Distributed Algorithms
Practical Byzantine Fault Tolerance

Alberto Montresor

Università di Trento

2020/12/03

Table of contents

Motivation

- Processes may exhibit arbitrary (Byzantine) behavior
  - Malicious attacks
    - They lie
    - They collude
  - Software error
    - Arbitrary states, messages

Examples

- Amazon outage (2008), "Root cause was a single bit flip in internal state messages"[1]
- Shuttle Mission STS-124 (2008), 3-1 disagreement on sensors during fuel loading (on Earth!)[2]

[2] `http://status.aws.amazon.com/s3-20080720.html`

[2] `https://c3.nasa.gov/dashlink/resources/624/`

History

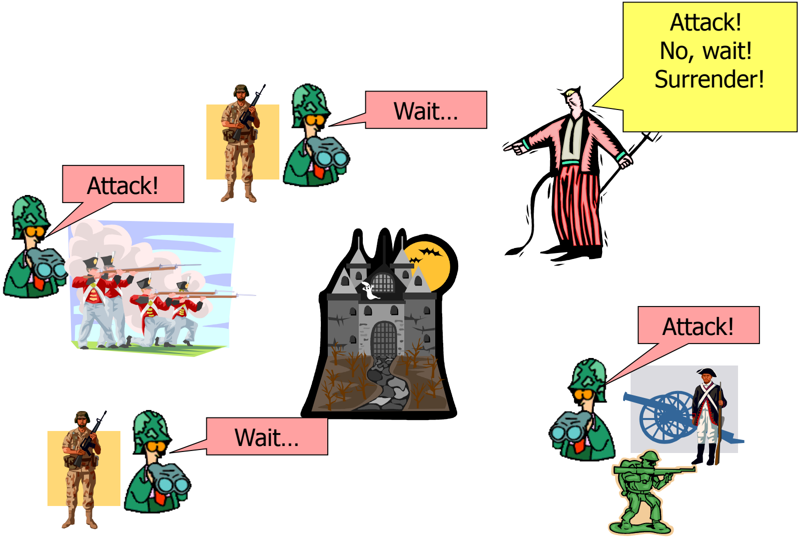
- State-of-the-art at the end of the 90's
  - Theoretically feasible algorithms to tolerate Byzantine failures, but inefficient in practice
  - Assume synchrony – known bounds for message delays and processing speed
  - Most importantly: synchrony assumption needed for correctness – what about DoS?

Bibliography

L. Lamport, R. Shostak, and M. Pease. The Byzantine generals problem. *ACM Transactions on Programming Languages and Systems (TOPLAS)*, 4(3):382–401, 1982.
http://www.disi.unitn.it/~montreso/ds/papers/ByzantineGenerals.pdf

Table of contents

Byzantine generals



Specification

A commanding general must send an order to his $n-1$ lieutenant generals such that:

- **IC1**: All loyal lieutenants obey the same order
- **IC2**: If the commanding general is loyal, then every loyal lieutenant obeys the order he sends

Assumption - "Oral" messages

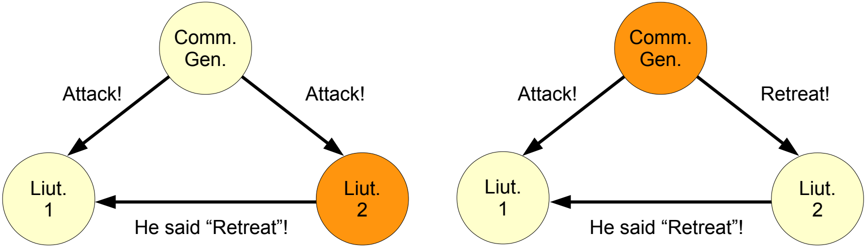
- Every message that is sent is received correctly
- The receiver of a message knows who sent it
- The absence of a message can be detected

Assumption - "Oral" messages

- Every message that is sent is received correctly
  Reliability
- The receiver of a message knows who sent it
  Symmetric encryption
- The absence of a message can be detected
  Synchrony

