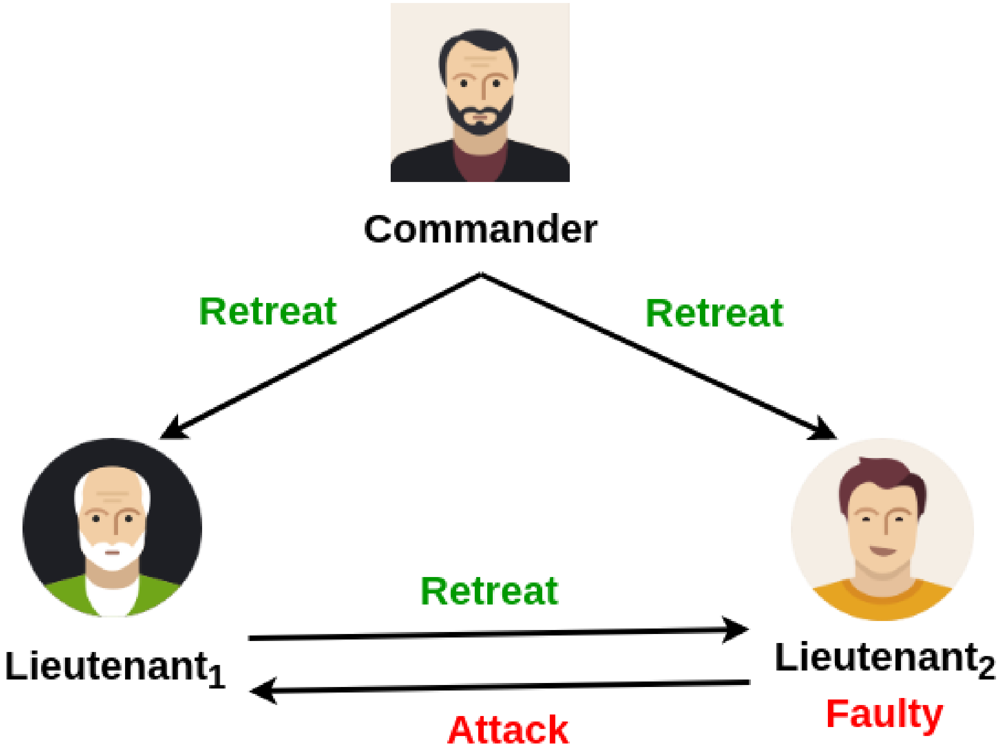
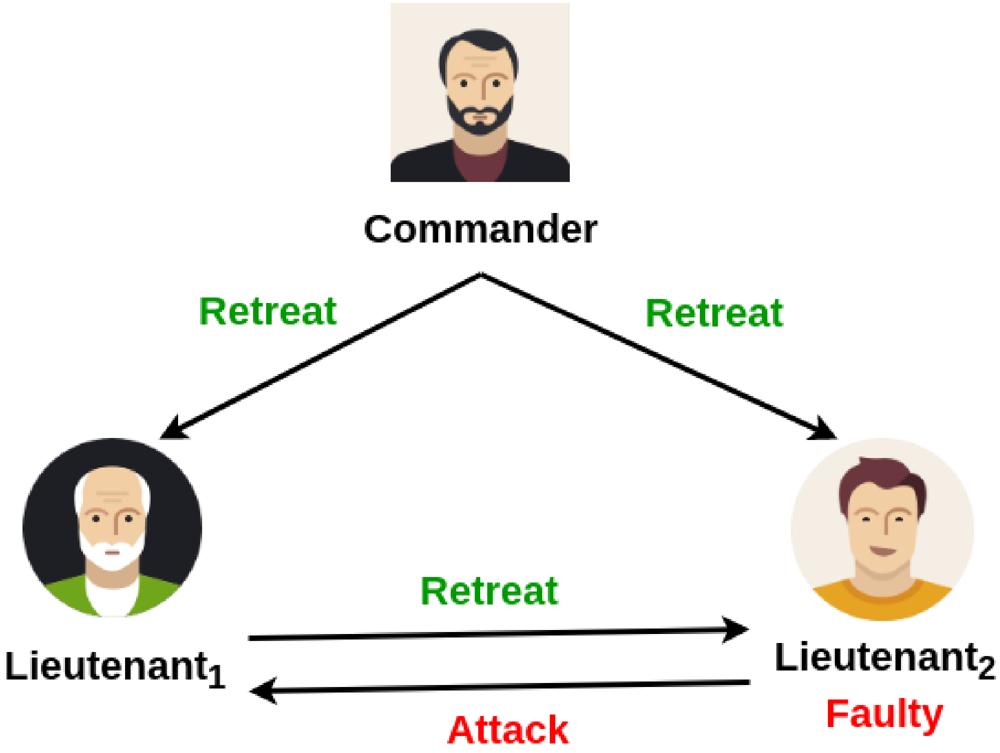
Byzantine Generals Problem

