Zyzzyva: Speculative Byzantine Fault Tolerance

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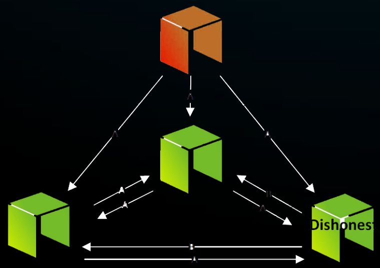
Sajjad Rahnama, November 1st

Agenda

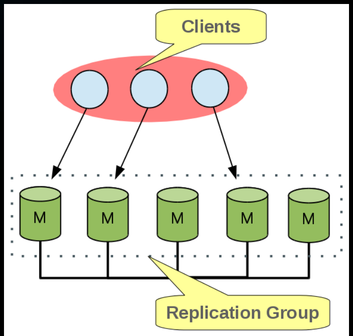
- Introduction
- Zyzzyva System Model
- Protocol Overview
- Node State and Checkpoints
- Agreement Protocol
- View Change
- Correctness
  - Safety
  - Liveness

Introduction

Byzantine Fault



State Machine Replication



Byzantine Fault Tolerant State Machine Replication

Introduction

PBFT

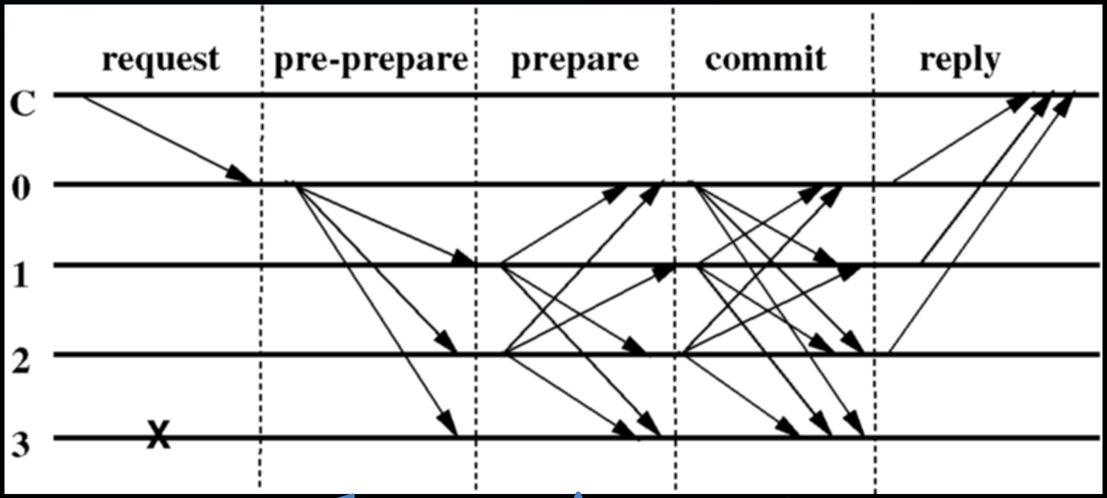
Practical Byzantine Fault Tolerant Protocol

- 3F+1 node
- Can Tolerate f faulty node
- 3 Phase
- Pre-Prepare, Prepare, Commit
- 4 One-way messages

