Byzantine fault tolerance

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Byzantine Generals and fault tolerance

- Overview and definition
- Naive solutions
- Solution with oral messages
- Solution with signed messages
- Communication paths
- Practical considerations

Motivation

- Coping with failures in distributed systems
- Failed component sends conflicting information
- No apriori assumption on behavior of faulty components
- Need for agreement in the presence of faults

Problem definition

- Each division of the Byzantine army is directed by its own General(computer components)
- There are n Generals some of whom are traitors
- Communicate with each other by messengers
- Unanimous agreement to ATTACK

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Naive solution

- G(i) sends v(i) to all other G
- All G combine their information v(1),v(2)....v(n) the same way
- Majority (v(1)...v(n)) agree on ATTACK ,else RETREAT
- Ignore minority traitors

Naive solution does not work!!

- Traitors may send different values to different G
- Loyal G may get conflicting values from traitors
- Any two loyal generals must use the same value of v(i) to decide on the same plan of action
- *Reduce the problem to General sending his orders to (n-1) other Lieutenants*

Consistency

- Interactive consistency1: All loyal lieutenants obey the same order
- Interactive consistency2:If G is loyal, then each L(i) obeys the order i.e IC1 implies IC2

3-General impossibility

- 3 Generals,one traitor among them
- Two messages: Attack or Retreat
- IMPOSSIBLE to satisfy both IC1 and IC2

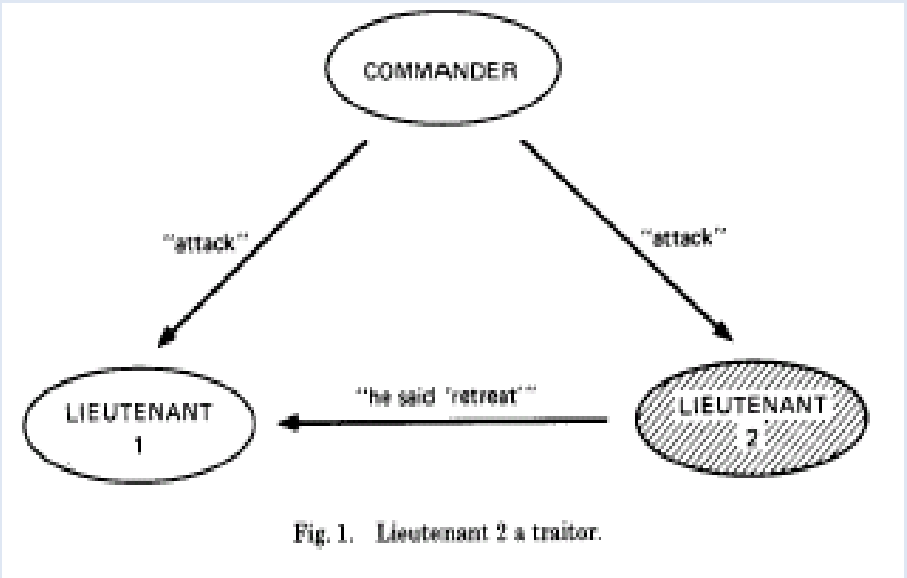

Fig. 1. Lieutenant 2 a traitor.