Impossibility results

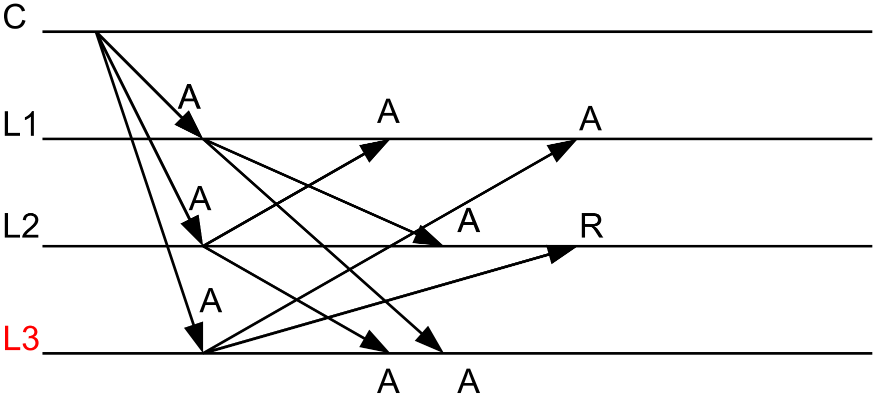
Under the "Oral" messages assumption, no solution with three generals can handle even a single traitor



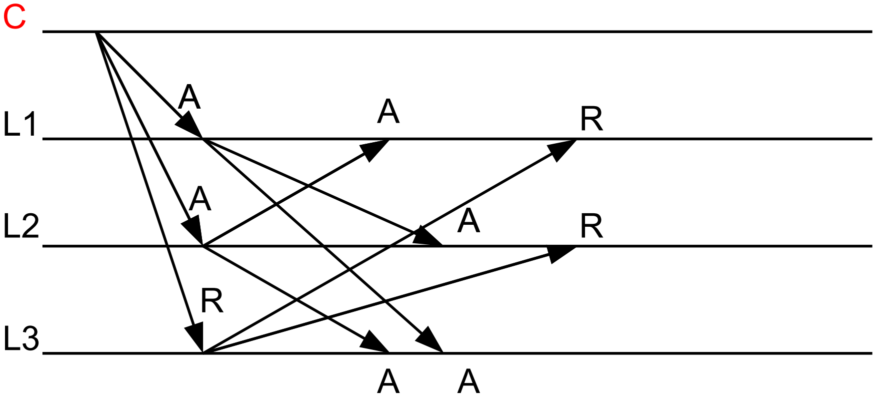
"Oral Message" algorithm $OM(m)$

- Algorithm $OM(0)$
  1. The commander sends its value to every lieutenant
  2. Each lieutenant uses the value he received from commander, or uses RETREAT if he received no value
- Algorithm $OM(m)$
  1. The commander sends its value to every lieutenant
  2. $\forall i$, let v_i be the value lieutenant i receives from the commander, or RETREAT if it has received no value. Lieutenant i acts as the commander of algorithm $OM(m-1)$ to send the value v_i to each of the other $n-2$ other lieutenants
  3. $\forall j \neq i$, let v_j be the value received by i from j in Step 2 of algorithm $OM(m-1)$ or RETREAT if no value. Lieutenant i uses the value $\mathsf{majority}(v_1, ..., v_{n-1})$ (deterministic function)

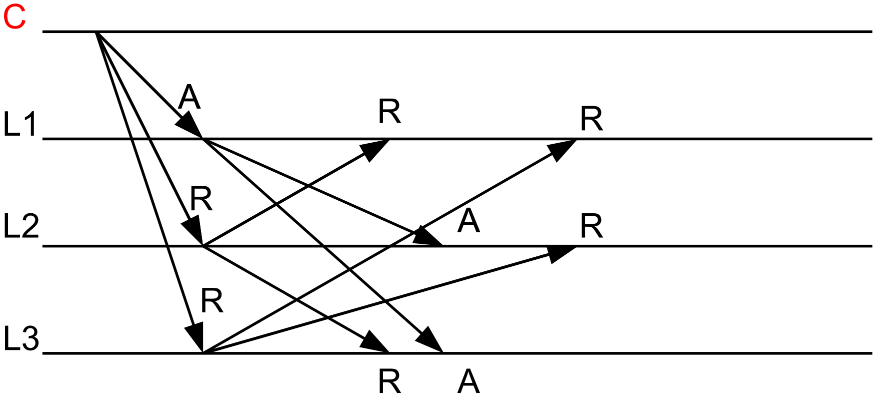
“Oral Message” Algorithm Examples – $OM(1)$