Introduction

PBFT

Practical Byzantine Fault Tolerant Protocol



Make sure that I didn't receive two same sequence number

I know That nobody receive two same sequence number

Everyone know that nobody receive two same sequence number

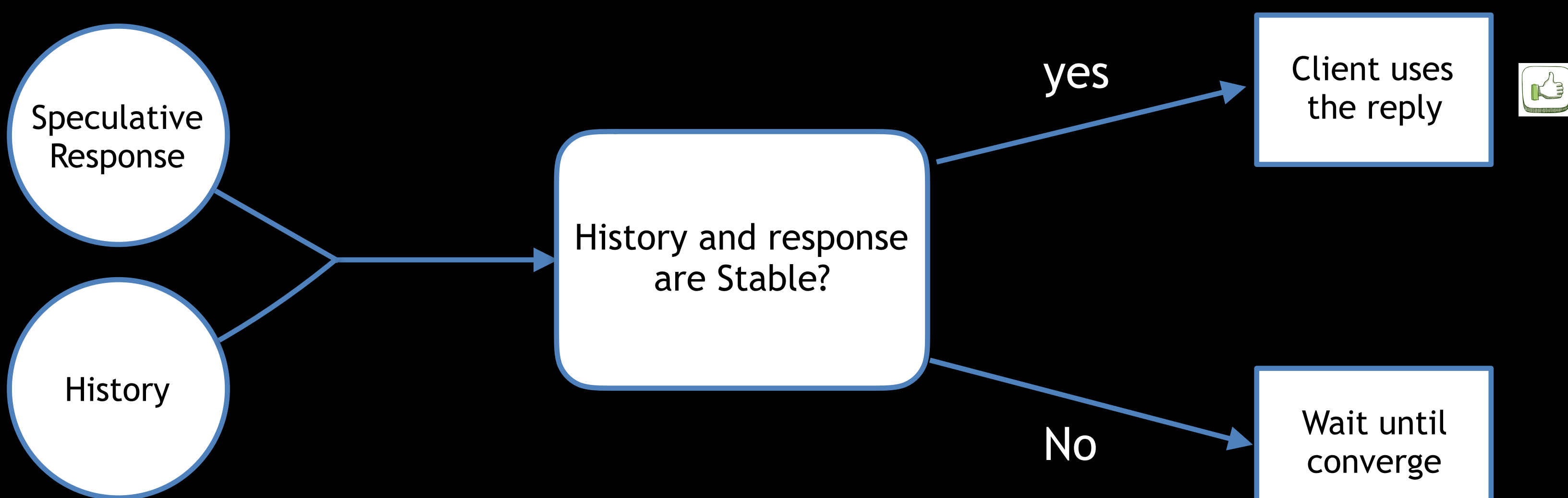
Zyzzyva

"A protocol that uses **Speculation** to reduce the cost and **Simplify** the design of BFT state machine replication"

Introduction

Zyzzyva

- Speculative Execution
- Replies to the client contain Sufficient history



Zyzzyva

- Challenge is ensuring that response to the client become stable
- Move output Commit to the client
- Clients act on request in one or two phases

Introduction

Why Zyzzyva?

Cost	PBFT	Zyzzyva
Total Replicas	3f+1	3f+1
Replica with application state	2f+1	2f+1
Critical path 1-way Latency	4	3

Assumptions

- Faulty nodes may behave Arbitrarily
- Faulty nodes cannot break cryptographic signs
- Messages may fail to deliver or delay

Protocol Overview

Subprotocols

Agreement

View Change

Checkpoint

Principles and Challenges

- Safety property as they are **observed** by **client**
- Replicas can be temporarily inconsistent
- Client detect them, drive them to convergence
- Client rely on consistent responses
- Replicas execute the orders before its Order **Fully Stablished**

Protocol Overview

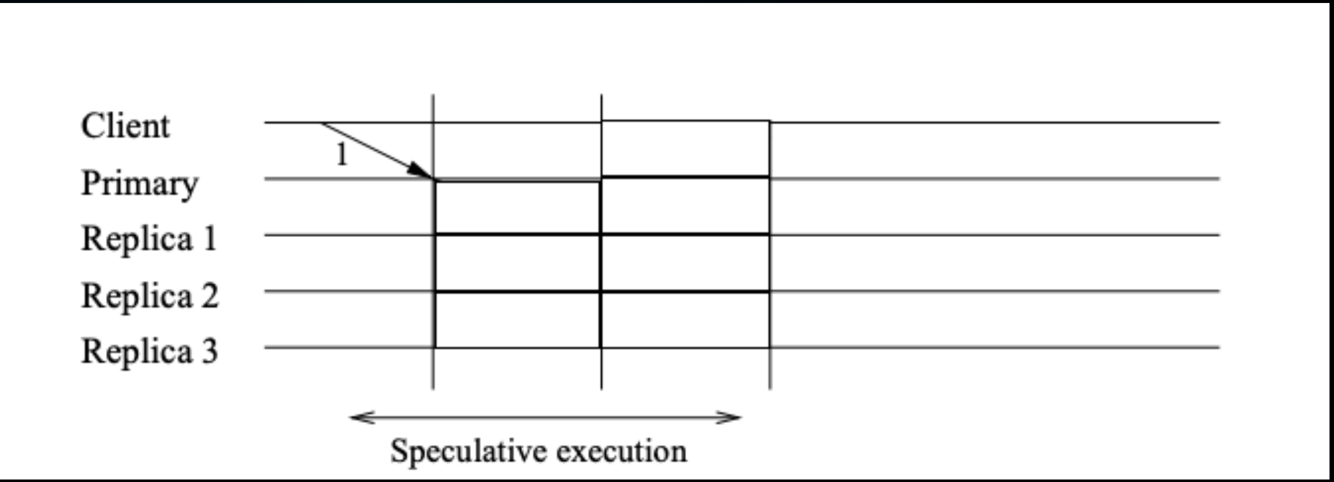
Safety

f If a request with sequence number **n** and history $\mathbf{h_n}$ completes, then any request that completes with a higher sequence number $\mathbf{n'} \geq \mathbf{n}$ has a history $\mathbf{h_{n'}}$ that includes $\mathbf{h_n}$ as a prefix.