Three Byzantine Generals Problem: Lieutenant Faulty



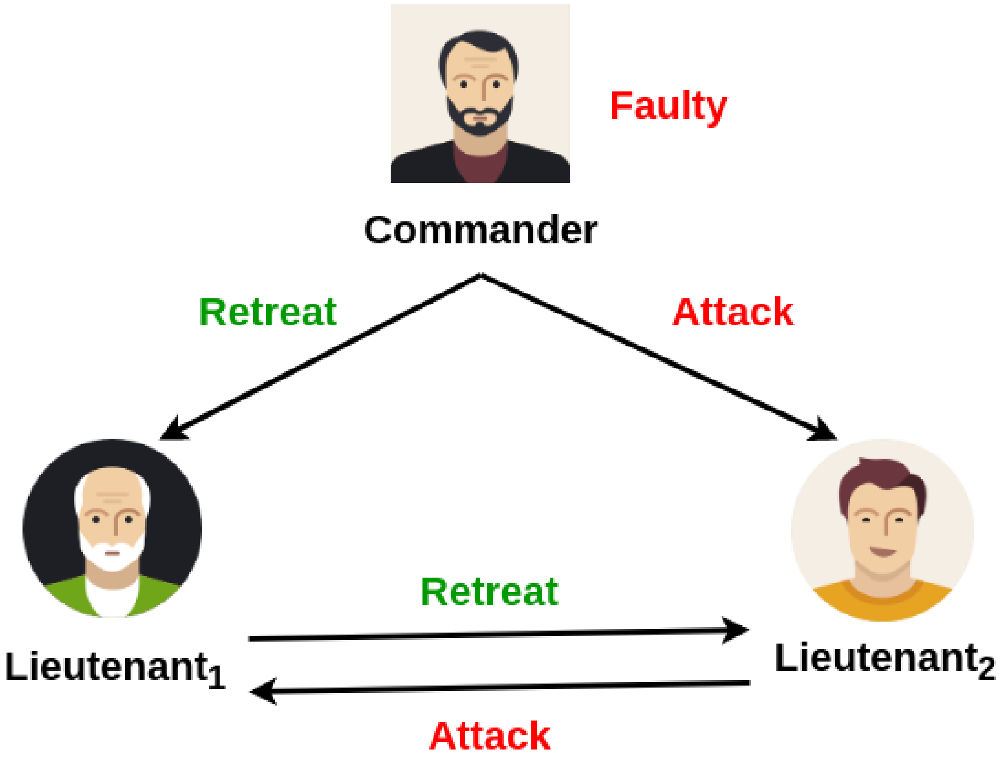
- Round1:
  - Commander correctly sends same message to Lieutenants
- Round 2:
  - $Lieutenant_1$ correctly echoes to $Lieutenant_2$
  - $Lieutenant_2$ **incorrectly** echoes to $Lieutenant_1$

Three Byzantine Generals Problem: Lieutenant Faulty



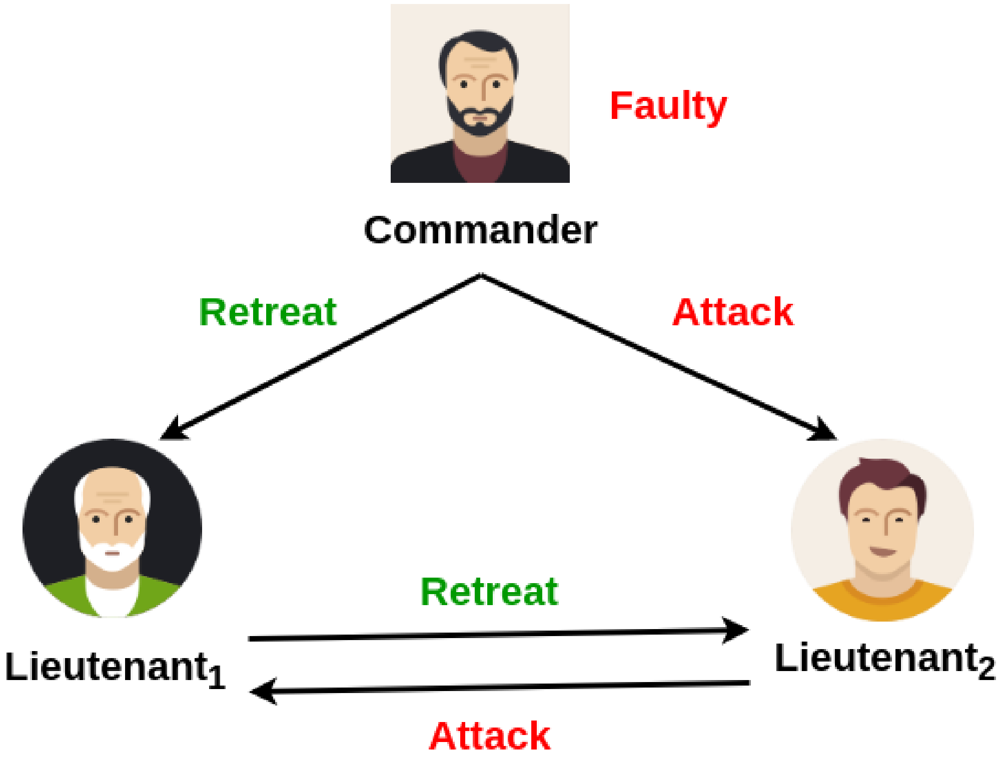
- Lieutenant$_1$ received **differing message**
- By integrity condition, Lieutenant$_1$ bound to decide on Commander message
- **What if Commander is faulty??**

