Why Distributed Consensus is difficult?

- Arbitrary message delays (asynchronous network)
- Independent parties (nodes) can go offline (and also back online)
- Network partitions
- Message reorderings
- Malicious (Byzantine) parties

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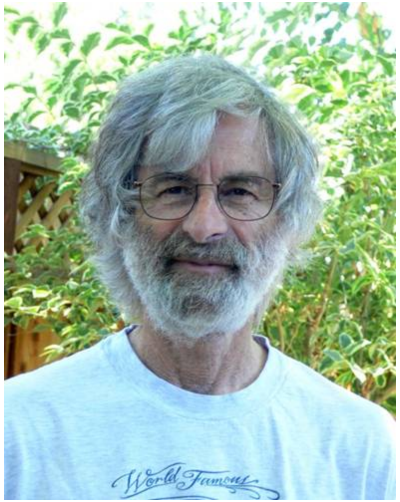
The Byzantine Generals Problem

Authors

- Leslie Lamport
  - you again!
  - we all know him
- Robert Shostak
  - PhD in Applied Math, Harvard
  - SRI International
  - Founder, Ansa Software
  - Founder, Mira Tech
  - Borland Software
  - Founder Portera System
  - Founder Vocera
- Marshall Pease



Another story from Lamport?

Time, Clocks, and the Ordering of Events in a Distributed System	1978
The part-time parliament	1990

Another story from Lamport?

Time, Clocks, and the Ordering of Events in a Distributed System	1978
The Byzantine Generals Problem	1982
The part-time parliament	1990

How this story came

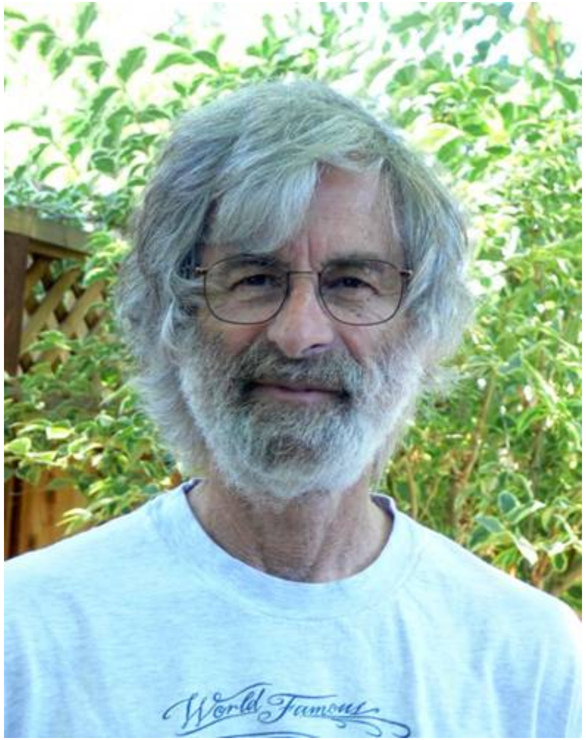
"

I have long felt that, because it was posed as a cute problem about philosophers seated around a table, Dijkstra's dining philosopher's problem received much more attention than it deserves.

……

The popularity of the dining philosophers problem taught me that the best way to attract attention to a problem is to present it in terms of a story.

"



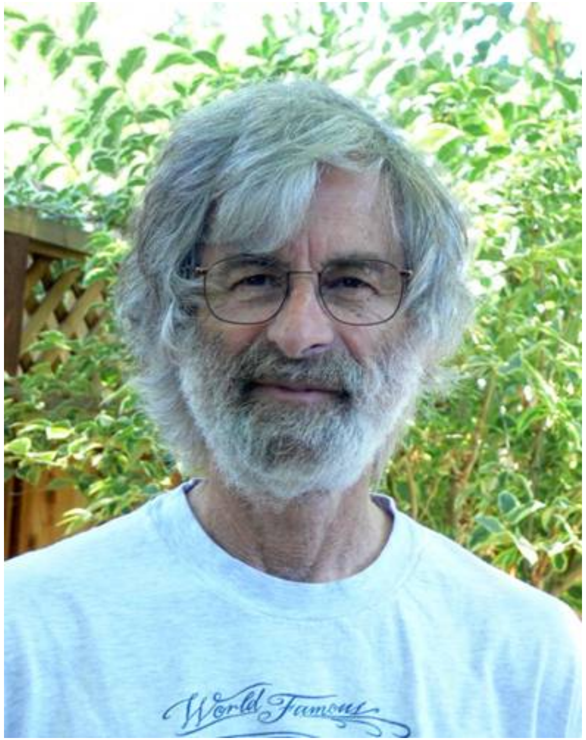
http://lamport.azurewebsites.net/pubs/pubs.html#byz

How this story came

"

There is a problem in distributed computing that is sometimes called the Chinese Generals Problem, in which two generals have to come to a common agreement on whether to attack or retreat, but can communicate only by sending messengers who might never arrive.