Liveness

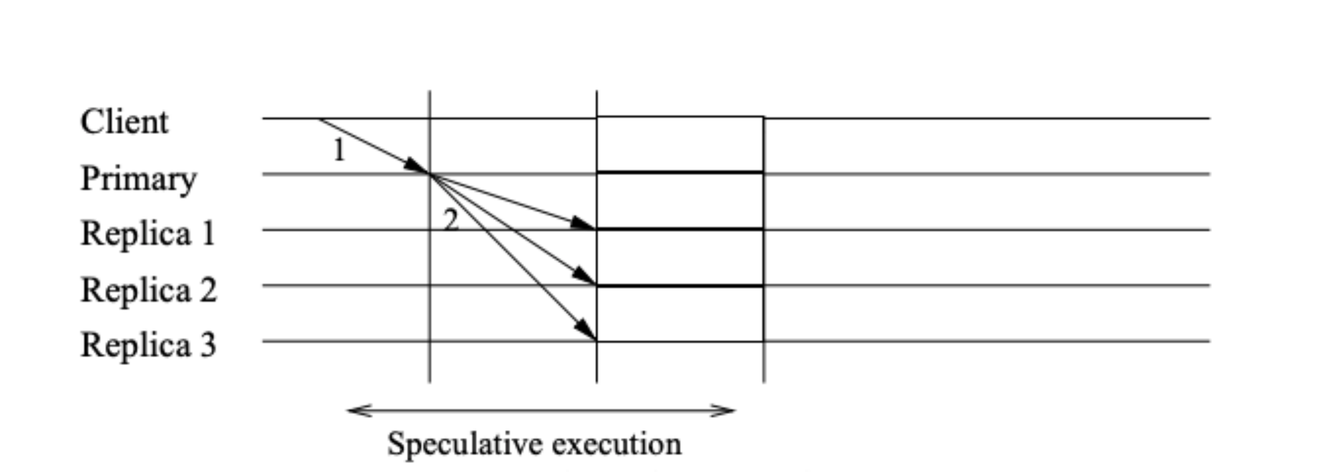
Any request issued by a correct client eventually completes.