Three Byzantine Generals Problem: Commander Faulty



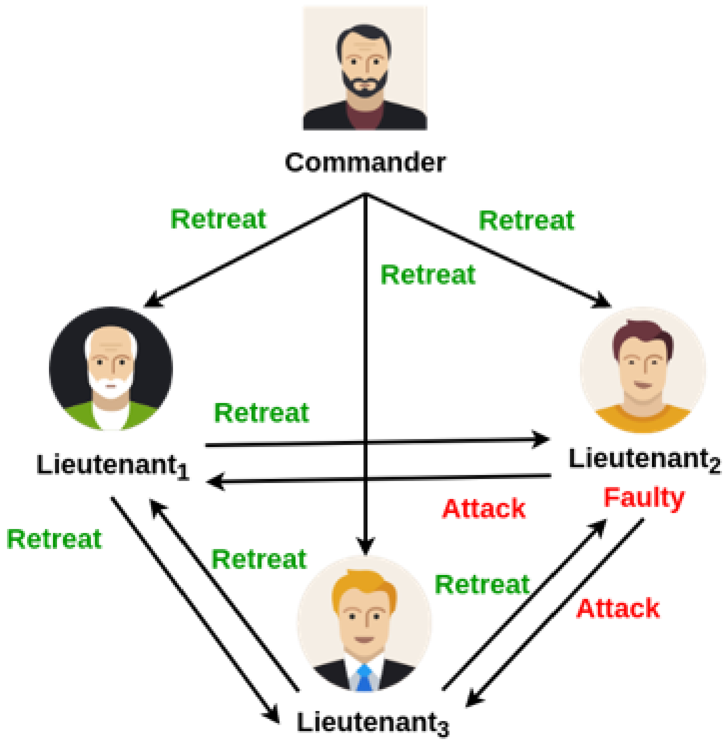
- Round 1:
  - Commander sends differing message to Lieutenants
- Round 2:
  - Lieutenant$_1$ correctly echoes to Lieutenant$_2$
  - Lieutenant$_2$ correctly echoes to Lieutenant$_1$

Three Byzantine Generals Problem: Commander Faulty



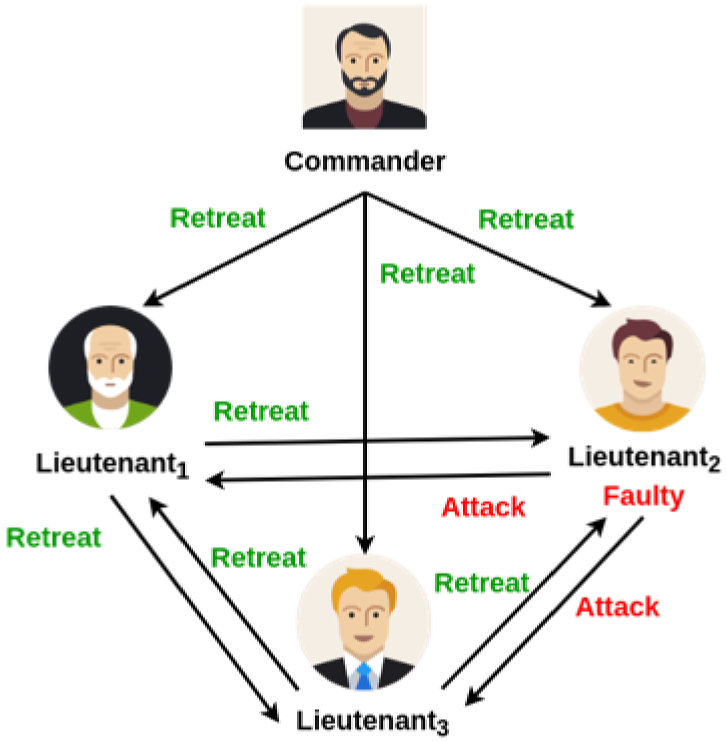
- Lieutenant$_1$ received **differing message**
- By integrity condition, both Lieutenants conclude with Commander's message
- This contradicts the agreement condition
- No solution possible for three generals including one faulty