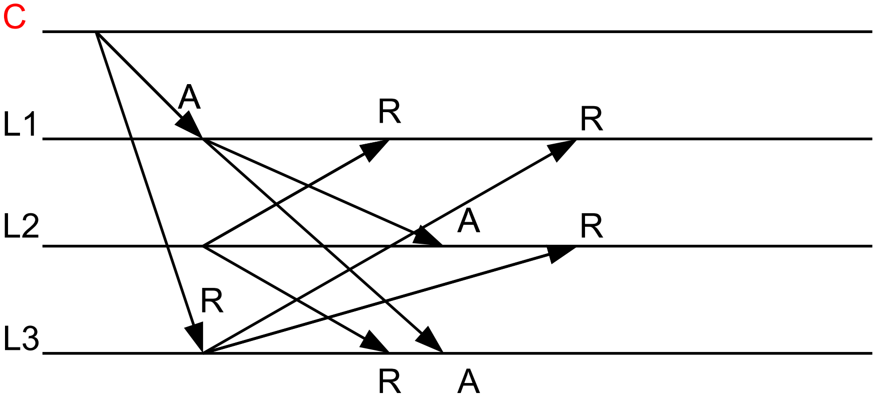
"Oral Message" Algorithm Examples – $OM(1)$



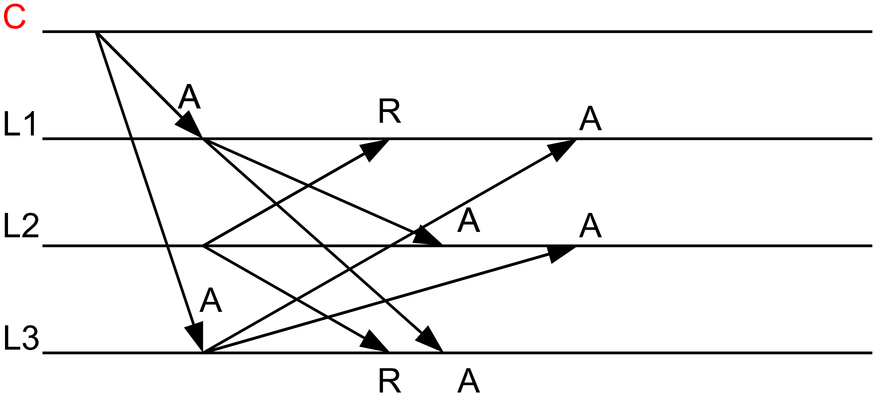
"Oral Message" Algorithm Examples – $OM(1)$



"Oral Message" Algorithm Examples – $OM(1)$



"Oral Message" Algorithm Examples – $OM(1)$



Formal proof

Theorem: Necessary Condition

For any $m > 1$, no solution with fewer than $3m+1$ generals can cope with m traitors.

Theorem: Correctness

For any m, Algorithm $OM(m)$ satisfies conditions **IC1** and **IC2** if there are $3m+1$ generals or more and at most m traitors

Necessary Condition – Proof by contradiction

Theorem: Necessary Condition

For any $m > 1$, no solution with fewer than $3m + 1$ generals can cope with m traitors.

- Let's assume that such solution exists.
- We can transform it in a solution for $m = 1$ and 3 machines, which cannot exist (see above)
- Transformation:
  - three machines "simulate" m generals each; so we have $3m$ generals
  - since one machine can be traitorous, at most m generals are traitorous
  - we use the solution to obtain a decision
  - we use this decision to solve the problem with 3 machines, $m = 1$

Lemma - By induction on m

Lemma 1

For any m and k, Algorithm $OM(m)$ satisfies condition **IC2** if there are more than $2k + m$ generals and at most k traitors

- Base case $m = 0$, with $k = m = 0$ traitors
  - Due to oral messages, $OM(0)$ trivially satisfies IC2
- Induction hypothesis: $OM(m-1)$ is correct
  - Each $OM(m-1)$ protocol involves $n-1$ generals
  - $OM(m-1)$ is correct if at most k generals are traitorous, and there are more than $2k + (m-1)$ generals:

$$n - 1 > 2k + (m - 1)$$

Lemma - By induction on m

Lemma 1

For any m and k, Algorithm $OM(m)$ satisfies condition **IC2** if there are more than $2k + m$ generals and at most k traitors