Protocol Communication



Client Send Request to the Primary

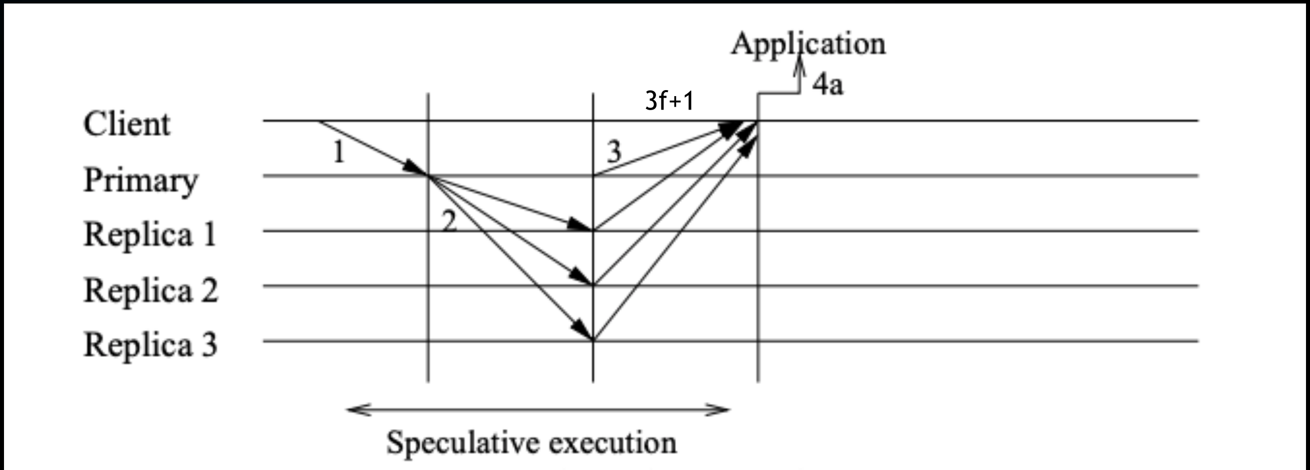
Protocol Communication



- Primary Forwards the Request to all replicas
- Replicas Executes the request

Protocol Communication

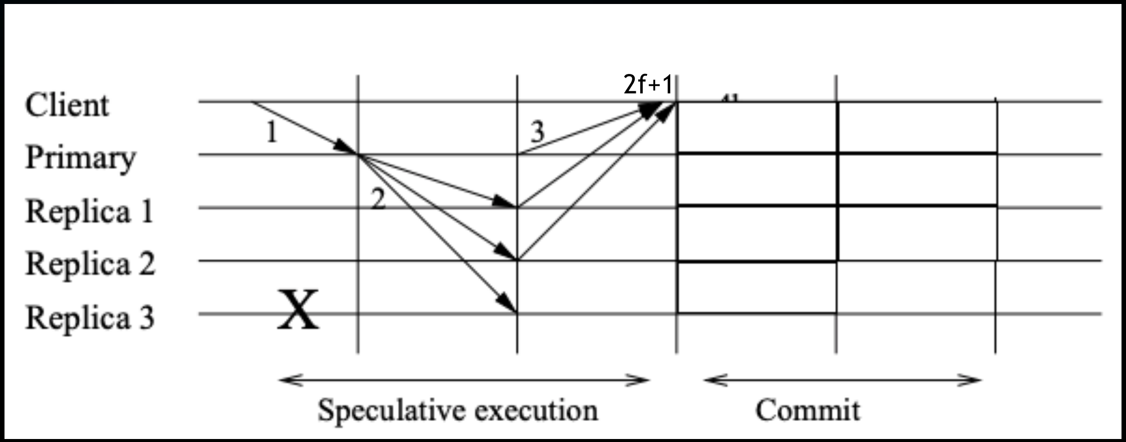
Gracious execution



- Replicas Send Response with history to the client
- **3f+1** mutually consistent response then it is done

Protocol Communication

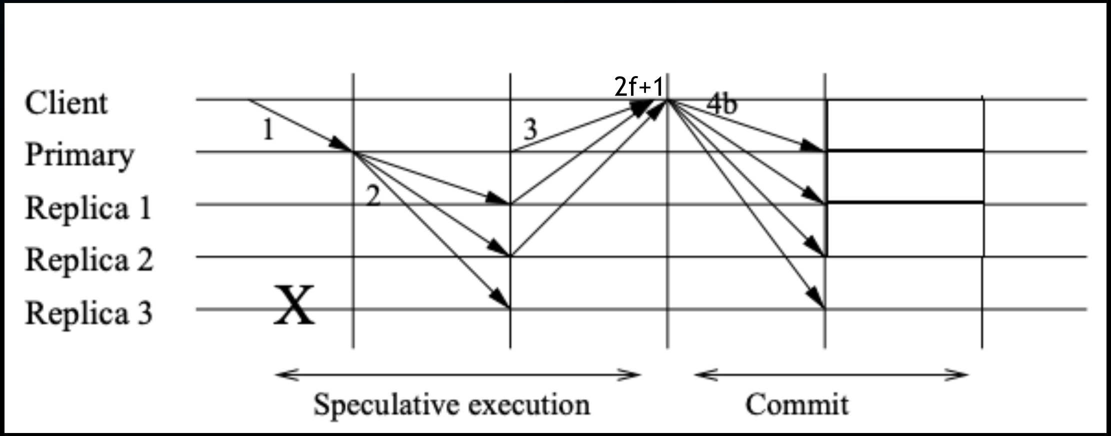
Faulty nodes



- Some of nodes are faulty
- Client Receive between 2f+1 and 3f+1 response

Protocol Communication

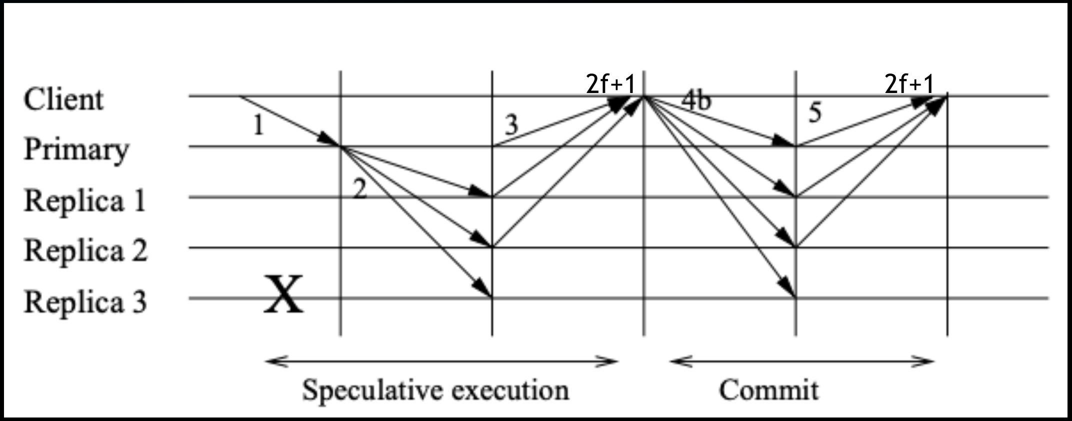
Faulty nodes



- Client Gather 2f+1 response and make **Commit Certificate**
- Send's commit certificate to all nodes

Protocol Communication

Faulty nodes



- Client Respond to CC and acknowledge to the Client
- Once 2f+1 acknowledgments received client act on request

