibani Mahtani

October 25, 2019

JAKARTA, Indonesia — Design flaws in an automated feature on Boeing's 737 Max, attached to a sensor that had likely been poorly repaired, plus regulatory lapses and false assumptions about pilots' responses to new systems, combined to cause last year's fatal Lion Air crash, Indonesian investigators said Friday.

Shortly after Flight 610 left Jakarta on Oct. 29, the sensor began sending bad information to the jet's computer, triggering the automated feature and driving down the plane's nose, according to the investigators' report. The pilots — who knew nothing about the feature, which was new to the Max — struggled to respond, grappling with controls that felt as though they weighed 100 pounds.

Byzantine Fault Tolerance

⬇

Design services that continue to function <u>correctly</u> despite Byzantine faults

⬇

Solve the replicated state machine problem with Byzantine faults

⬇

Solving <u>consensus</u> with Byzantine faults

Can we reach consensus in the presence of Byzantine Faults with Paxos/Raft?

Can't use Paxos/Raft with Byzantine Faults

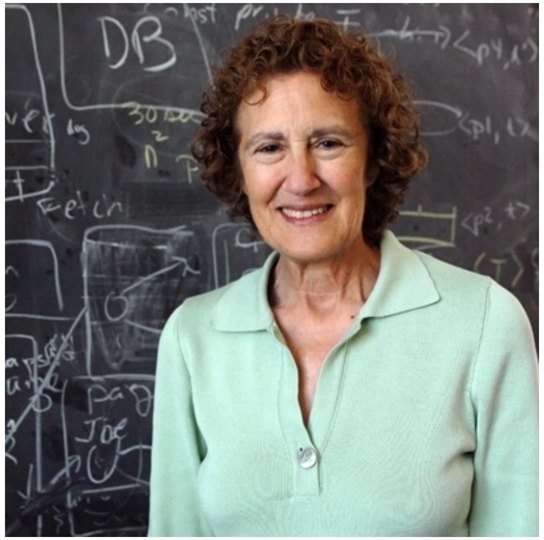
- The intersection of two majority (f + 1 node) quorums may be a byzantine node
- Byzantine node tells different quorums different things!
  - Leading to nodes committing different values
- Raft: Can't rely on the leader to assign log index
  - Could assign same log index to different requests

Bare majority quorums may not be enough in the presence of byzantine faults

A leader might be a byzantine node so we can't trust it

Byzantine Fault Tolerance

- Practical Byzantine Fault Tolerance (PBFT) Algorithm
  - [Liskov and Castro, 1999]



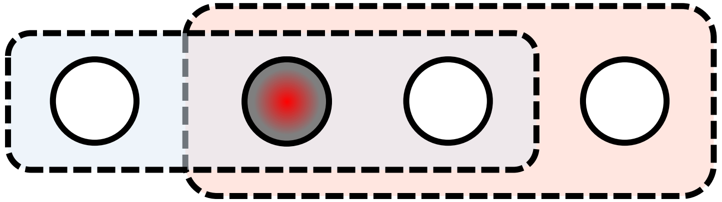
Barbara Liskov

PBFT: Impact

- Seminal work on byzantine fault tolerance
  - Byzantine fault tolerance was for long considered an exotic topic
- PBFT showed Byzantine fault tolerance is possible under certain assumptions
  - Has inspired a large body of work in the last two decades
- Used by multiple blockchains like Zilliqa, Hyperledger fabric, etc.

PBFT Overview

- $3f + 1$ replicas to survive f byzantine failures
  - Shown to be minimal
- Quorum of $2f + 1$ replicas



- Three phases (instead of two)
- Primary-backup protocol
  - Since primary can be byzantine node, replicas observe, can trigger change
  - Change through the idea of views; primary = view mod |R|
- Clients: need $f + 1$ matching responses from different replicas

Key assumptions

- No more than f out of $3f + 1$ replicas can be faulty
    - The other $2f + 1$ replicas operate correctly – follow the PBFT protocol
- No client failure – clients can never do anything bad
- Worst case
    - A single attacker controlling f faulty replicas to break the system
- Note: faulty → could be experiencing byzantine faults

What are the attacker’s powers?

What are the attacker's powers?

- Supplies the code that faulty replicas run
- Knows the code the non-faulty replicas are running
- Knows the faulty replicas' crypto keys
- Can read network messages
- However, can't forge messages of non-faulty nodes
  - Messages are encrypted -- no guessing of crypto keys or breaking of cryptography

PBFT is a primary-backup protocol

- What can go wrong if we have a Byzantine primary?
  - It can send a wrong result to the client
  - Different updates to different replicas
  - Ignore a client request

- How do clients interact with the system?
  - If they just contact the primary, and the primary is byzantine, then the system is in trouble

Views

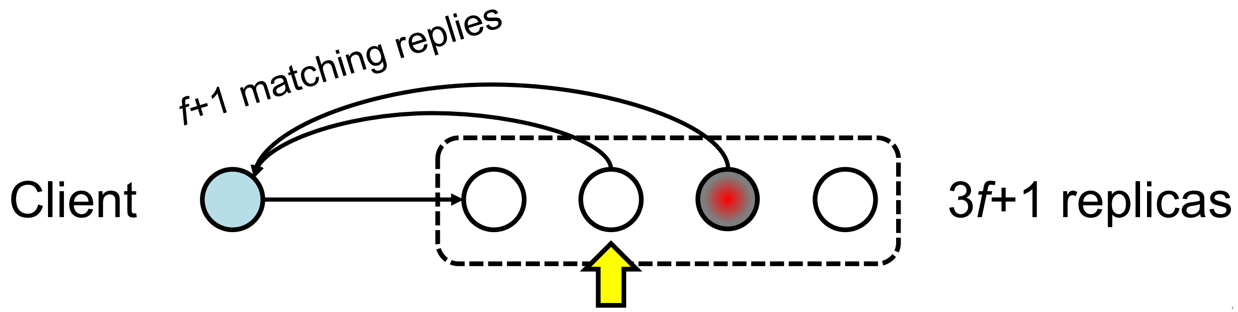
Views

- Identify each replica by an integer
  - For a set of R replicas *{0,…, |R-1|}*
- The replicas move through succession of configurations called views
- In a view, one replica is the primary and the rest are backups
- The primary of a view is a replica p such that *p = v mod |R|* where v is the view number

How Clients determine success?

How Clients determine success?

- Clients wait for $f+1$ identical replies from different replicas
- But ≥ one reply is from a non-faulty replica



What Clients exactly do?