- Induction $m > 0$, with max k traitors
  - The loyal commander sends v to all $n - 1$ liutenents
  - All loyal liutenents send v using $OM(m - 1)$
  - Since $n > 2k + m$, we have

$$n - 1 > 2k + m - 1 = 2k + (m - 1)$$

  - We can thus apply the induction hypothesis: every loyal liutenent i gets $v_j = v$ for each loyal liutenent j
  - In $OM(m - 1)$, traitorous generals $\leq k$, loyal generals $\geq n - 1 - k$
  - There is a majority of loyal generals if

$$n - 1 - k > k \Leftrightarrow n - 1 > 2k$$

which is true because $n - 1 > 2k + (m - 1) \geq 2k$ for $m \geq 1$

Correctness

Theorem: Correctness

For any m, Algorithm $OM(m)$ satisfies conditions **IC1** and **IC2** if there are $3m + 1$ generals or more and at most m traitors

IC2:

- Since we have at most $k = m$ traitors, by Lemma 1 we have IC2 is satisfied if $n > 2k + m = 3m$

IC1 - Loyal commander:

- By IC2 all loyal liutenents follow the order sent by the commander, so IC1 is satisfied

Correctness

Theorem: Correctness

For any m, Algorithm $OM(m)$ satisfies conditions **IC1** and **IC2** if there are $3m+1$ generals or more and at most m traitors

IC1 - Traitorous commander – we prove it by induction on m

- Base case $m = 0$: $OM(0)$ satisfies both $IC1$ and $IC2$
- Induction hypothesis:
  - $O(m-1)$ is correct with $> 3(m-1)$ generals and $\leq m-1$ traitors
- Induction:
  - There are more than $3m-1$ liutenents
  - At most $m-1$ liutenents are traitors
  - So, we can apply induction and $O(m-1)$ is correct
  - Every loyal liutenent will receive the same values from the loyal liutenents and will decide the same majority

Problems with this approach

- Message paths of length up to $m + 1$ (expensive)
- Absence of messages must be detected via time-out (vulnerable to DoS)

An attacker may compromise the safety of a service by delaying non-faulty nodes or the communication between them until they are tagged as faulty and excluded from the replica group. Such a denial-of-service attack is generally easier than gaining control over a non-faulty node.

Signed messages

- A loyal general's signature cannot be forged, and any alteration of the contents of his signed messages can be detected
- Anyone can verify the authenticity of a general's signature

Algorithm $SM(m)$

For any m, Algorithm $SM(m)$ solves the Byzantine Generals Problem if there are at most m traitors.

Table of contents

A Byzantine “renaissance”

Bibliography

M. Castro and B. Liskov. Practical Byzantine fault tolerance and proactive recovery.
ACM Trans. Comput. Syst., 20:398–461, Nov. 2002.
http://www.disi.unitn.it/~montreso/ds/papers/PbftTocs.pdf

Contributions

- First state machine replication protocol that survives Byzantine faults in asynchronous networks
- Live under weak Byzantine assumptions – Byzantine Paxos/Raft!
- Implementation of a Byzantine, fault tolerant distributed FS
- Experiments measuring cost of replication technique

Assumptions

- System model
  - Asynchronous distributed system with N processes
  - Unreliable channels
- Unbreakable cryptography
  - Message m is signed by its sender i, and we write $\langle m \rangle_{\sigma(i)}$, through:
    - Public/private key pairs
    - Message authentication codes (MAC)
  - A digest $d(m)$ of message m is produced through collision-resistant hash functions

Assumptions

- Failure model
  - Up to f Byzantine servers
  - $N > 3f$ total servers
  - (Potentially Byzantine clients)
- Independent failures
  - Different implementations of the service
  - Different operating systems
  - Different root passwords, different administrator

Specification

- State machine replication
  - Replicated service with a state and deterministic operations operating on it
  - Clients issue a request and block waiting for reply
- Safety
  - The system satisfies linearizability, provided that $N > 3f + 1$
  - Regardless of "faulty clients"...
    - all operations performed by faulty clients are observed in a consistent way by non-faulty clients
  - The algorithm does not rely on synchrony to provide safety...
- Liveness
  - It relies on synchrony to provide liveness
  - Assumes $delay(t)$ does not grow faster than t indefinitely
  - Weak assumption – if network faults are eventually repaired
  - Circumvent the impossibility results of FLP

Optimality

Theorem

To tolerate up to f malicious nodes, N must be equal to $3f + 1$

Proof

Optimality

Theorem

To tolerate up to f malicious nodes, N must be equal to $3f + 1$

Proof

- It must be possible to proceed after communicating with $N - f$ replicas, because the faulty replicas may not respond