Four Byzantine Generals Problem: Lieutenant Faulty



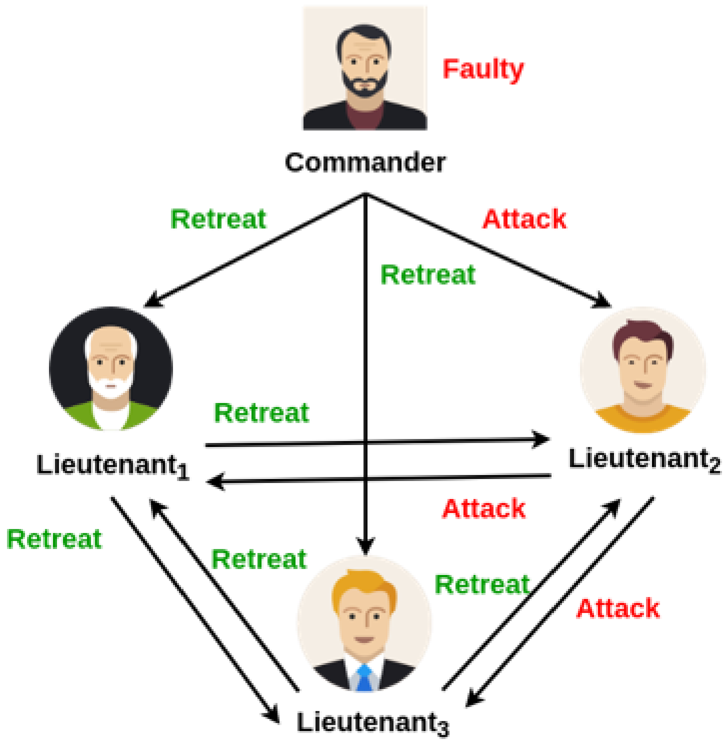
- Round 1:
  - Commander sends a message to each of the Lieutenants
- Round 2:
  - Lieutenant_1 and Lieutenant_3 correctly echo the message to others
  - Lieutenant_2 **incorrectly** echoes to others

Four Byzantine Generals Problem: Lieutenant Faulty



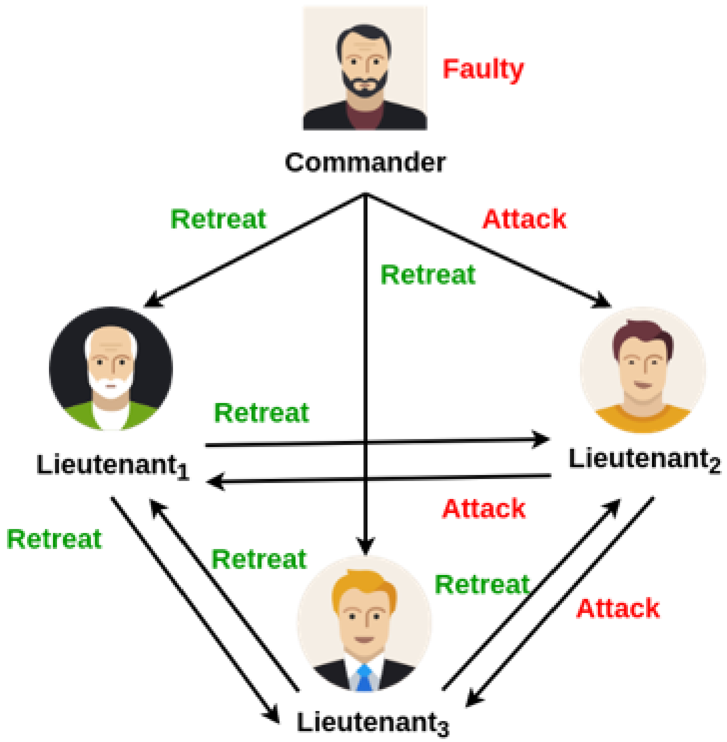
- Lieutenant$_1$ decides on *majority*(Retreat,Attack,Retreat)= Retreat
- Lieutenant$_3$ decides on *majority*(Retreat,Retreat,Attack)= Retreat

Four Byzantine Generals Problem: Commander Faulty



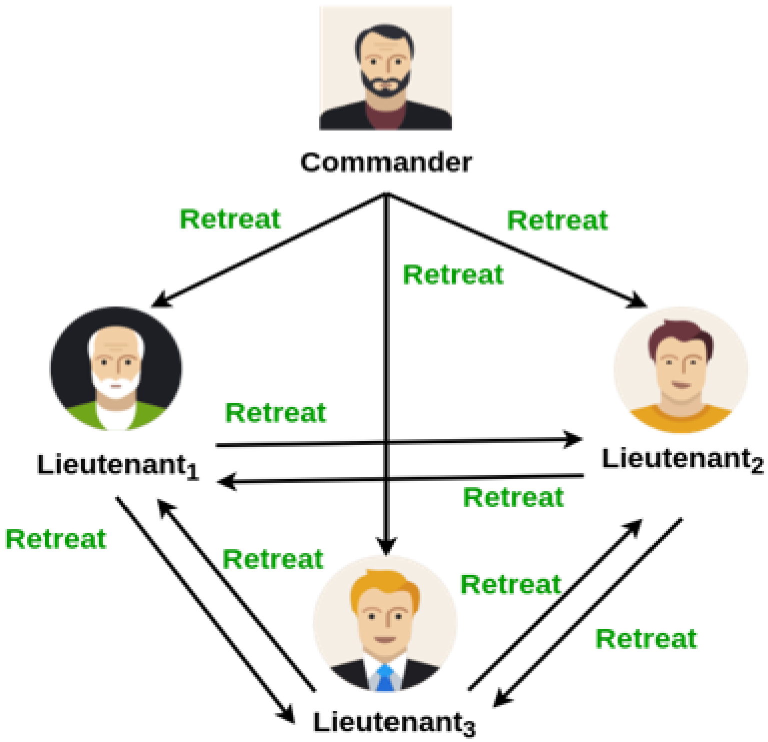
- Round 1:
  - Commander sends differing message to Lieutenants
- Round 2:
  - Lieutenant$_1$, Lieutenant$_2$ and Lieutenant$_3$ correctly echo the message to others