"



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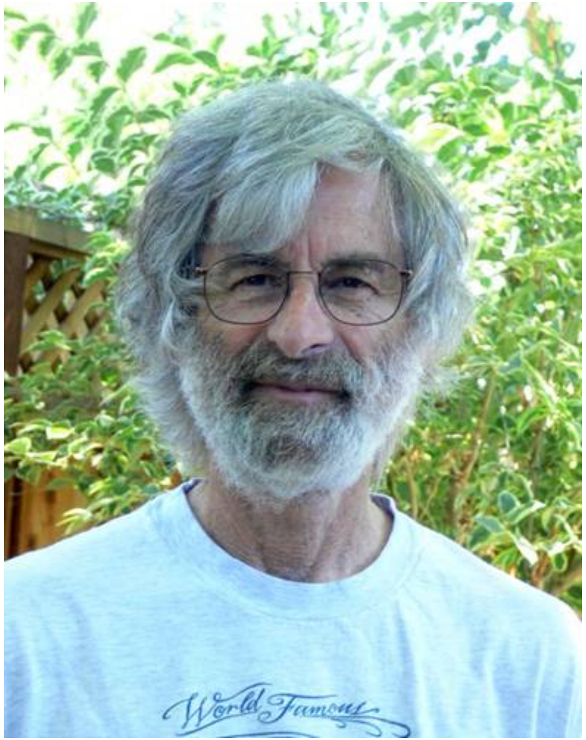
How this story came

"

I stole the idea of the generals and posed the problem in terms of a group of generals, some of whom may be traitors, who have to reach a common decision.

"



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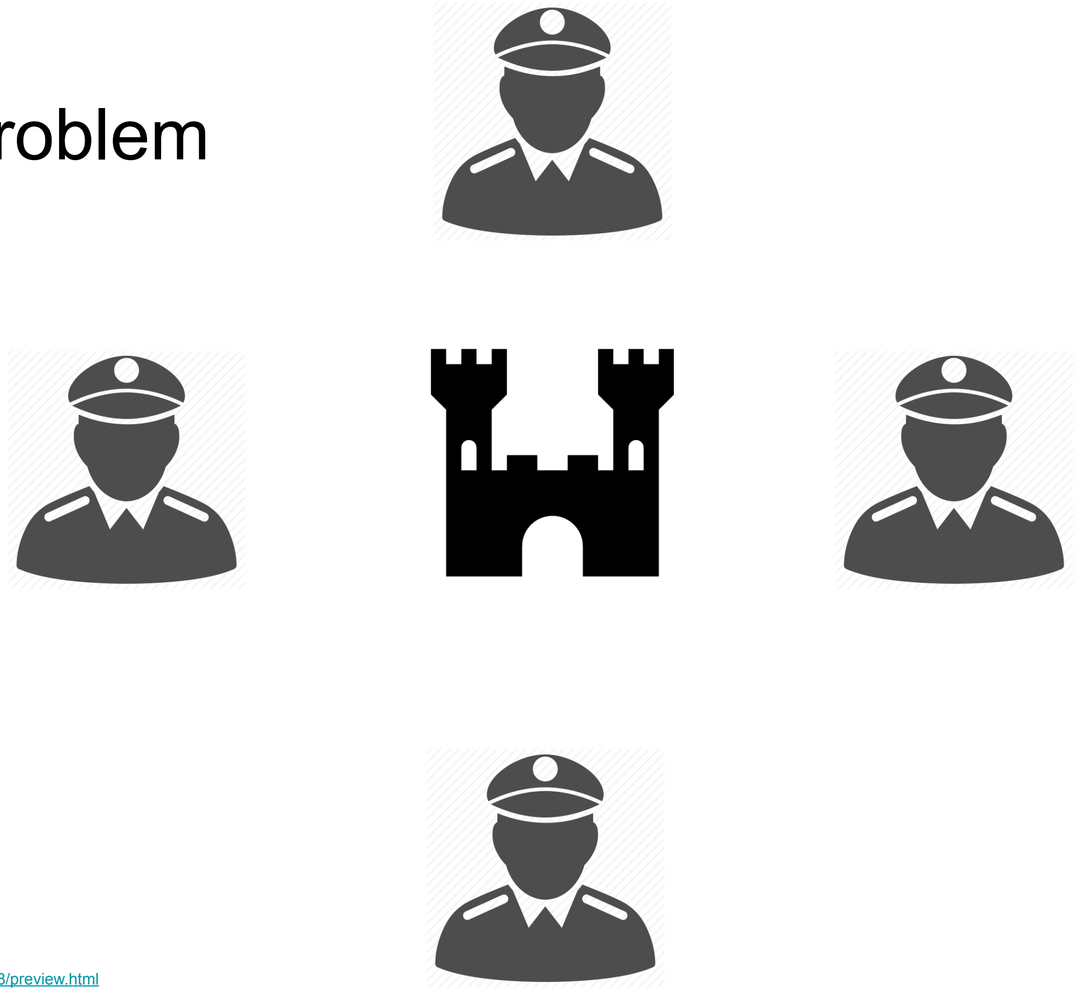
What is the Byzantine generals problem