- Send requests to the primary replica
  - The primary multicasts the request to the backups
  - Replicas execute the request and send a reply to the client
- If the client does not receive replies soon enough, it broadcasts the request to all replicas
  - If the request has already been processed, the replicas simply resend reply
    - Replicas remember the last reply message they sent to each client
  - Otherwise, if the replica is not the primary it relays the request to the primary
    - If the primary does not multicast the request to the group, it will eventually be suspected to be faulty by enough replicas to cause a view change

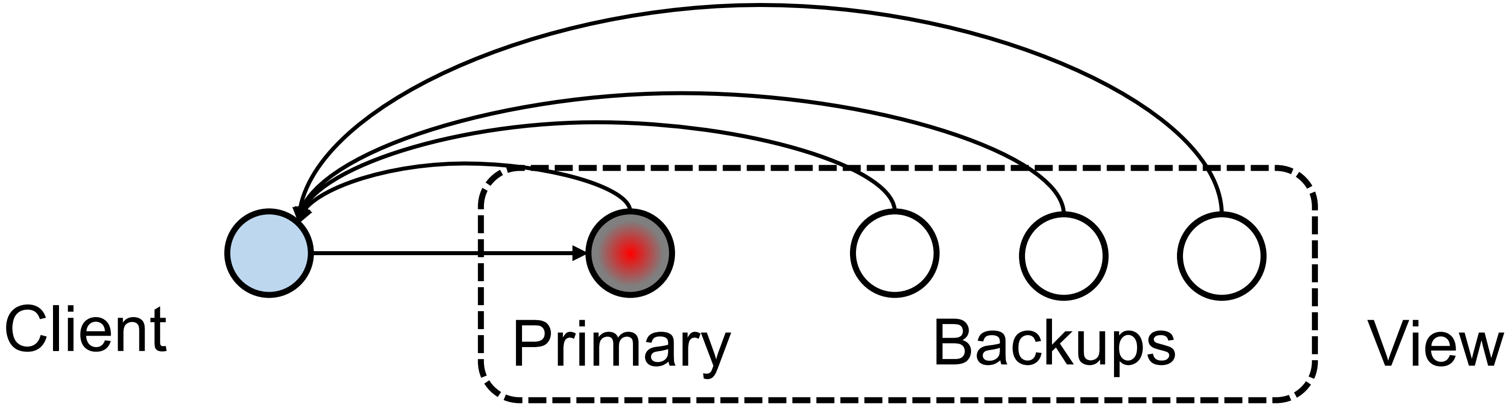
What Replicas do?

- Carry out a protocol that ensures that
  - Replies from honest (non-faulty) replicas are correct
  - Enough replicas process each request to ensure that
    - The non-faulty replicas process the same requests
    - In the same order
- Non-faulty replicas obey the protocol

Ordering Requests

Ordering Requests

- Primary picks the ordering of requests
  - But the primary might be a byzantine node

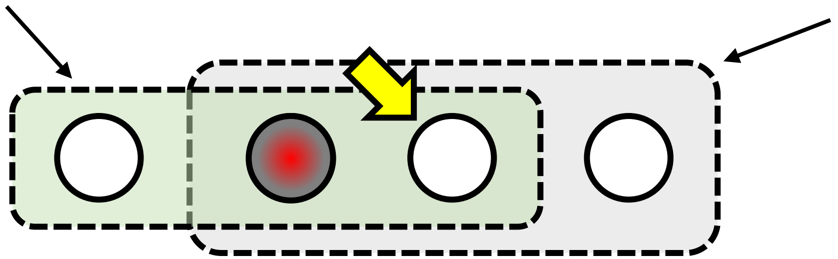


- Backups ensure primary behaves correctly
  - Check and certify ordering
  - Trigger view changes to replace faulty primary

Byzantine Quorums

Byzantine Quorums

- A Byzantine quorum contains ≥ 2f+1 replicas (given 3f+1 total nodes)



- One operation's quorum overlaps with the next operation's quorum
  - There are 3f+1 replicas, in total
    - So overlap is ≥ f+1 replicas
- f+1 replicas must contain ≥ 1 non-faulty replica

Message Authentication?

Message Authentication

- Public-key cryptography for signatures
- Each client and server has a private and public key
- All hosts know all public keys
- Signed messages are signed with private key
- Public key can verify that message came from host with the private key

How many phases of interactions?

Three Phases

- Pre-prepare: pick order of request and inform replicas
- Prepare: ensures order within views
- Commit: ensures order across views

Normal Operation (primary is not faulty)

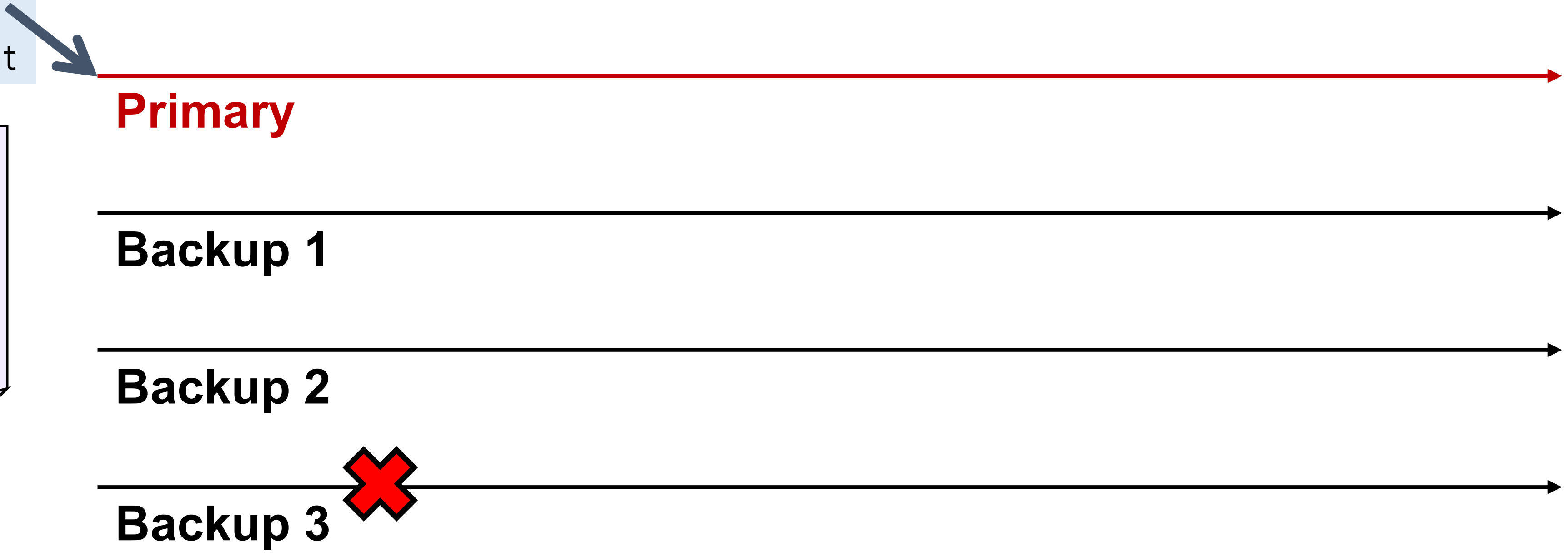
Normal Operation (primary is not faulty)