Node State and Checkpoint

Ordered History — History of executed requests

Max Commit Certificate — CC seen by node with the largest seq number

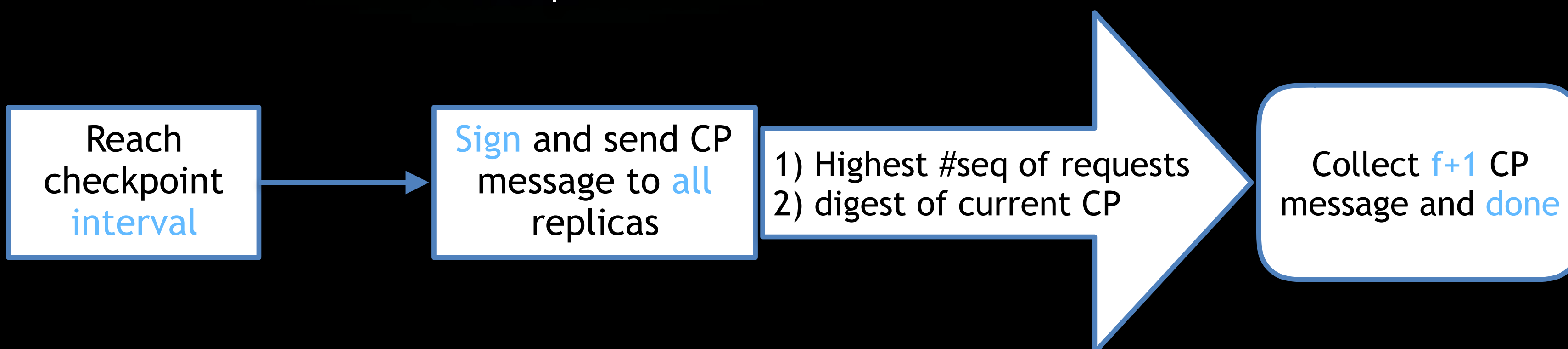
Committed History — History up to seq number of max commit certificate

Speculative History — History follows the committed history

Node State and Checkpoint

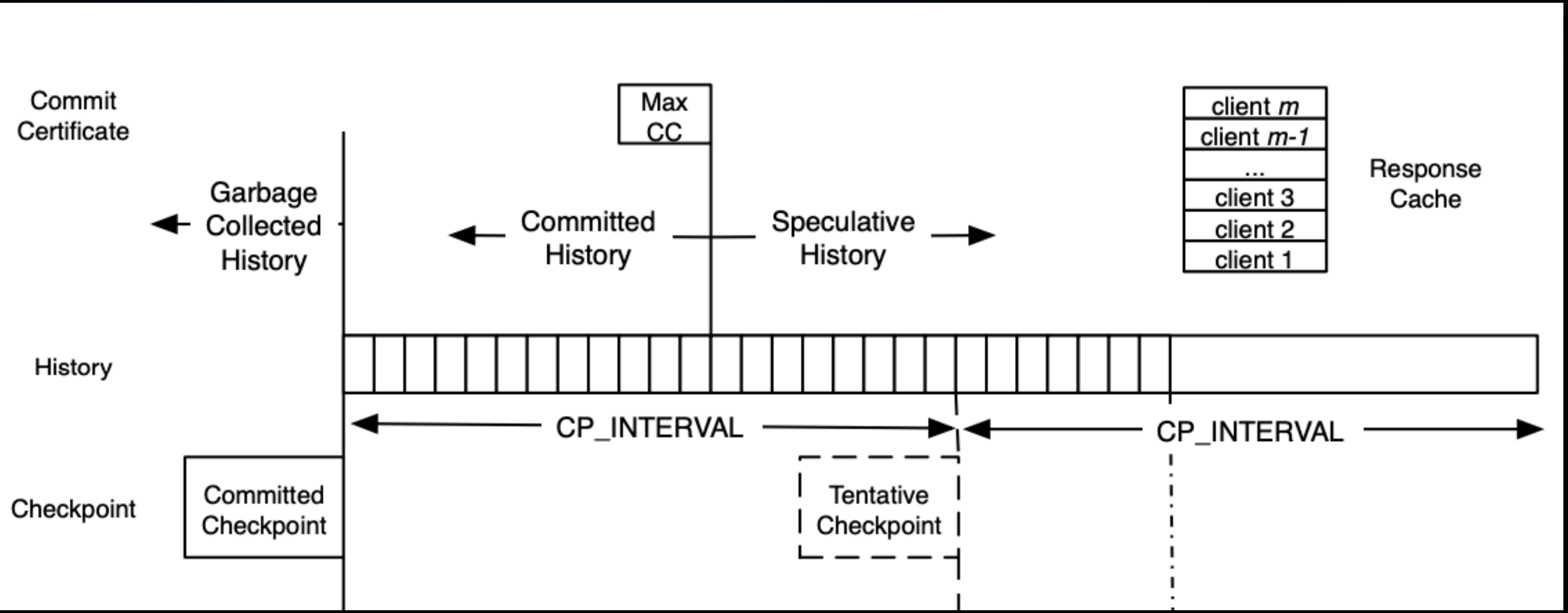
Checkpoint

- A replica constructs a checkpoint every CP_INTERVAL requests.
- Similar to other BFT protocols like PBFT