Four Byzantine Generals Problem: Commander Faulty



- Lieutenant$_1$ decides on *majority*(Retreat,Attack,Retreat)= Retreat
- Lieutenant$_2$ decides on *majority*(Attack,Retreat,Retreat)= Retreat
- Lieutenant$_3$ decides on *majority*(Retreat,Retreat,Attack)= Retreat

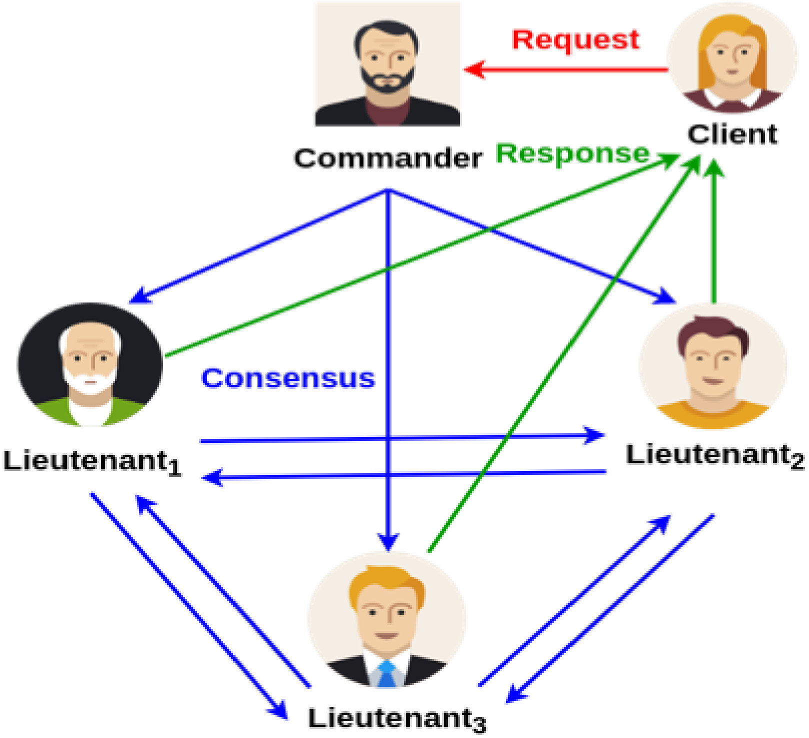
Byzantine Generals Model



- *N* number of process with at most *f* Faulty = 2f+1
- Receiver always knows the identity of the sender
- Fully connected
- Reliable communication medium

Practical Byzantine Fault Tolerant Model

Practical Byzantine Fault Tolerant Model



- Asynchronous distributed system
  - delay, out of order message
- Byzantine failure handling
  - arbitrary node behavior
- Privacy
  - tamper-proof message, authentication

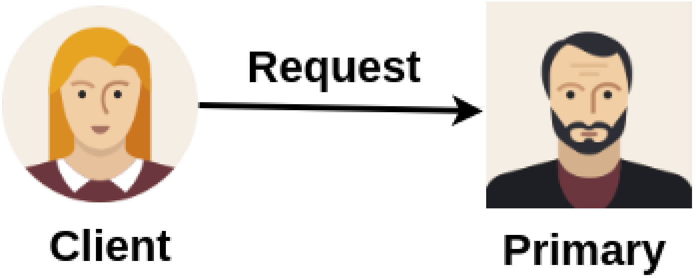
Practical Byzantine Fault Tolerant Model

- $3f + 1$ replicas are there where f is the number of faulty replicas
- The replicas move through a successions of configurations, known as *views*
- One replica in a *view* is *primary* and others are *backups*