Normal Operation (primary is not faulty)

request: $m_{Signed,Client}$

Message contains *operation*, *timestamp*, client id

Assumption
A client sends operations one by one



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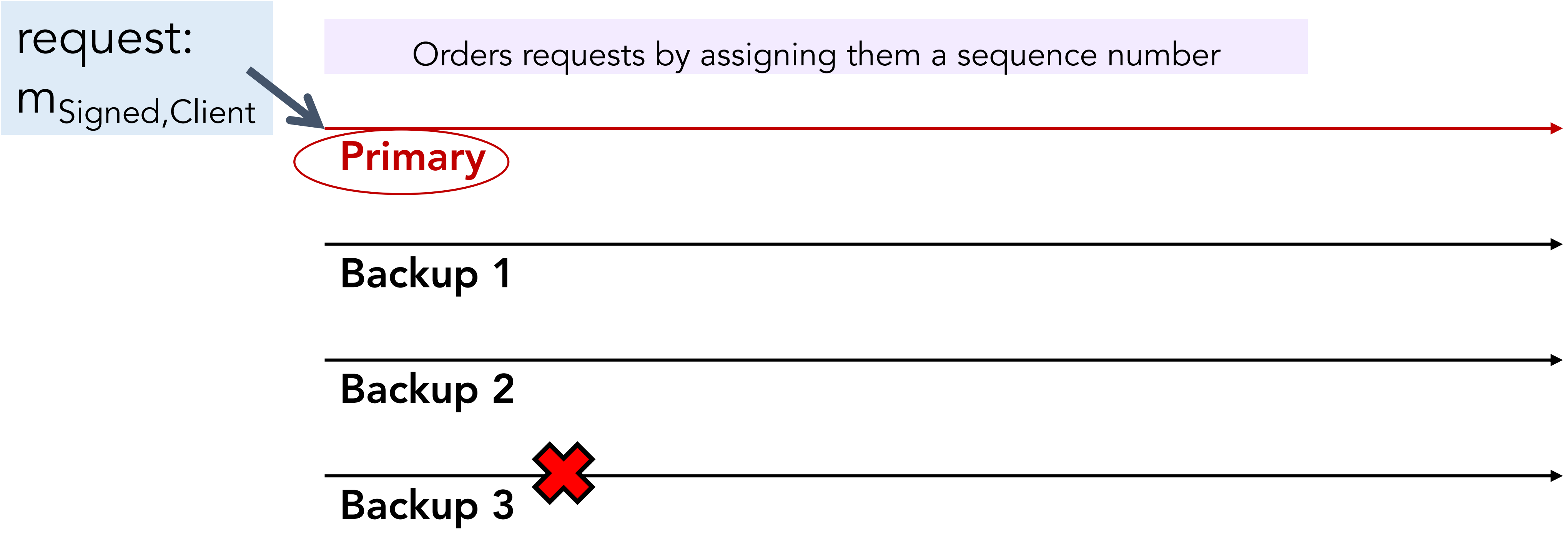
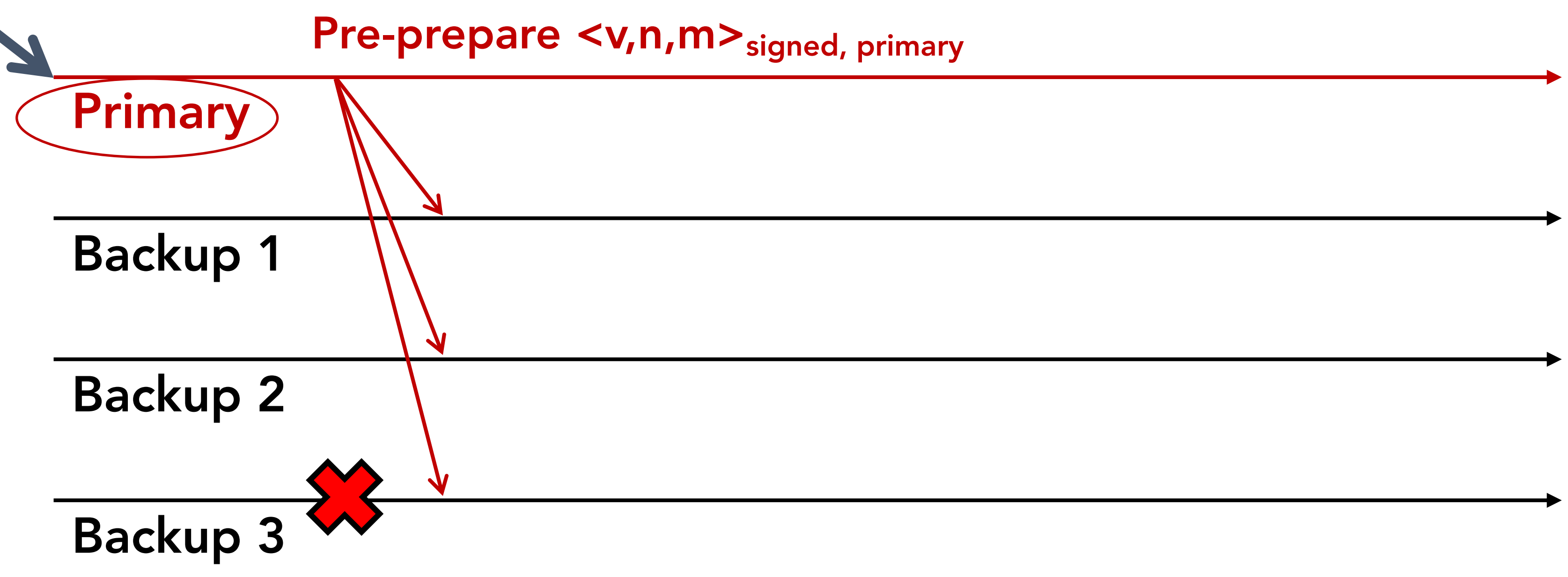


- Primary chooses the request's sequence number
  - Sequence number determines order of execution