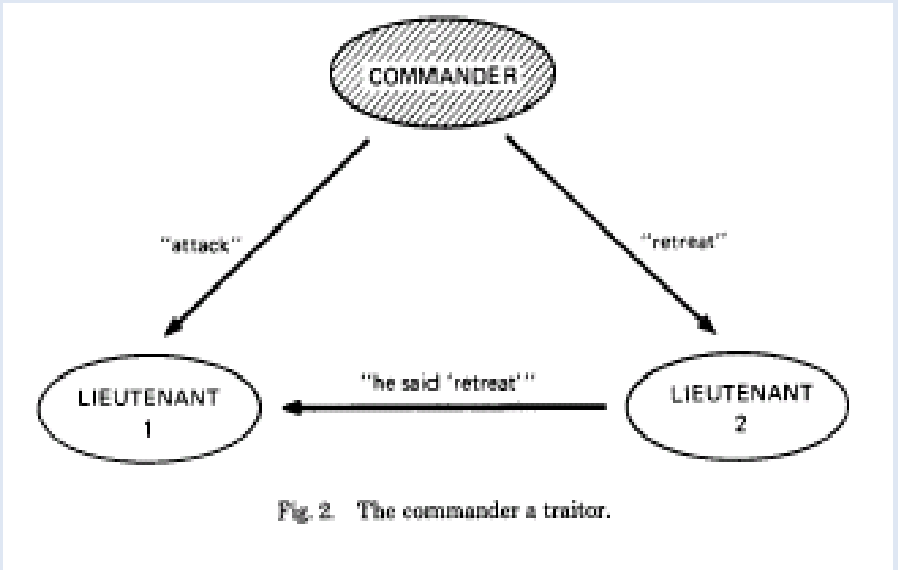

Fig. 2. The commander a traitor.

n-General Impossibility

- Theorem1: No solution with fewer than 3n+1 generals can cope with n traitors
- Proof: By contradiction, assume there is a solution for a group of 3n or fewer and use it to construct a 3-G solution to BGP that works with one traitor
- But this is impossible. Hence the initial assumption was wrong
- Q.E.D!

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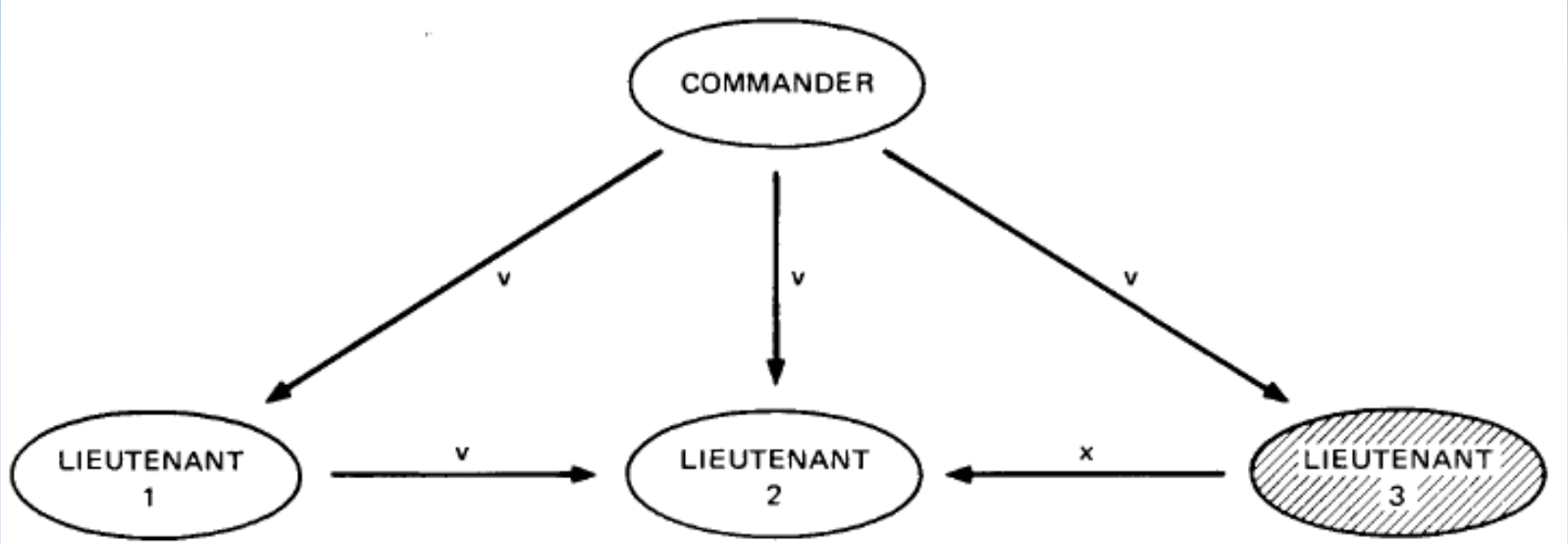
Solution with Oral messages

- Sending of content is entirely under the control of sender
- Each message sent is delivered correctly(A1)
- Receiver of message knows who sent it(A2)
- Absence of message can be detected(A3)

Oral solutions(cont)