Practical Byzantine Fault Tolerant Model

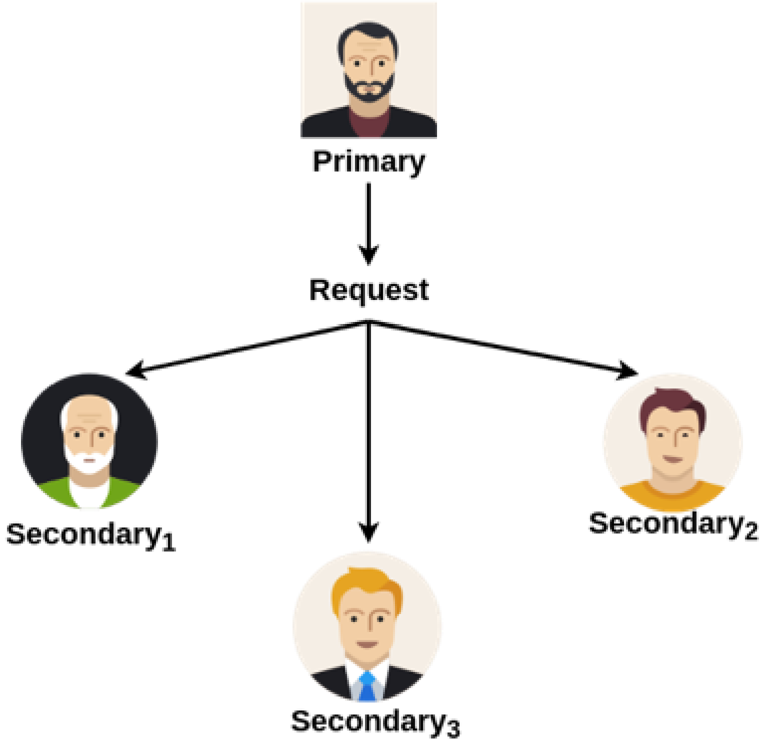
- Views are changed when a *primary* is detected as faulty
- Every view is identified by a unique integer number v
- Only the messages from the current views are accepted

Practical Byzantine Fault Tolerant Algorithm



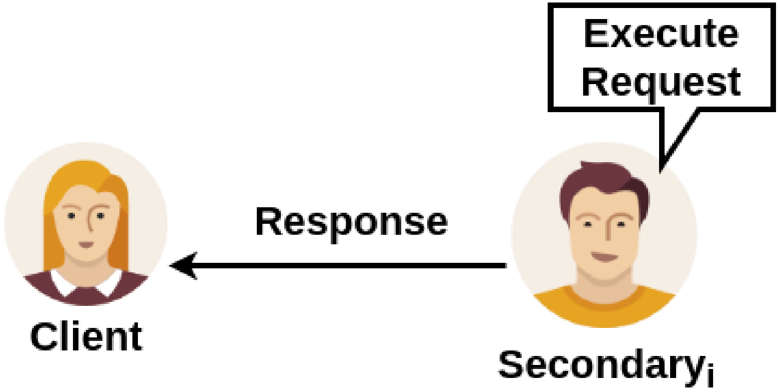
- A client sends a request to invoke a service operation to the primary

Practical Byzantine Fault Tolerant Algorithm



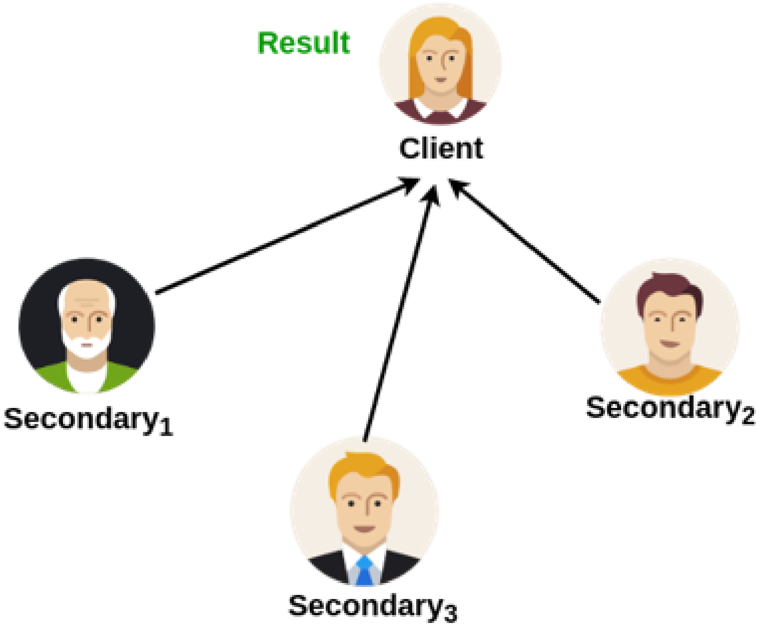
- The primary multicasts the request to the backups/Secondary nodes