Normal Operation (primary is not faulty)

request:
$m_{Signed,Client}$

Phase 1: Send **pre-prepare** messages to all backups



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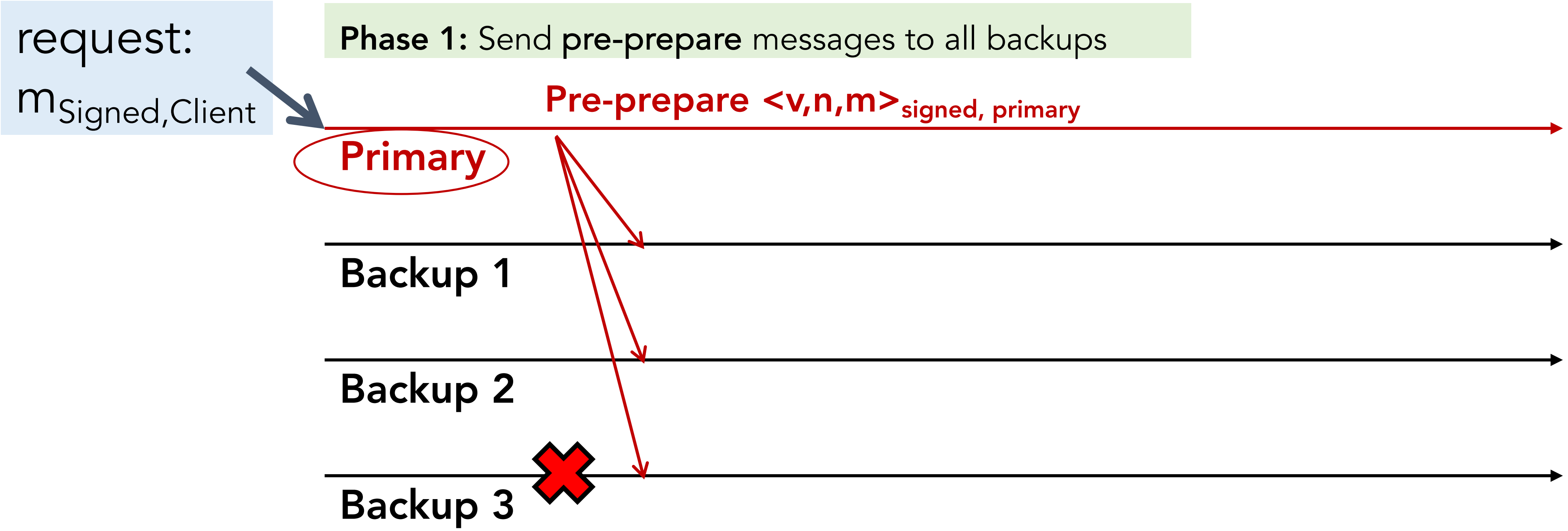
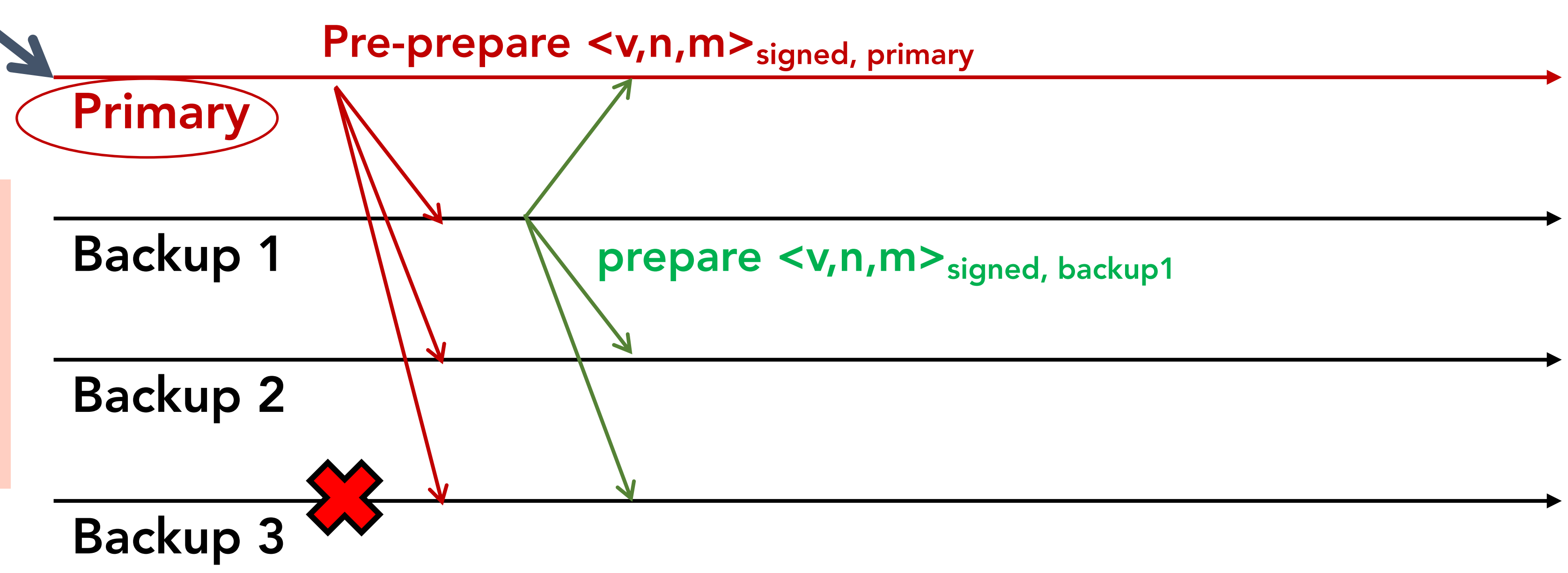


- Backups do the following (and some other checks):
  - They check they are in view v
  - It has not seen another message with view v and sequence number n

Normal Operation (primary is not faulty)

request:
$m_{\text{Signed,Client}}$

Phase 2: Each backup which accepts **pre-prepare** msgs broadcasts a **prepare** message