Byzantine generals problem

"several divisions of the Byzantine army are camped outside an enemy city, each division commanded by its own general. The generals can communicate with one another only by messenger. After observing the enemy, they must decide upon a common plan of action."



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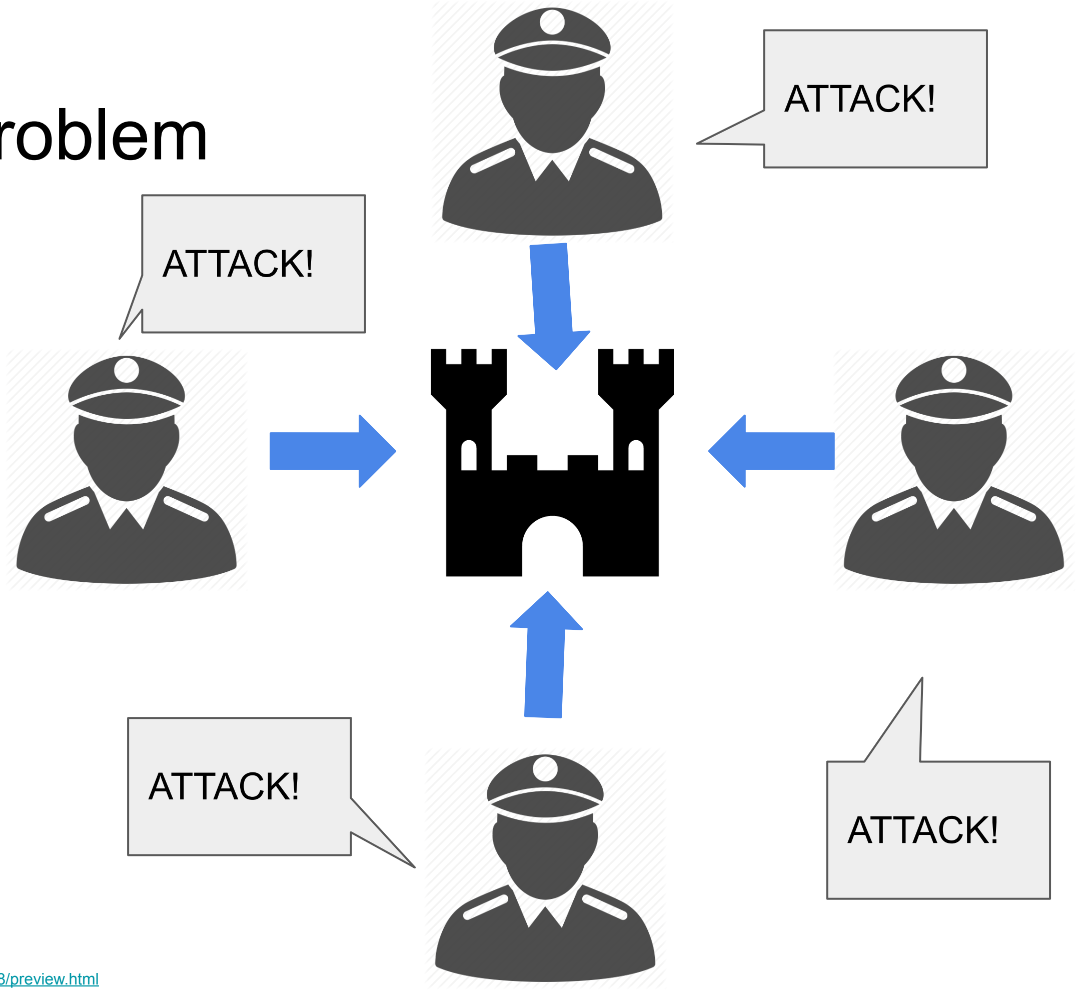
*lieutenant: https://www.clipartmax.com/max/m2i8Z5i8b1H7N4H7/