Practical Byzantine Fault Tolerant Algorithm



- Backups execute the request and send a reply to the client

Practical Byzantine Fault Tolerant Algorithm

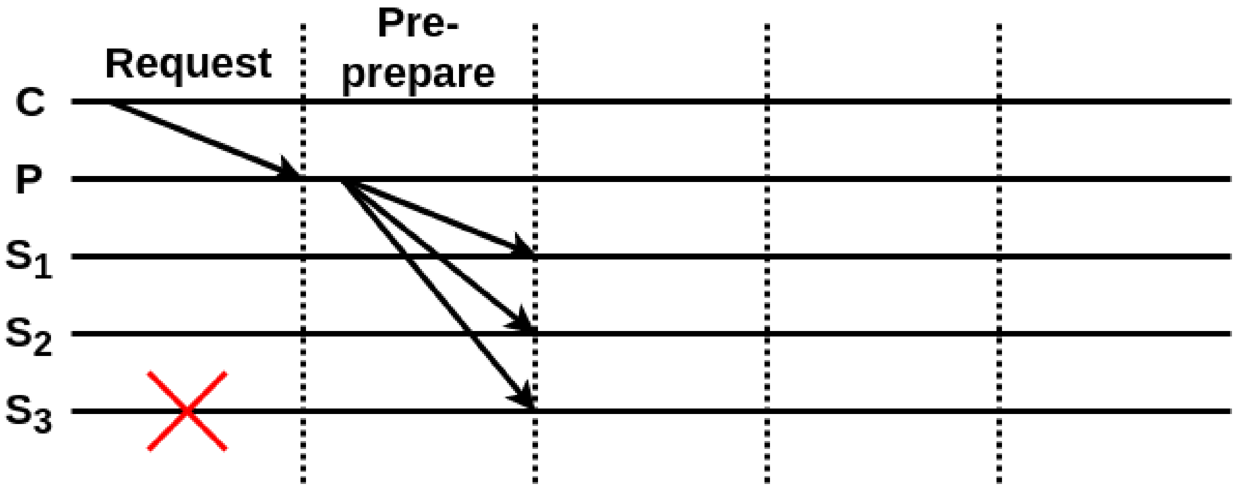


- The client waits for $f + 1$ replies from different backups with the same result
  - f is the maximum number of faulty replicas that can be tolerated

Three Phase Commit Protocol - Pre-Prepare

- **Pre-prepare:** Primary assigns a sequence number n to the request and multicast a message $<< PRE-PREPARE, v, n, d>_{\sigma p}, m >$ to all the backups
  - v is the current view number
  - n is the message sequence number
  - d is the message digest
  - σ_p is the private key of primary - works as a digital signature
  - m is the message to transmit

Three Phase Protocol

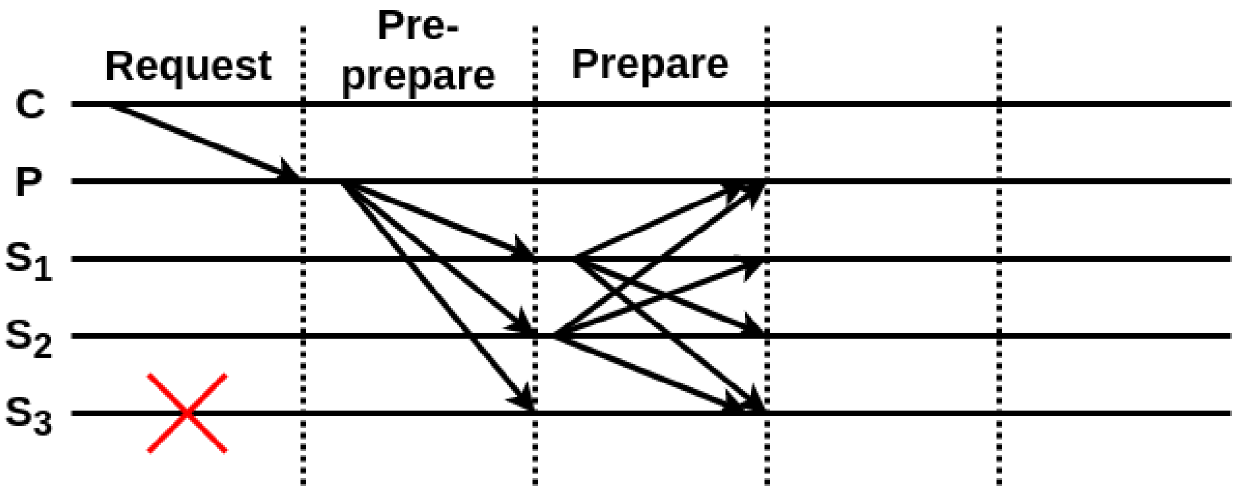


- Pre-prepare:
  - Acknowledge the request by a unique sequence number

Three Phase Commit Protocol - Pre-Prepare

- Pre-prepare messages are used as a proof that request was assigned sequence number n is the view v
- A backup accepts a pre-prepare message if
  - The signature is correct and d is the digest for m
  - The backup is in view v
  - It has not received a different PRE-PREPARE message with sequence n and view v with a different digest
  - The sequence number is within a threshold

Three Phase Protocol



- Prepare:
  - Replicas agree on the assigned sequence number

Three Phase Commit Protocol - Prepare

- If the backup accepts the PRE-PREPARE message, it enters prepare phase by multicasting a message $< PREPARE, v, n, d, i >_{\sigma\_i}$ to all other replicas

- A replica (both primary and backups) accepts prepare messages if
  - Signatures are correct
  - View number equals to the current view
  - Sequence number is within a threshold

Three Phase Commit Protocol

- Pre-prepare and prepare ensure that non-faulty replicas guarantee on a total order for the requests within a view

- Commit a message if
  - $2f$ prepares from different backups matches with the corresponding pre-prepare
  - You have total $2f + 1$ votes (one from primary that you already have!) from the non-faulty replicas