Node State and Checkpoint

Replica State



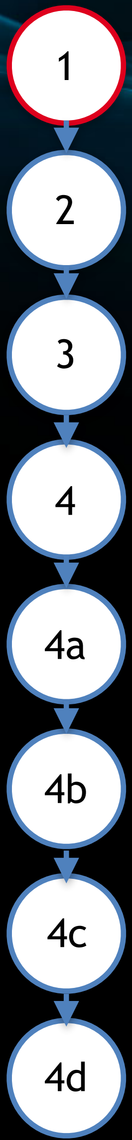
Agreement Protocol

Step 1

- Client Sends Request to the Primary

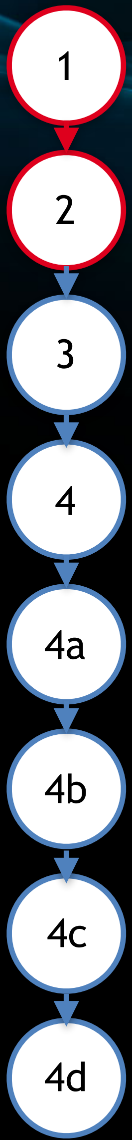
$$\langle \text{REQUEST}, o, t, c \rangle_{\sigma_c}$$

- o: operation
- t: timestamp
- c: client Id



Agreement Protocol

Step 2



- Primary receive request and assign seq number
- Forward ordered request to all primary

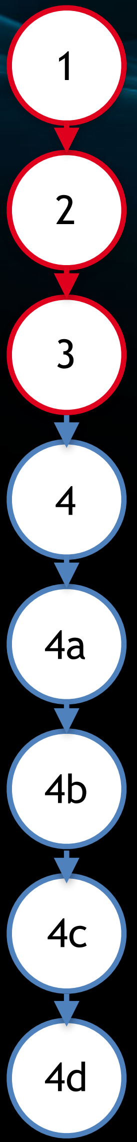
$$\langle\langle \text{ORDER-REQ}, v, n, h_n, d, ND\rangle_{\sigma_p}, m\rangle$$

- v: view number
- n: sequence number
- m: client message
- d: H(m)
- h_n: $H(h_{n-1}, d)$
- ND: application values

Agreement Protocol

Step 3

- Replica receive ordered Request
- Check that:
  - m is wellformed and d is correct digest
  - $n = max_n + 1$
  - $h_n = H(h_{n-1}, d)$
- Execute the request and create Spec-Response



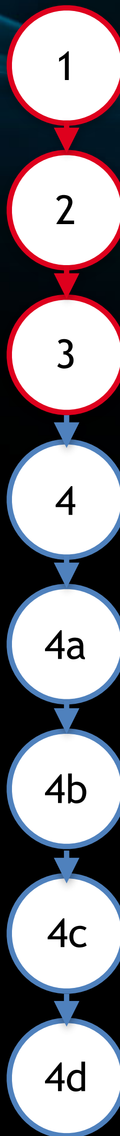
Agreement Protocol

Step 3

$$\langle\langle \text{SPEC-RESPONSE}, v, n, h_n, H(r), c, t\rangle_{\sigma_i}, i, r, OR\rangle$$

- r: reply to the operation
- i: replica id
- OR: order request

Question :What will happen to out of order Sequence numbers?



Agreement Protocol

Step 3

Out of order Sequence numbers:

$n <= max_n + 1$ — Discard the request

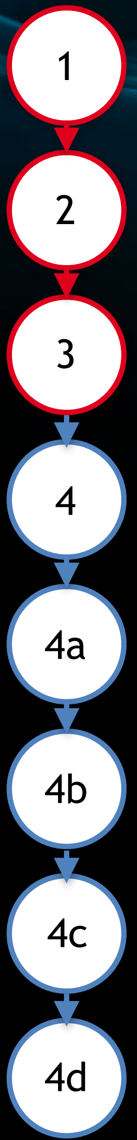
$n > max_n + 1$ — The replica has some gap in its history

- Replica send Fill-Hole message to the primary

$$\langle \text{FILL-HOLE}, v, max_n + 1, n, i \rangle_{\sigma_i}$$

- Primary respond with order request for $k \leq n' \leq n$

Question :What will happen if primary doesn't answer?

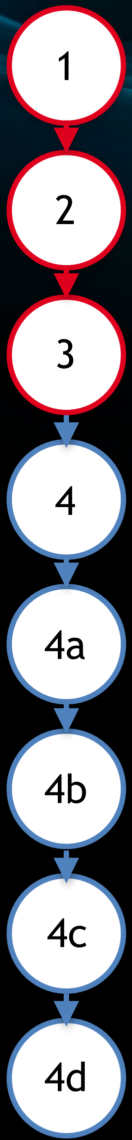


Agreement Protocol

Step 3

If primary doesn't answer to Fill-Hole Message:

- After replica timer for fill-hole message expires replica broadcast Fill-Hole message to all replicas
- Start view change timer
- Replicas which receive Fill-Hole message, will forward Order-Req of corresponding holes to sender if they already have
- If timer expires and still replica doesn't receive Order-Reqs it will initiate view change