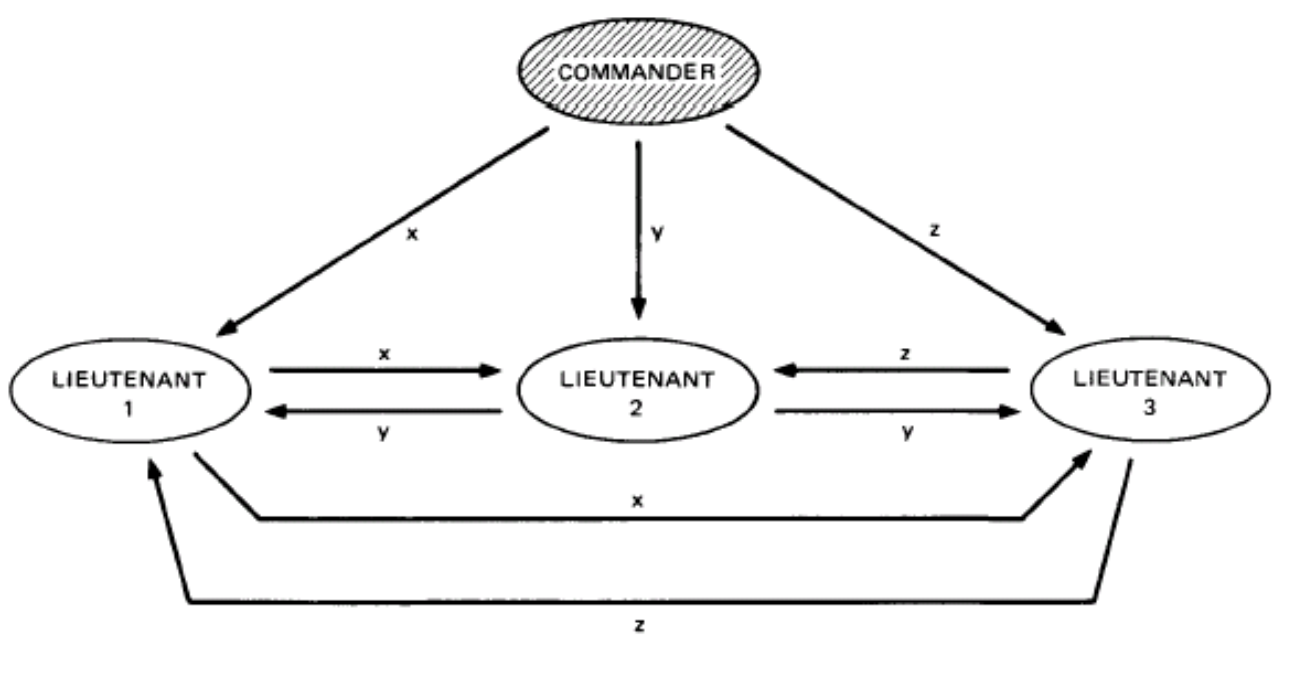
- OM(m=0)
  - Commander send his value to every lieutenant.
  - Each lieutenant (L) use the value received from commander, or RETREAT if no value is received.
- Algorithm OM(m), m>0
  - Commander sends his value to every Lieutenant
  - Each Lieutenant acts as commander for OM(m-1) and sends v(i) to the other n-2 lieutenants (or RETREAT)
  - For each i, and each j not equals i, let v(j) be the value lieutenant i receives from lieutenant j in step (2) using OM(m-1). Lieutenant i uses the value majority (v(1),v(2)....,v(n-1)).

Example (n=4, m=1)



- Algorithm OM(1): L3 is a traitor.
- L1 and L2 both receive v,v,x. (IC1 is met.)
- IC2 is met because L1 and L2 obeys C

Example (n=4, m=1)



- Algorithm OM(1): Commander is a traitor.
- All lieutenants receive x,y,z. (IC1 is met).
- IC2 is irrelevant since commander is a traitor.

Complexity

- OM(m-1) invokes n-2 OM(m-2)
- OM(m-2) invokes n-3 OM(m-3)
- …
- OM(m-k) will be called (n-1)…(n-k) times
- OM(m) invokes n-1 OM(m-1)
- $O(n^m)$ – algorithm grows exponentially to number of failures-Expensive!