Optimality

Theorem

To tolerate up to f malicious nodes, N must be equal to $3f + 1$

Proof

- It must be possible to proceed after communicating with $N - f$ replicas, because the faulty replicas may not respond
- But the f replicas not responding may be just slow, so f of those that responded might be faulty

Optimality

Theorem

To tolerate up to f malicious nodes, N must be equal to $3f + 1$

Proof

- It must be possible to proceed after communicating with $N - f$ replicas, because the faulty replicas may not respond
- But the f replicas not responding may be just slow, so f of those that responded might be faulty
- The correct replicas who responded $(N - 2f)$ must outnumber the faulty replicas, so

$$N - 2f > f \Rightarrow N > 3f$$

Optimality

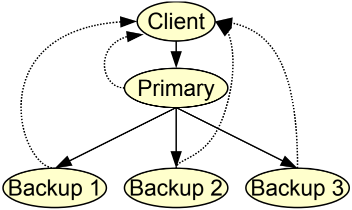
- So, $N > 3f$ to ensure that at least a correct replica is present in the reply set
- $N = 3f + 1$; more is useless
  - more and larger messages
  - without improving resiliency

Processes and views

- Replicas IDs: $0 \dots N-1$
- Replicas move through a sequence of configurations called views
- During view v:
  - Primary replica is i: $i = v \bmod N$
  - The other are backups
- View changes are carried out when the primary appears to have failed

The algorithm

- To invoke an operation, the client sends a request to the primary
- The primary multicasts the request to the backups
- Quorums are employed to guarantee ordering on operations
- When an order has been agreed, replicas execute the request and send a reply to the client
- When the client receives at least $f + 1$ identical replies, it is satisfied

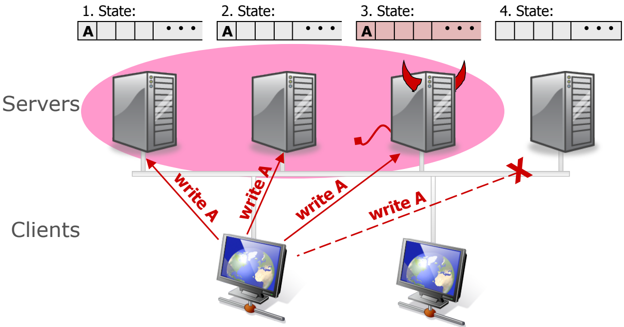


Problems

- The primary could be faulty!
  - could ignore commands; assign same sequence number to different requests; skip sequence numbers; etc
  - backups monitor primary's behavior and trigger view changes to replace faulty primary
- Backups could be faulty!
  - could incorrectly store commands forwarded by a correct primary
  - use dissemination Byzantine quorum systems
- Faulty replicas could incorrectly respond to the client!
  - Client waits for $f + 1$ matching replies before accepting response

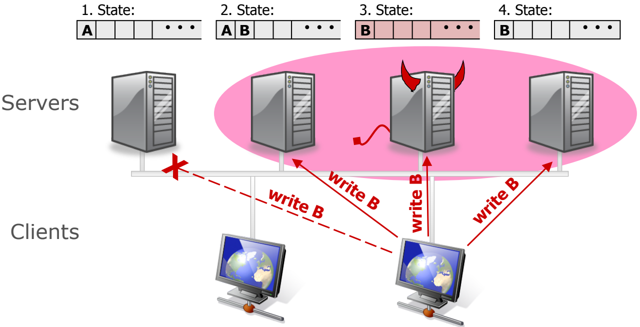
The general idea

- Algorithm steps are justified by certificates
  - Sets (quorums) of signed messages from distinct replicas proving that a property of interest holds
- With quorums of size at least $2f + 1$
  - Any two quorums intersect in at least one correct replica
  - There is always one quorum that contains only non-faulty replicas



The general idea

- Algorithm steps are justified by certificates
  - Sets (quorums) of signed messages from distinct replicas proving that a property of interest holds
- With quorums of size at least $2f + 1$
  - Any two quorums intersect in at least one correct replica
  - There is always one quorum that contains only non-faulty replicas