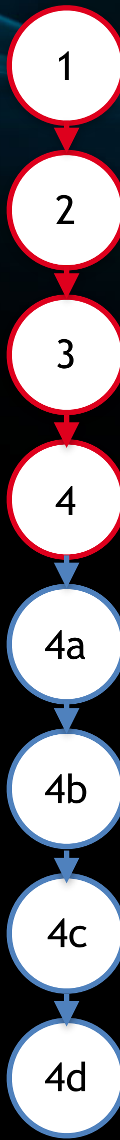
Agreement Protocol

Step 4

Client Gathers Speculative Responses

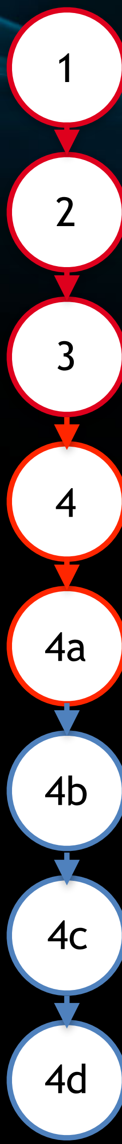
- Spec-Response messages must mach following properties:
  - v: view number
  - n: sequence number
  - c: client id
  - H(r): reply digest
  - h_n: $H(h_{n-1},d)$
  - t: request timestamps

Based on number of speculative response and OR four case could happen



Step 4a

- Client Receive 3f+1 matching response
- It assumes that request is completed
- No acknowledgement will send to replicas
- Replicas cannot determine that request is committed



Agreement Protocol

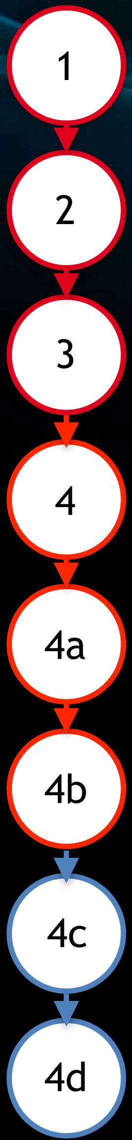
Step 4b

When some of nodes are faulty:

- Client Receive between 2f+1 and 3f+1 matching response
- It assembles 2f+1 response as a Commit-Certificate
- Send commit message with CC to all replicas

$$\langle \mathrm{COMMIT},\ c,\ CC \rangle_{\sigma_c}$$

CC is the list of all 2f+1 matching speculative responses



Agreement Protocol

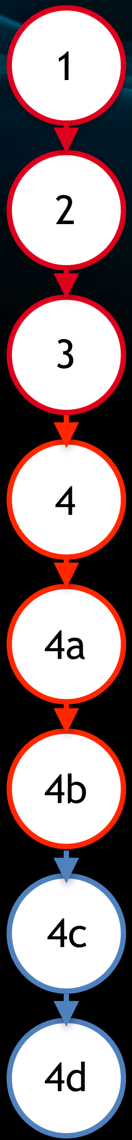
Step 4b-1

- Replica receive a commit message from a client containing CC
- Replica acknowledge to the client with Local-Commit message
- Send CC to all replicas

1) It already has executed request — Send Commit Local

2) It hasn't execute request — Update max sequence number and execute operations and send Commit local message

3) Replica has holes in its history — Fill the hole as previously discussed



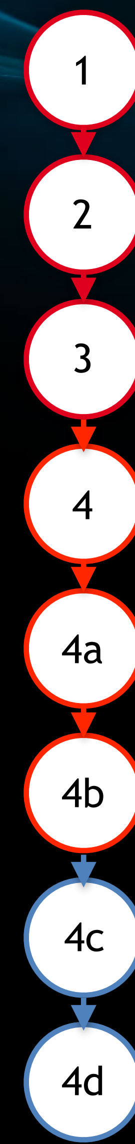
Agreement Protocol

Step 4b-2

- Client Receive a Local Commit from a 2f+1 replica
- Assume that request is completed
- Send CC to all replicas

Question :What will happen if doesn’t receive 2f+1 local-commit?

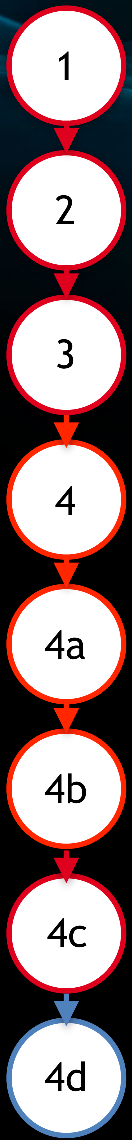
- It starts timer when send commit message
- If timer expires before 2f+1 one local-commit message then it will act same as 4c step