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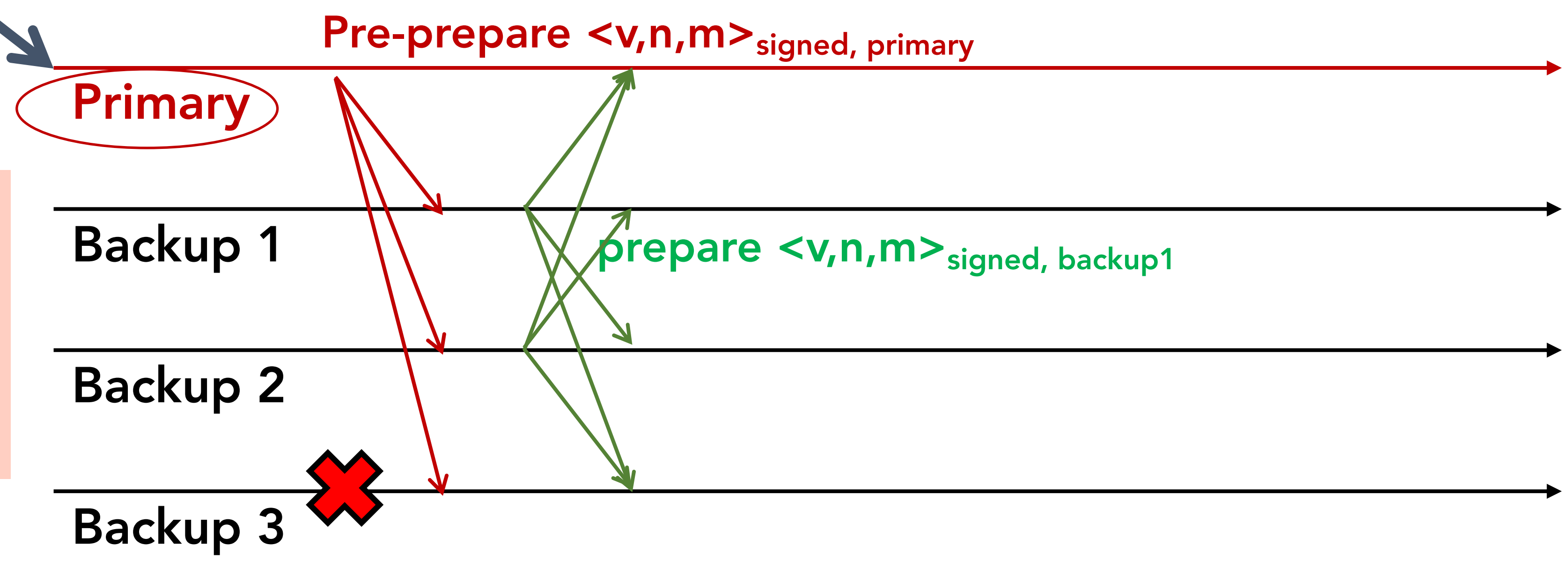
request: $m_{\text{Signed,Client}}$



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- Backups wait for:
  - <u>Prepared certificate:</u> a collection of 2f matching prepare messages from replicas (including itself) + 1 matching pre-prepare message from the primary

Normal Operation (primary is not faulty)

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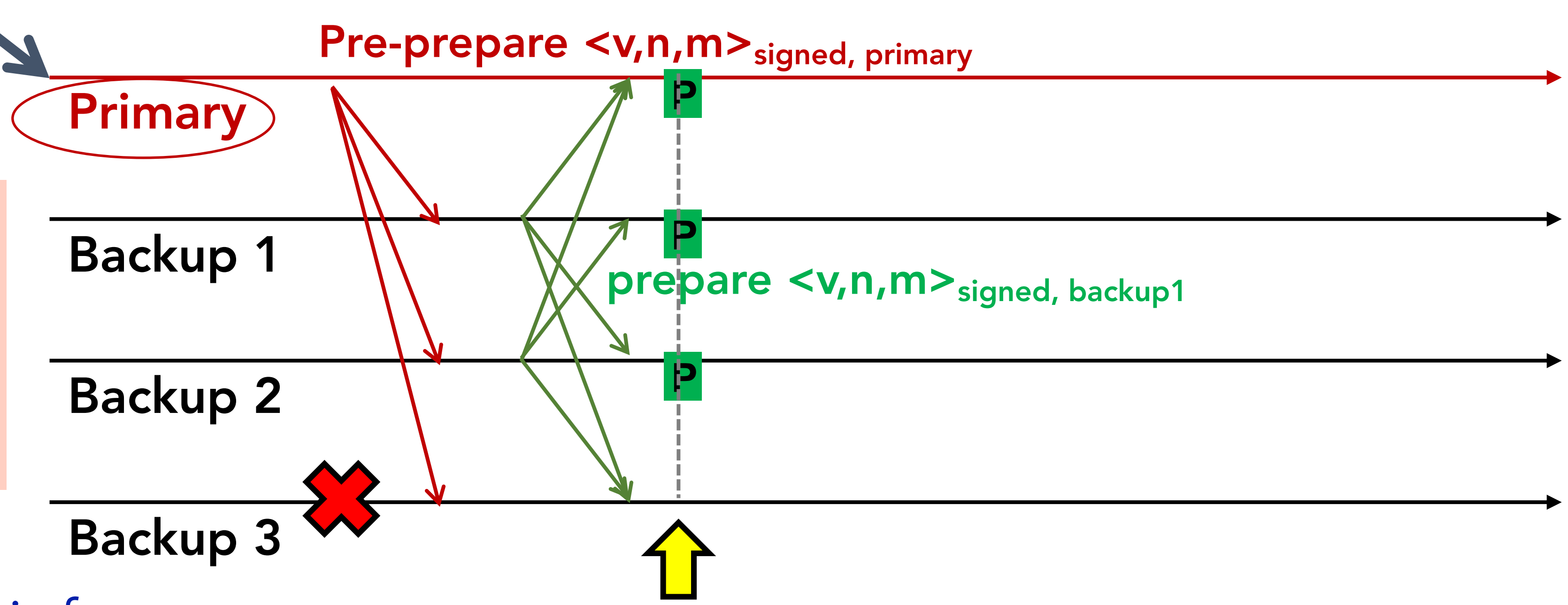