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Solution II: Signed messages

- Additional Assumption A4:
  - A loyal general's signature cannot be forged.
  - Anyone can verify authenticity of general's signature.
- Use a function *choice(…)* to obtain a single order

Signed Messages (Cont)

- The commander sends a signed order to lieutenants
- A lieutenant receives an order from someone (either from commander or other lieutenants),
  - Verifies authenticity and puts it in V.
  - If there are less than m *distinct* signatures on the order
    - Augments orders with signature
    - Relays messages to lieutenants who have not seen the order.
- Use choice(V) as the desired action.

Example-Signed messages

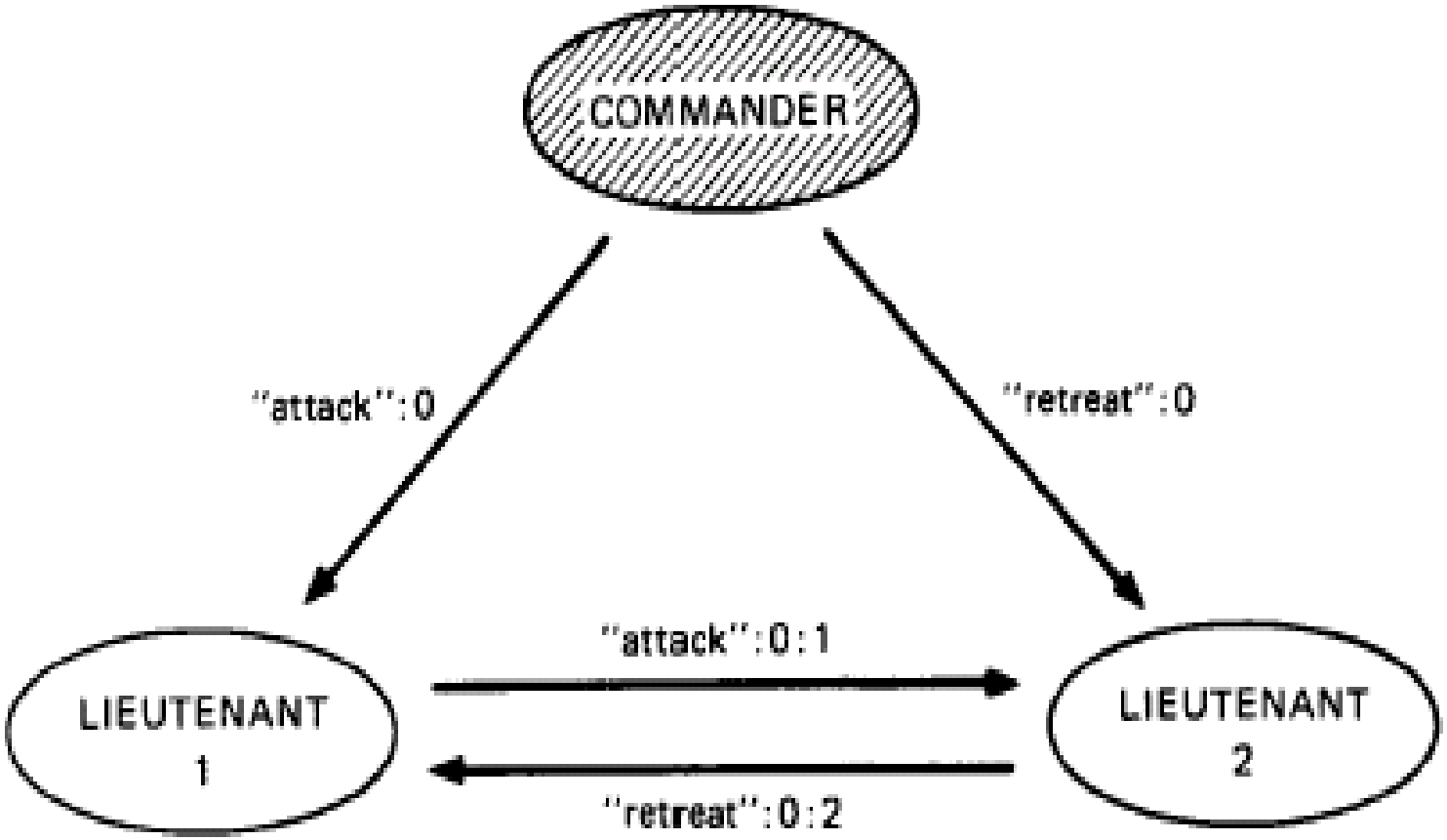

Fig. 5. Algorithm SM(1); the commander a traitor.