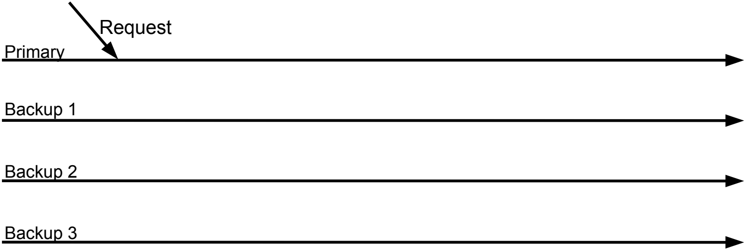
Protocol schema

- Normal operation
  - How the protocol works in the absence of failures
  - hopefully, the common case
- View changes
  - How to depose a faulty primary and elect a new one
- Garbage collection
  - How to reclaim the storage used to keep certificates
- Recovery
  - How to make a faulty replica behave correctly again (not here)

State

- The internal state of each of the replicas include:
  - the state of the actual service
  - a message log containing all the messages the replica has accepted
  - an integer denoting the replica current view

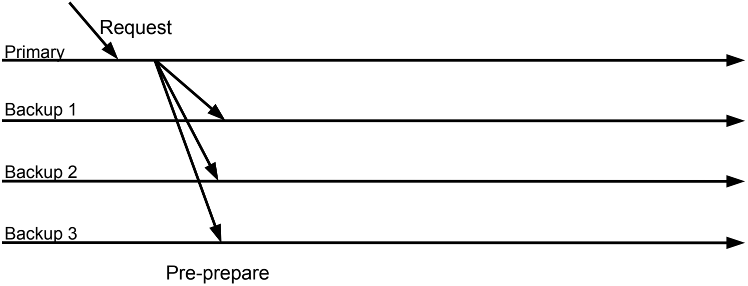
Client request



$\langle \text{REQUEST}, o, t, c \rangle_{\sigma(c)}$

- o: state machine operation
- t: timestamp (used to ensure exactly-once semantics)
- c: client id
- $\sigma(c)$: client signature

Pre-prepare phase



$\langle\langle \textsc{pre-prepare}, v, n, d(m)\rangle_{\sigma(p)}, m\rangle$

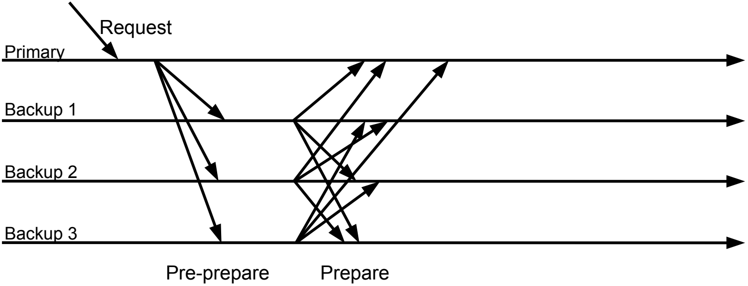
- v: current view
- n: sequence number
- $d(m)$: digest of client message
- $\sigma(p)$: primary signature
- m: client message

Pre-prepare phase

$\langle\langle \textsc{pre-prepare}, v, n, d(m)\rangle_{\sigma(p)}, m\rangle$

- Correct replica i accepts PRE-PREPARE if:
    - the PRE-PREPARE message is well-formed
    - the current view of i is v
    - i has not accepted another PRE-PREPARE for $\langle v, n\rangle$ with a different digest
    - n is between two water-marks L and H
      (to avoid sequence number exhaustion caused by faulty primaries)
- Each accepted PRE-PREPARE message is stored in the accepting replica's message log (including the primary's)
- Non-accepted PRE-PREPARE messages are just discarded

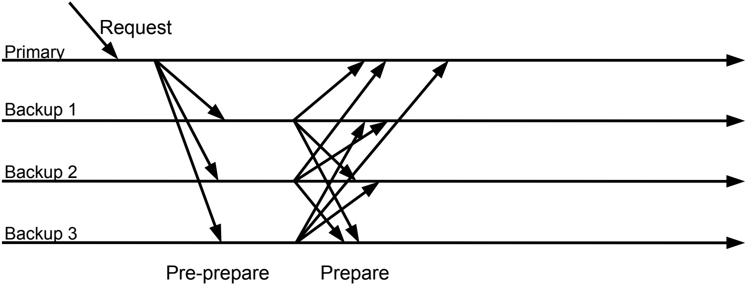
Prepare phase



$\langle \text{PREPARE}, v, n, d(m) \rangle_{\sigma(i)}$

- Accepted by correct replica j if:
  - the PREPARE message is well-formed
  - current view of j is v
  - n is between two water-marks L and H