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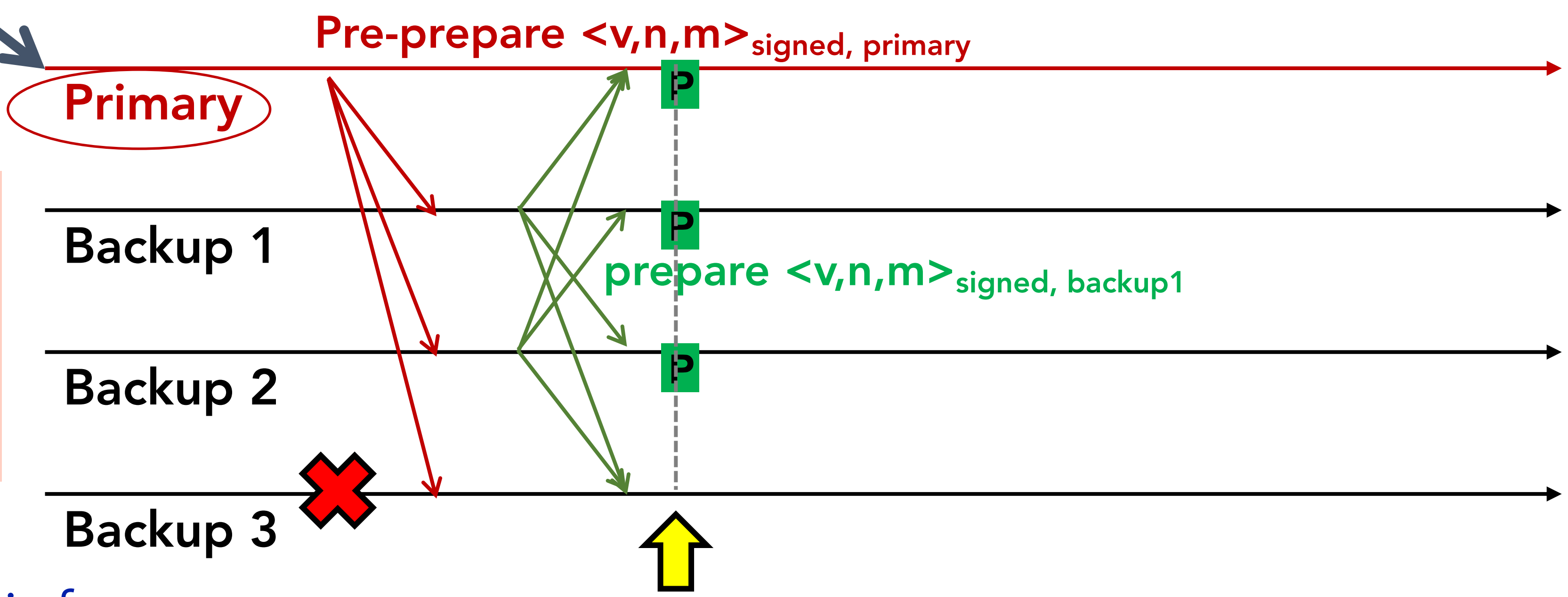


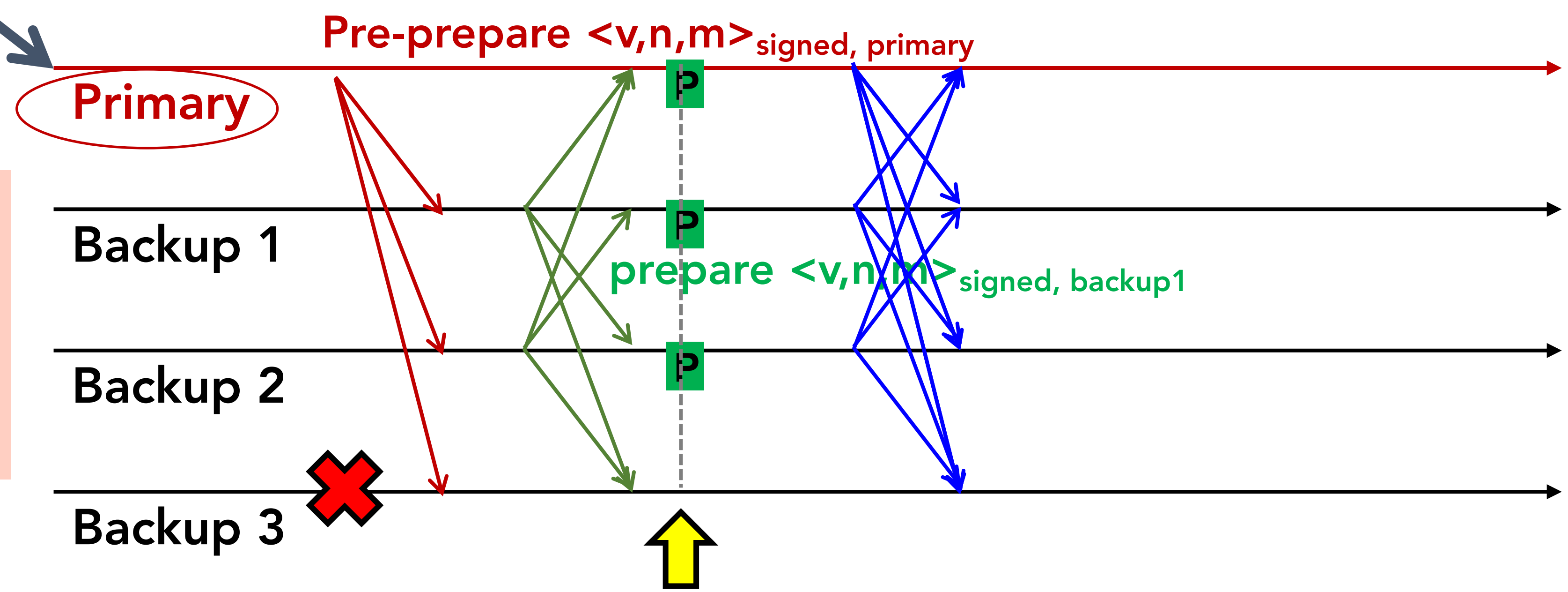
- Backups wait for:
  - Prepared certificate: a collection of 2f matching prepare messages from replicas (including itself) + 1 matching pre-prepare message from the primary

Each correct node has a prepared certificate **locally,** but does not **know** whether the **other correct nodes** do too! So, we **can't commit** yet!

Normal Operation (primary is not faulty)