Agreement Protocol

Step 4c

- Client Receive fewer than 2f+1 matching Spec-Response
- It Resend the its request to all Replicas
- Replicas will forward client request to the primary
- A non-primary replica which receive client request
  - 1) If it has cached response it will send that to client
  - 2) if the sequence number is new then send Confirm Message to the primary

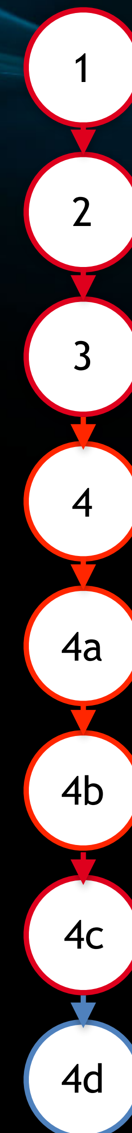


Step 4c

- Replica send Confirm-Message to primary and ask for Order-Request

$$\langle \text{CONFIRM-REQ}, v, m, i \rangle_{\sigma_i}$$

- m is client request
- Replica start timer after sending Confirm-Message
- If primary accepts then it send response to client
- If timer expires then it will initiate view change



Agreement Protocol

Step 4d

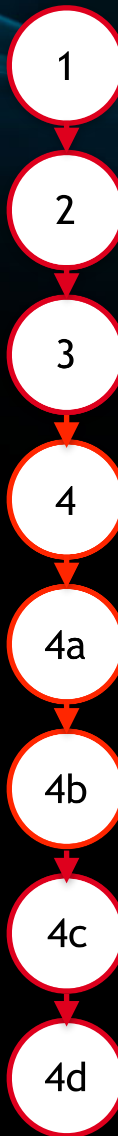
- Client receive response indicating inconsistent ordering by primary
- It sends Proof of Misbehaver to all replicas
- They will initiate view change

$$OR = \langle \text{ORDER-REQ}, v, n, h_n, d, ND \rangle_{\sigma_j}$$

- Inconsistent Ordering: two spec response with valid OR and view number and different sequence number

$$\langle \text{POM}, v, POM \rangle_{\sigma_c}$$

Proof of Misbehavior message



View Change Sub Protocol

- Elect new primary
- Must guarantee no change will happen in committed history
- The View Change sub protocol is like previous BFT's ones

View Change step 1

- Replica Initiate view change by sending accusation to all replicas

$$\langle \text{I-HATE-THE-PRIMARY},\ v \rangle_{\sigma_i}$$

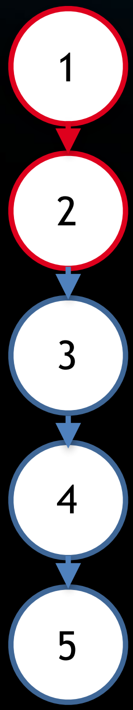
- In previous protocols, this message would indicate that replica is no longer participating in the current view
- This message is only a hint that a replica would like to change views

View Change step 2

- Replica receives f+1 accusations that the primary is faulty
- Replica commits to the view change
- No longer participate in current view

$$\langle \text{VIEW-CHANGE}, v+1, CC, O, i \rangle_{\sigma_i}$$

- Sends view Change message to all replicas
- CC: last commit certificate
- O: ordered request since commit certificate



View Change step 3

- Replica Receives 2f+1 view change message
- New primary will send New-View message to all replicas

$$\langle \text{NEW-VIEW}, v+1, P \rangle_{\sigma_p}$$

- P: is collection of 2f+1 view change message
- A replica after sending view-change message starts a timer
- If replicas timer expires it initiate new view change for v+2

View Change step 4

- Replica receives valid New-View Message
- It sends a View-Confirmation Message to all replicas
- The most recent request with a corresponding CC will be accepted as the last committed history
- The most recent request that is ordered subsequent to the CC by at least f+1 view-change messages will be accepted.

$$\langle \text{VIEW-CONFIRM}, v+1, n, h, i \rangle_{\sigma_i}$$

View Change step 5

- New Primary receive 2f+1 View-Confirm message
- The replica will begin new view

Correctness

Safety

- Show no 2 request with same sequence number
- Show if n' > n is committed then h is prefix of h'
- Within a View
  - 3f+1 speculative response or 2f+1 local-commit
  - 1) Correct node send one speculative response
  - 2) Correct node just send local commit after seeing 2f+1 speculative response
- Across Views:
  - In case 2f+1 CC message at least one correct node will send CC in their view change message
  - In case of 3f+1 spec-response every correct replica will include spec response in their view change message

Liveness

- If the primary is correct
  - In case of 3f+1 spec response it will immediately completes
  - In case of 2f+1 spec response because at most f nodes are faulty then it definitely receive 2f+1 local commit

- If the request does not complete during the current view then view change will happen
- If the request does not complete by protocol step 4c client resends request to all replicas
- Any replica that does not receive order-req from primary will send I-Hate-Primary
- There will be f+1 I hate primary or 2f+1 spec response and view change occur or request will complete