Prepare phase



$\langle \text{PREPARE}, v, n, d(m) \rangle_{\sigma(i)}$

- Replicas that send PREPARE accept the sequence number n for m in view v
- Each accepted PREPARE message is stored in the accepting replica's message log

Prepare certificate (P-certificate)

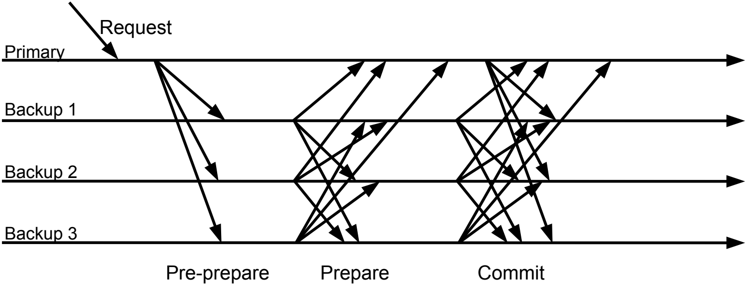
- Replica i produces a prepare certificate **prepared**(m, v, n, i) iff its log holds:
  - The request m
  - A PRE-PREPARE for m in view v with sequence number n
  - Log contains $2f$ PREPARE messages from different backups that match the PRE-PREPARE
- **prepared**(m, v, n, i) means that a quorum of $(2f + 1)$ replicas agrees with assigning sequence number n to m in view v

Theorem

There are no two non-faulty replicas i, j such that **prepared**(m, v, n, i) and **prepared**(m', v, n, j), with $m \neq m'$

Proof?

Commit phase



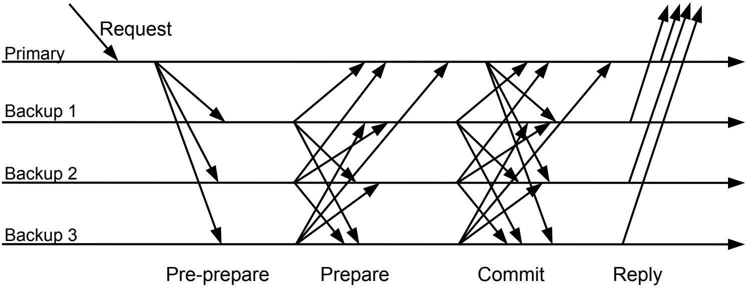
$\langle \text{COMMIT}, v, n, d(m), i \rangle_{\sigma(i)}$

- After having collected a P-certificate **prepared**(m, v, n, i), replica i sends a COMMIT message
- Accepted if:
  - The COMMIT message is well-formed
  - Current view of i is v
  - n is between two water-marks L and H

Commit certificate (C-Certificate)

- Commit certificates ensure total order across views
  - we guarantee that we can't miss prepare certificates during a view change
- A replica has a certificate **committed**(m, v, n, i) if:
  - it had a P-certificate **prepared**(m, v, n, i)
  - log contains $2f + 1$ matching COMMIT from different replicas (possibly including its own)
- Replica executes a request after it gets commit certificate for it, and has cleared all requests with smaller sequence numbers

Reply phase



$\langle \text{REPLY}, v, t, c, i, r \rangle_{\sigma(i)}$

- r is the reply
- Client waits for $f + 1$ replies with the same t, r
- If the client does not receive replies soon enough, it broadcast the request to all replicas

View change

- A un-satisfied replica backup i mutinies:
  - stops accepting messages (except VIEW-CHANGE and NEW-VIEW)
  - multicasts $\langle \text{VIEW-CHANGE}, v+1, P, i\rangle_{\sigma(i)}$
  - P contains a P-certificate P_m for each request m (up to a given number, see garbage collection)
- Mutiny succeeds if the new primary collects a new-view certificate V:
  - a set containing $2f+1$ VIEW-CHANGE messages
  - indicating that $2f+1$ distinct replicas (including itself) support the change of leadership

View change

The "primary elect" p' (replica $v + 1 \bmod N$):

- extracts from the new-view certificate V the highest sequence number h of any message for which V contains a P-certificate
- creates a new PRE-PREPARE message for any client message m with sequence number $n \leq h$ and add it to the set O
  - if there is a P-certificate for n, m in V

$$O \leftarrow O \cup \langle \text{PRE-PREPARE}, v+1, n, d_m \rangle_{\sigma(p')}$$

  - Otherwise

$$O \leftarrow O \cup \langle \text{PRE-PREPARE}, v+1, n, d_{null} \rangle_{\sigma(p')}$$