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Missing communication paths

- Nature of processor graph
- Strong connectivity: The graph be 3m-regular
- Strong connectivity is impractical
- Weakest connectivity requirement: Subgraph formed by the loyal generals be connected

Practical Considerations

- What does it take for majority voting to work?
  - Non-faulty processors to produce same outputs (IC1)
  - If input unit (commander) is non-faulty ,all non-faulty processes use the value it provides as input (IC2)
- A1 – Every message sent by non-faulty process is delivered correctly.
  - Failure of communication line cannot be distinguished from failure of nodes.
  - OK because we still are tolerating m failures.
- A2 – Processor can determine origin of message
  - Use of signatures(A4)

Practical Considerations(Cont)

- A3 – Absence of a message can be detected.
  - Timeouts
  - Synchronized clocks
- A4 – Unforgeable signatures.
  - Anyone can verify Sig

Concluding thoughts

- BGP solutions are expensive (communication overheads and signatures)
- Use of redundancy and voting to achieve reliability.
- What if >1/3 nodes (processors) are faulty?
- 3m+1 replicas for m failures. Is that expensive?
- Tradeoffs between reliability and performance
- Nature of processor graph

Practical Byzantine fault tolerance

- Miguel Castro and Barbara Liskov

Byzantine research

- 1980-Reaching agreement in presence of faults-Lamport,Pease,Shostak
- 1982-Byzantine Generals problem-Lamport et.al
- 1983-Byzantine Generals strike again-Dolev
- 1983-Randomized Byzantine generals-Rabin
- 1988-ViewStamped replication-Liskov et.al

Byzantine research-1990's

- 1992-Optimal async Byzantine agreement-Canneti
- 1998-SecureRing protocol for group comm-Kihlstorm et.al
- 1998-Byzantine quorum systems-Dahlia et.al
- 1999-Practical Byzantine fault tolerance-Liskov and Castro!

The problem

- Provide a reliable answer to a computation even in the presence of Byzantine faults.
- A client would like to
  - Transmit a request
  - Wait for k replies
  - Conclude that the answer is a true answer

Failures of previous algorithms

- Theoretically feasible but inefficient in practice
- Assumes synchrony – known bounds of message delays and process speeds
- Synchrony assumption for correctness
- Can we do better?

The Model

- Networks are unreliable
  - Can delay, reorder, drop,retransmit
- Some fraction of nodes are unreliable
  - May behave in any way, and need not follow the protocol.
- Nodes can verify the authenticity of messages
- ***Message delay does not grow exponentially***

FLP impossibility?

- Strong adversary can delay correct nodes in order to cause most damage to the replicated service
- Assume adversary cannot delay nodes indefinitely
- Rely on synchrony to provide liveness
- Does not rely on synchrony to guarantee safety
- Otherwise it could be used to implement consensus in async setting
- NOT POSSIBLE!

Protocol overview

- Form of Lamport&Schneider state machine replication
- Service modelled as a state machine replicated across nodes
- Replicas maintains service state
- Cryptography to detect message corruption

Views

- Replicas move through a succession of configurations called views
- View=Primary+Backup nodes
- Primary = v mod n
  - N is number of nodes
  - V is the view number

Nodes

- Maintain a state
  - Log
  - View number
  - state
- Can perform a set of operations
  - Need not be simple read/write
  - Must be deterministic
- Well behaved nodes must:
  - start at the same state
  - Execute requests in the same order

Replica requirements

- Deterministic replicas
- All replicas start in same state
- Safety: Agree on total order
- Primary picks ordering
- Backups ensure primary behaves correct
- Trigger view changes

Why doesn't traditional RSM work with Byzantine nodes?

- Cannot rely on the primary to assign seq-no
  - Malicious primary can assign the same seq-no to different requests!
- Cannot use Paxos for view change
  - Paxos uses a majority accept-quorum to tolerate f benign faults out of 2f+1 nodes
  - Bad node tells different things to different quorums!