Three Phase Commit Protocol

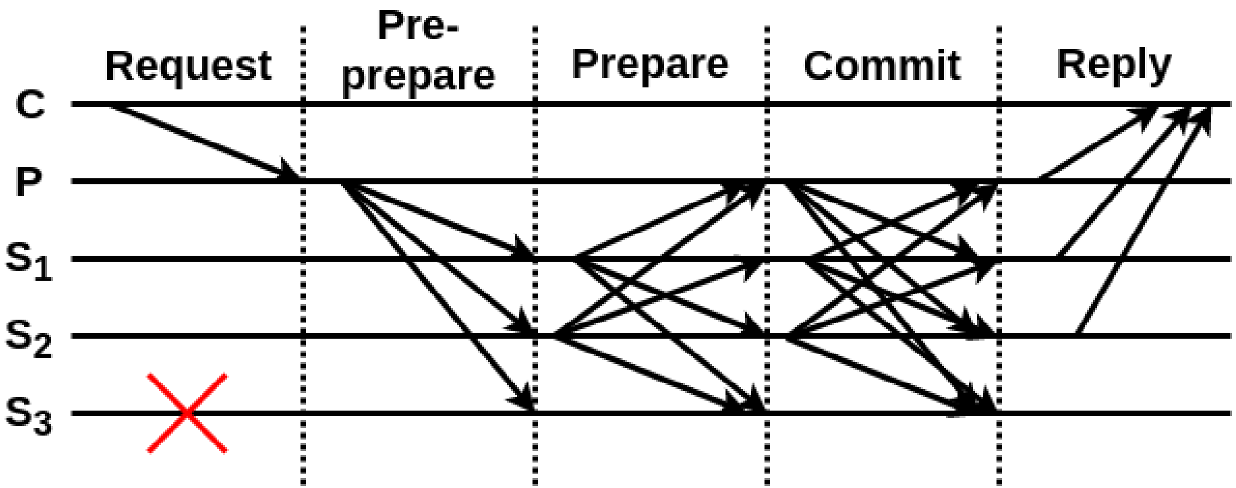
- **Why do you require $3F+1$ replicas to ensure safety in an asynchronous system when there are F faulty nodes?**
  - If you do not receive a vote
    - The node is faulty and not forwarded a vote at all
    - The node is non-faulty, forwarded a vote, but the vote got delayed
  - Majority can be decided once $2f+1$ votes have arrived - even if f are faulty, you know $f+1$ are from correct nodes, do not care about the remaining f votes

Three Phase Commit Protocol - Commit

- Multicast $<\mathrm{COMMIT}, v, n, d, i>_{\sigma\_i}$ message to all the replicas including primary

- Commit a message when a replica
  - Has sent a commit message itself
  - Has received $2f + 1$ commits (including its own)

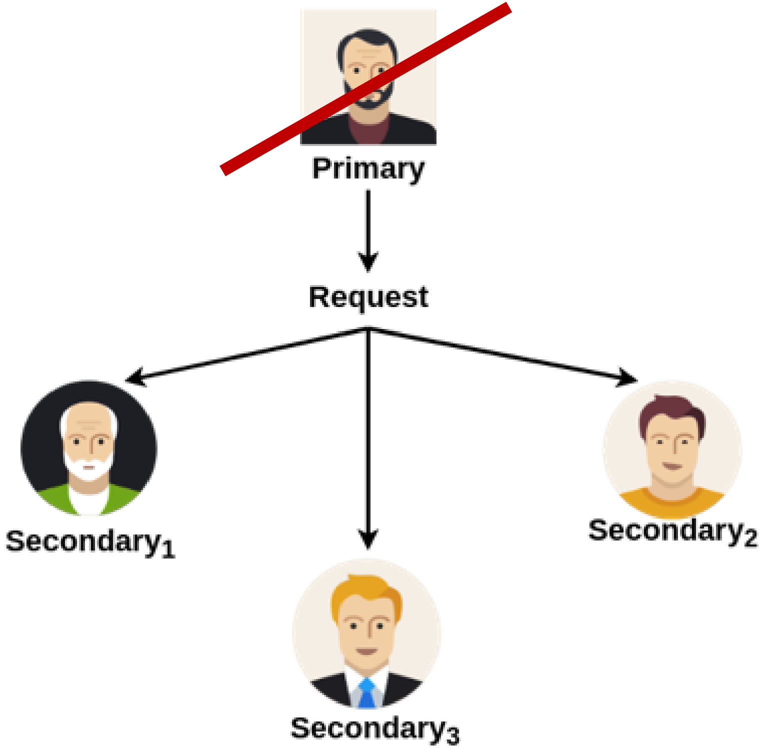
Three Phase Protocol



- Commit:
  - Establish consensus throughout the views

View Change

- What if the **primary** is **faulty**??
  - non-faulty replicas detect the fault
  - replicas together start view change operation



View Changes

- View-change protocol provides **liveness**
  - Allow the system to make progress when primary fails

- If the primary fails, backups will not receive any message (such as PRE_PREPARE or COMMIT) from the primary

- View changes are triggered by timeouts
  - Prevent backups from waiting indefinitely for requests to execute

Practical Byzantine Fault Tolerant

- Why **Practical**?
  - Ensures safety over an asynchronous network Byzantine Failure
  - Low overhead
- **Real Applications**
  - Tendermint
  - IBM's Openchain
  - ErisDB
  - Hyperledger