request:
$m_{\text{Signed,Client}}$

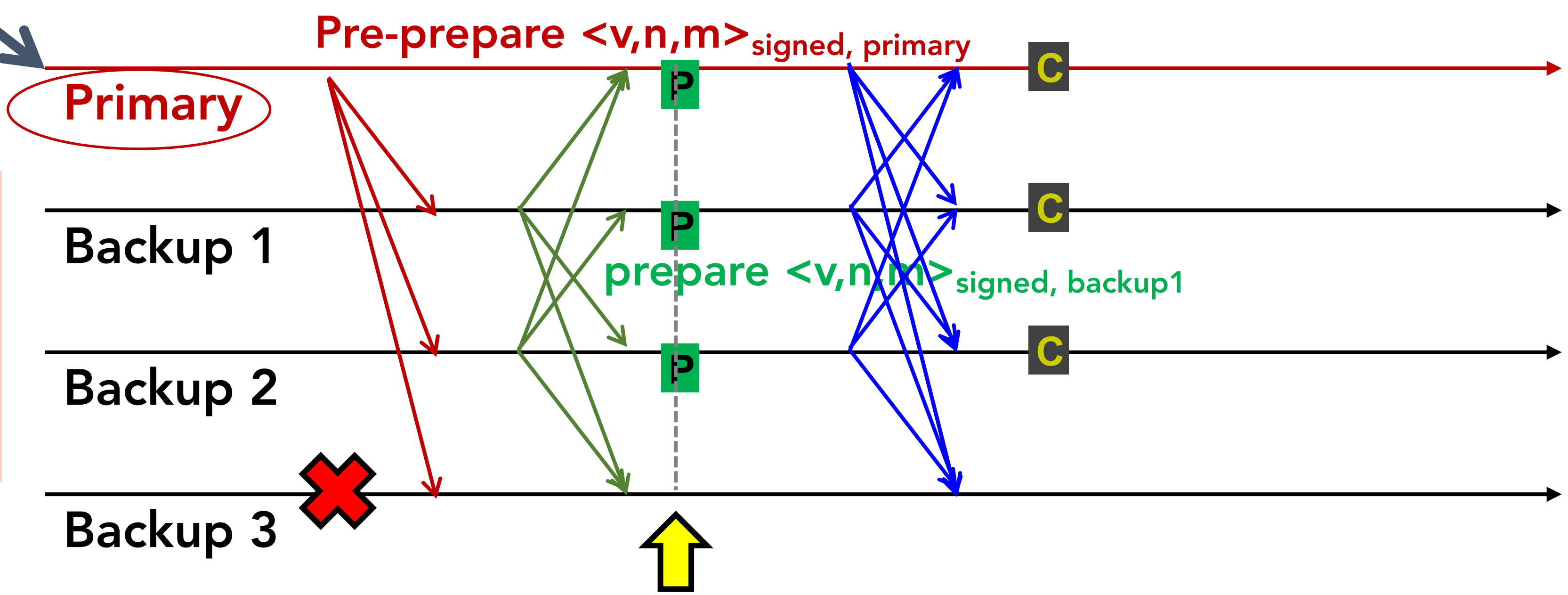
Phase 3: Each backup which has a **prepared** certificate broadcasts a **commit** message



Normal Operation (primary is not faulty)

request:
$m_{Signed,Client}$

Phase 3: Each backup which has a **prepared certificate** broadcasts a **commit** message

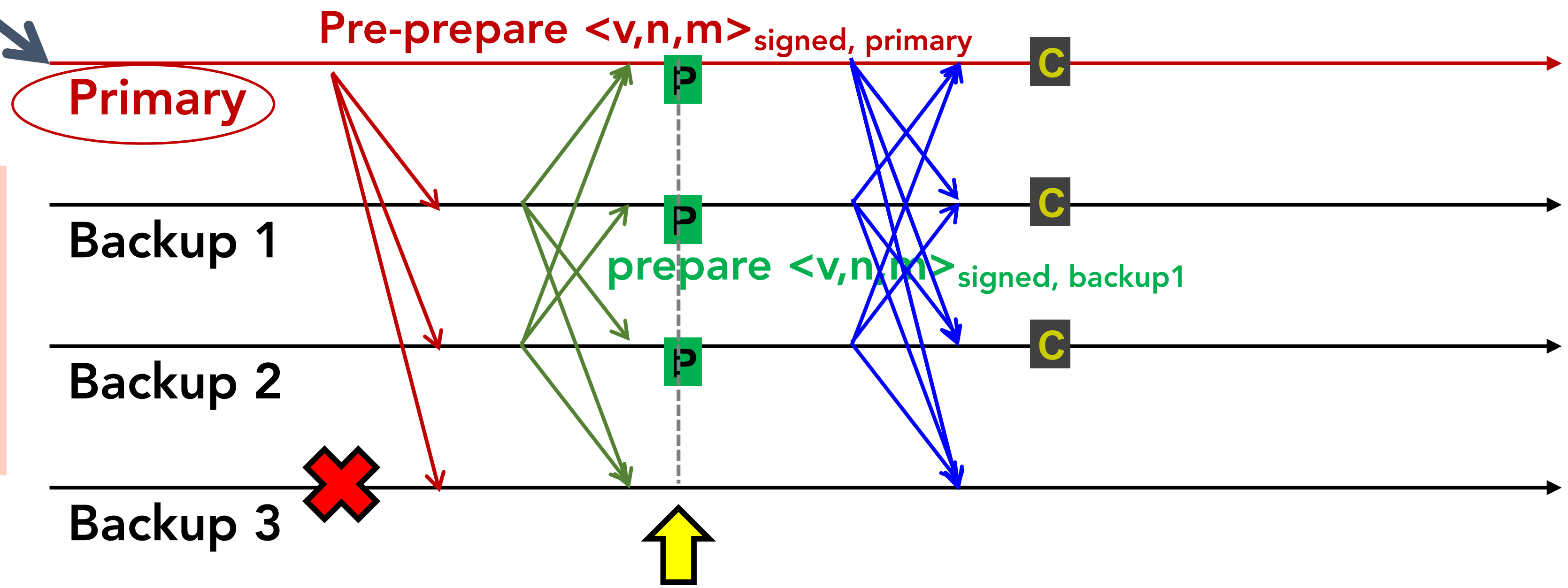


- Backups wait for:
  - **Commit certificate**: a collection of 2f+1 matching commit messages
    - Same view, sequence number and message

Normal Operation (primary is not faulty)

request: $m_{\text{Signed,Client}}$

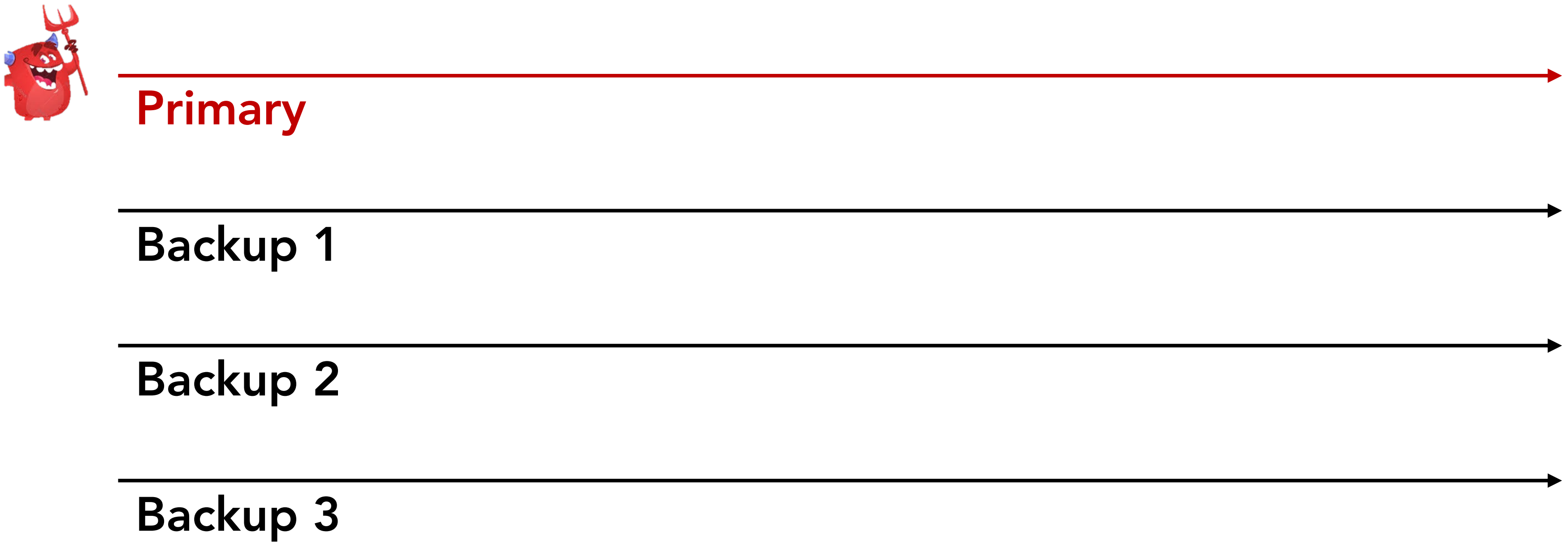
Phase 3: Each backup which has a **prepared certificate** broadcasts a **commit** message