Basic Algorithm

- Three-phase protocol to multicast requests to replicas
- Pre-prepare and prepare order within views
- Prepare and commit order across views
- Messages are authenticated
- Replicas remember messages -maintain log

Normal Case operation

- Primary receives request and starts a 3-phase protocol
- Pre-prepare: Accept requests only if valid
- Prepare:Multicasts prepare messages
- Wait for 2f+1 replicas to agree
- Commit: Commit if 2f+1 agree to commit

The Algorithm

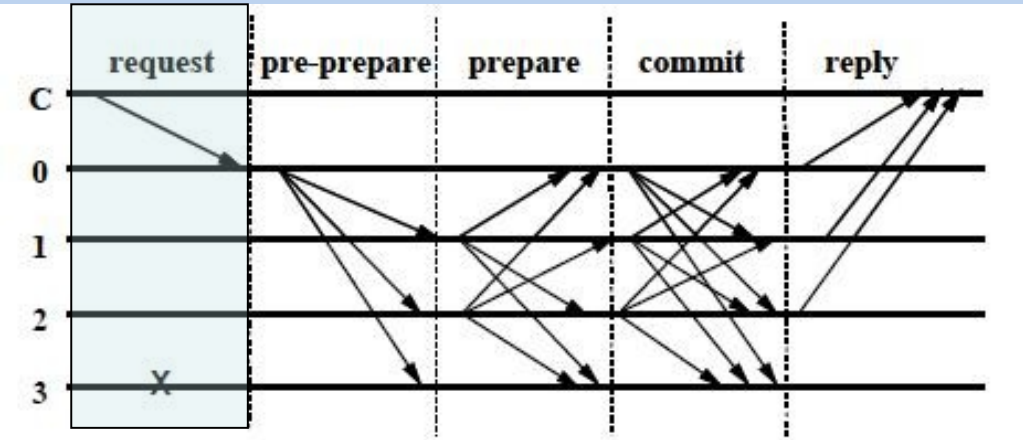

Figure 1: Normal Case Operation

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

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

o= requested operation

t= timestamp

c= client

б= signature

The Algorithm

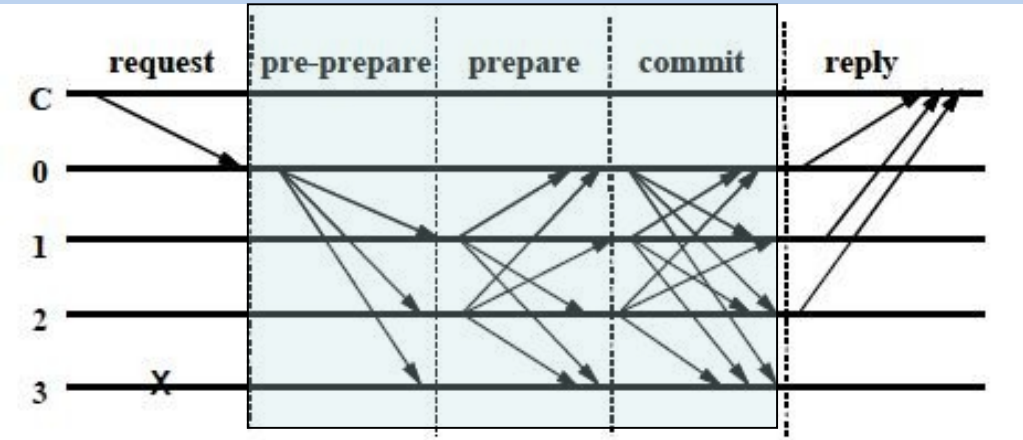

Figure 1: Normal Case Operation

- 2. The primary multicasts the request to the backups (three-phase protocol)