- p' multicasts $\langle \text{NEW-VIEW}, v+1, V, O \rangle_{\sigma(p')}$

View change

- Backup accepts a $\langle \textsc{new-view}, v+1, V, O \rangle_{\sigma(p')}$ message for $v+1$ if
  - it is signed properly by p'
  - V contains valid VIEW-CHANGE messages for $v+1$
  - the correctness of O can be locally verified (repeating the primary's computation)
- Actions:
  - Adds all entries in O to its log (so did p'!)
  - Multicasts a PREPARE for each message in O
  - Adds all PREPAREs to the log and enters new view

Garbage collection

- A correct replica keeps in log messages about request o until:
  - o has been executed by a majority of correct replicas, and
  - this fact can proven during a view change
- Truncate log with stable checkpoints
  - Each replica i periodically (after processing k requests) checkpoints state and multicasts $\langle \text{CHECKPOINT}, n, d, i \rangle$
    - n: last executed request
    - d: state digest
- A set S containing $2f + 1$ equivalent CHECKPOINT messages from distinct processes are a proof of the checkpoint's correctness (stable checkpoint certificate)

View Change, revisited

- Message $\langle \text{VIEW-CHANGE}, v+1, n, S, C, P, i \rangle_{\sigma(i)}$
  - n: the sequence number of the last stable checkpoint
  - S: the last stable checkpoint
  - C: the checkpoint certificate ($2f+1$ checkpoint messages)
- Message $\langle \text{NEW-VIEW}, v+1, n, V, O \rangle_{\sigma(p')}$
  - n: the sequence number of the last stable checkpoint
  - V, O: contains only requests with sequence number larger than n

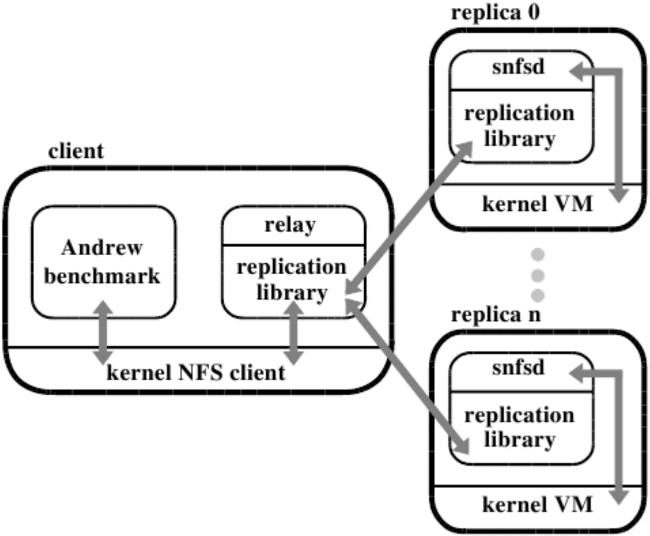
Optimizations

- Reducing replies
    - One replica designated to send reply to client
    - Other replicas send digest of the reply
- Lower latency for writes (4 messages)
    - Replicas respond at Prepare phase (tentative execution)
    - Client waits for $2f + 1$ matching responses
- Fast reads (one round trip)
    - Client sends to all; they respond immediately
    - Client waits for $2f + 1$ matching responses

Optimizations: cryptography

- Reducing overhead
  - Public-key cryptography only for view changes
  - MACs (message authentication codes) for all other messages
- To give an idea (Pentium 200Mhz)
  - Generating 1024-bit RSA signature of a MD5 digest: 43ms
  - Generating a MAC of the same message: 10μs

Application: Byzantine NFS server



Application: Byzantine NFS server

phase	BFS		NFS-std
	strict	r/o lookup	
1	0.55 (-69%)	0.47 (-73%)	1.75
2	9.24 (-2%)	7.91 (-16%)	9.46
3	7.24 (35%)	6.45 (20%)	5.36
4	8.77 (32%)	7.87 (19%)	6.60
5	38.68 (-2%)	38.38 (-2%)	39.35
total	64.48 (3%)	61.07 (-2%)	62.52

Table 3: Andrew benchmark: BFS vs NFS-std. The times are in seconds.

Reality Check

Example of systems that have adopted Byzantine Fault Tolerance:

- Boeing 777 Aircraft Information Management System
- Boeing 777/787 flight control system
- SpaceX Dragon flight control system