- Backups wait for:
  - Commit certificate: a collection of 2f+1 matching commit messages
    - Same view, sequence number and message

Once the request is **committed**, replicas **execute** the operation and send a reply directly back to the client.

Byzantine Primary



Byzantine Primary

Primary

Pre-prepare <v,n,m>$_{\text{signed, primary}}$

Backup 1

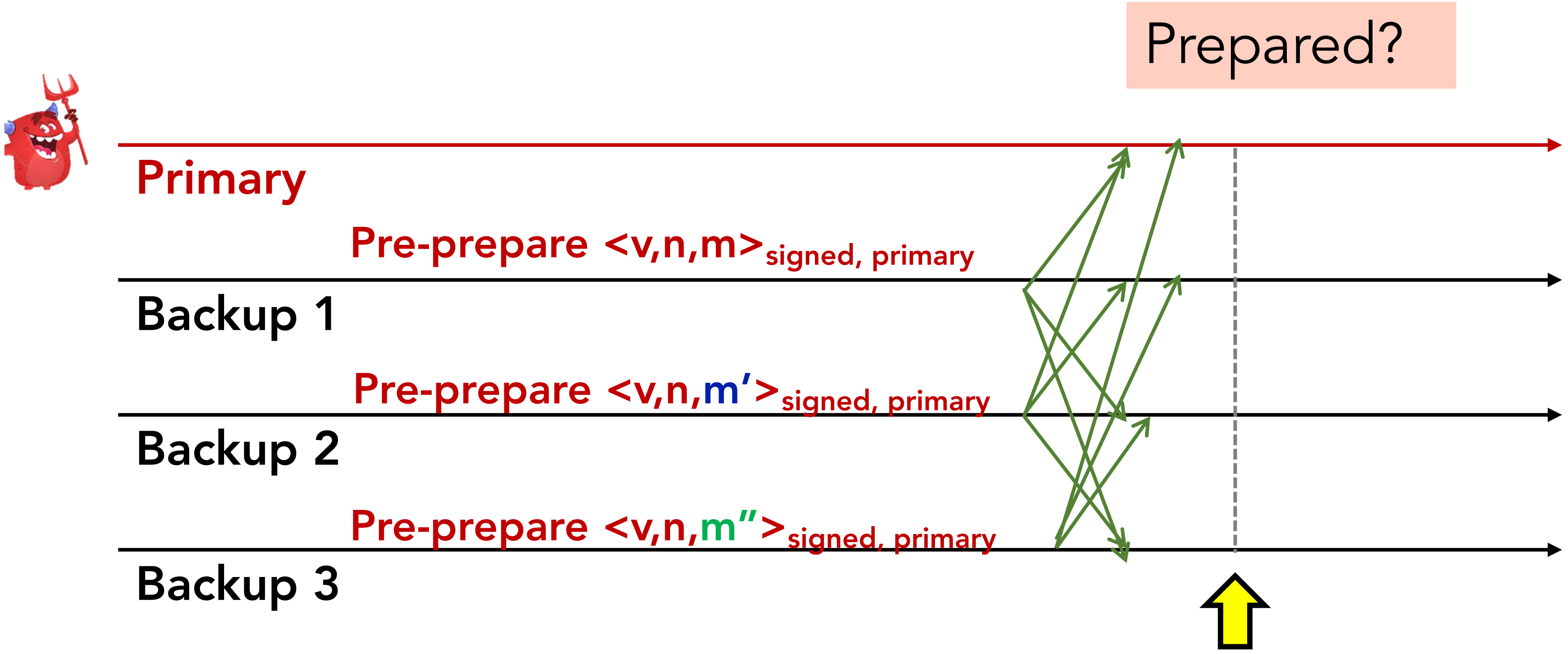
Pre-prepare <v,n,m’>$_{\text{signed, primary}}$

Backup 2

Pre-prepare <v,n,m”>$_{\text{signed, primary}}$

Backup 3

Byzantine Primary



Byzantine primary

- In general, backups **won't prepare** if primary lies
- **Suppose they did:** two distinct requests **m** and **m′** for the same sequence number n
  - Then prepared quorum certificates (each of size $2f+1$) would **intersect** at an **honest** replica
  - So that honest replica would have sent a prepare message for both m and m′
    - So m = m′

View Change

- If a replica suspects the primary is faulty, it requests a *view change*
  - Sends a *view change* request to all replicas
    - Everyone acks the view change request
- New primary collects a quorum of $(2f+1)$ responses
  - Sends a ***new-view*** message with this certificate
- Need committed operations to survive into next view
  - Client may have gotten answer
  - View change request contain checkpoints + newer prepare certificates

Other Bits

- Garbage collection
  - Can’t let log grow without bound
  - So shrink log when its gets too big
- Proactive recovery
  - Recover the replica to a known good state whether faulty or not

Summary of key ideas

- 2f+1 Quorum
  - We need 2f+1 replicas in a quorum to deal with byzantine faults
  - Assuming a total of 3f+1 replicas with atmost f byzantine faults
- Primary backup with view changes
- Three Rounds
  - Pre-prepare: pick order of request and inform clients
  - Prepare: ensures order within views
  - Commit: ensures order across views
- Replicas directly contact the clients
  - Clients wait for f+1 matching responses

PBFT Conclusion

- Byzantine fault tolerence was for long considered an exotic topic
  - 1980s focused primarily on fail-stop failures
- PBFT showed Byzantine fault tolerance is possible under certain assumptions
- But there were still challenges around performance
  - Challenges: lots of coordination with three phases
  - The paper and a lot of the followup work is about making byzantine fault tolerance more performant