The Algorithm

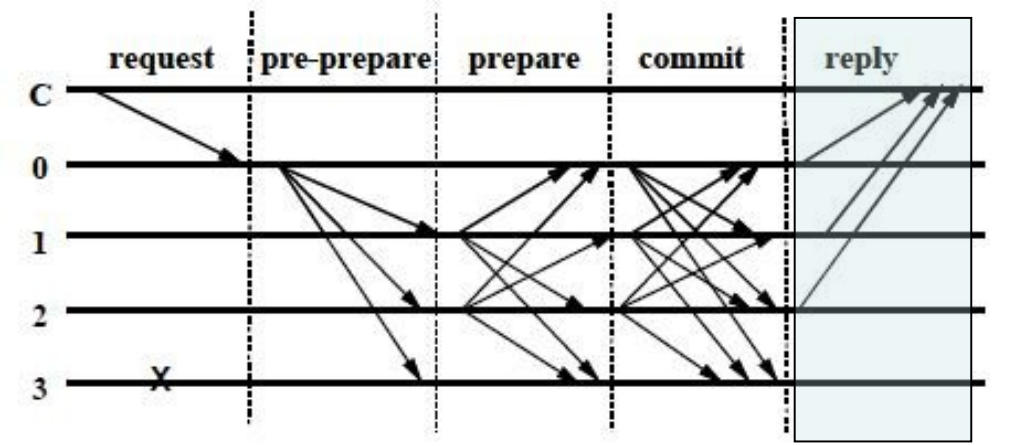

Figure 1: Normal Case Operation

- 3. Replicas execute the request and send a reply to the client

$$\langle \text{REPLY}, v, t, c, i, r \rangle_{\sigma_i}$$

o= requested operation
t= timestamp
c= client
б= signature

v= view
i= replica
r= result

The Algorithm

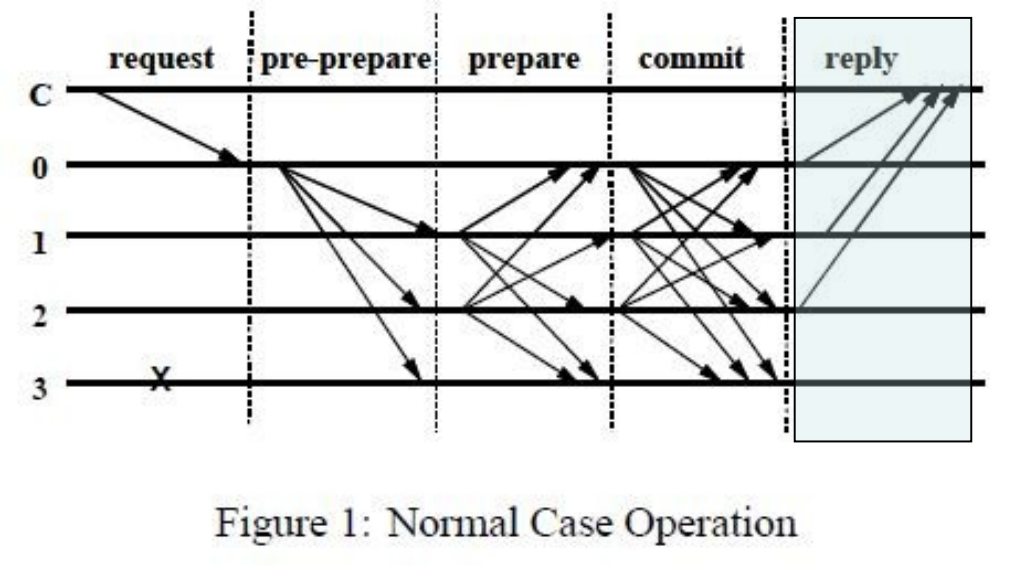

Figure 1: Normal Case Operation

- 4. The client waits for f+1 replies from different replicas with the same result; this is the result of the operation

Improvements in this algorithm

- Does not rely on synchrony of safety
- Magnitude order improvement
- Efficient authentication using message authentication codes (MAC)
- Public key cryptography
- Handling malicious primary

Byzantine-Fault-tolerant File System

- BFS is implemented using replication library
- Replicas
- User-level relay processes mediate communication between the standard NFS client and the replicas.
- Relay receives NFS requests, invokes procedure of replication library and sends the result back to NFS client.
- The performance of BFS is only 3% worse than the standard NFS implementation.

Conclusion

- Able to tolerate Byzantine failures
- Works in an asynchronous system like Internet
- Better lower bounds than previous known algorithms
- No assumptions on synchrony for safety
- Can we reduce the number of replicas used?
- Fault tolerant privacy-faulty replica may leak information to attacker
- Zyzzyva: Speculative Byzantine Fault Tolerance-SOSP07