Byzantine generals problem

- Generals should reach a consensus on the plan
- It could be ATTACK



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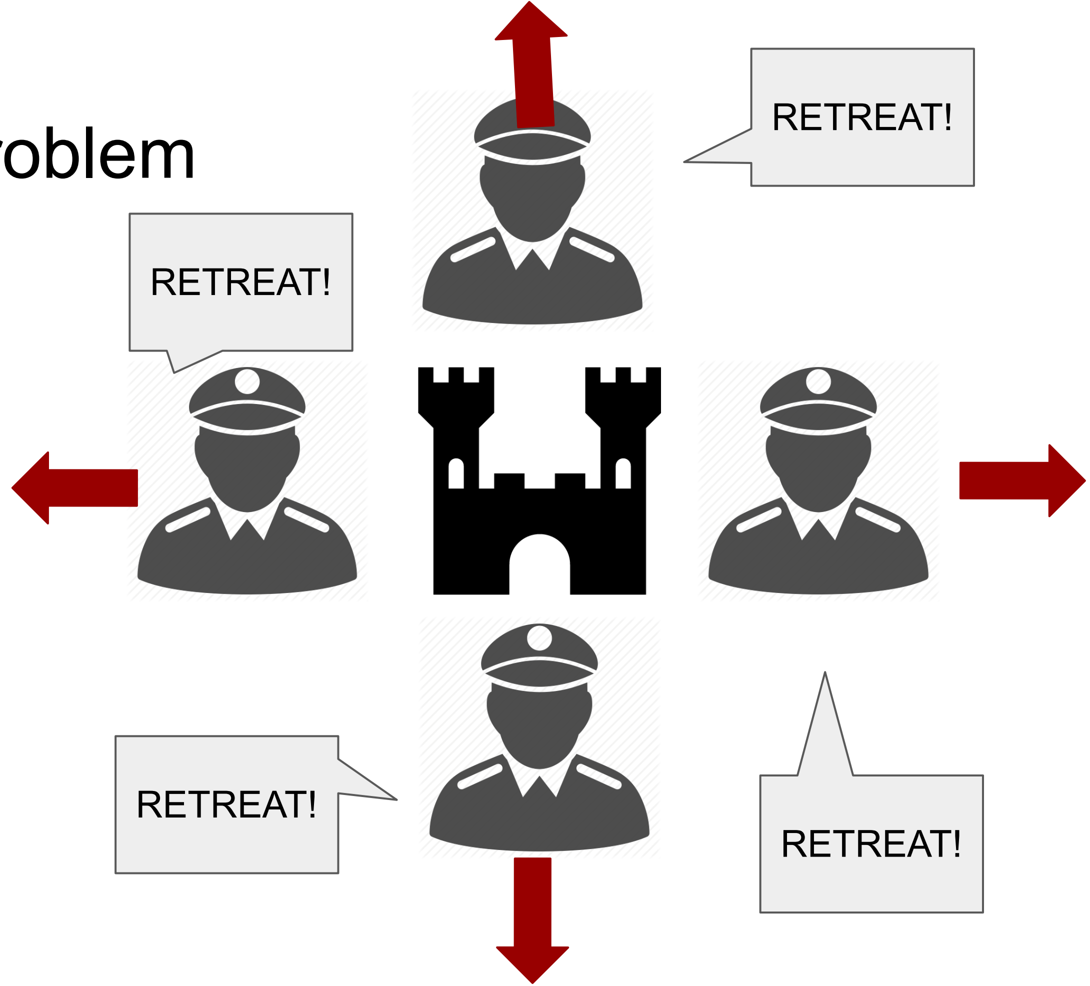
Byzantine generals problem

- Generals should reach a consensus on the plan
- Or RETREAT



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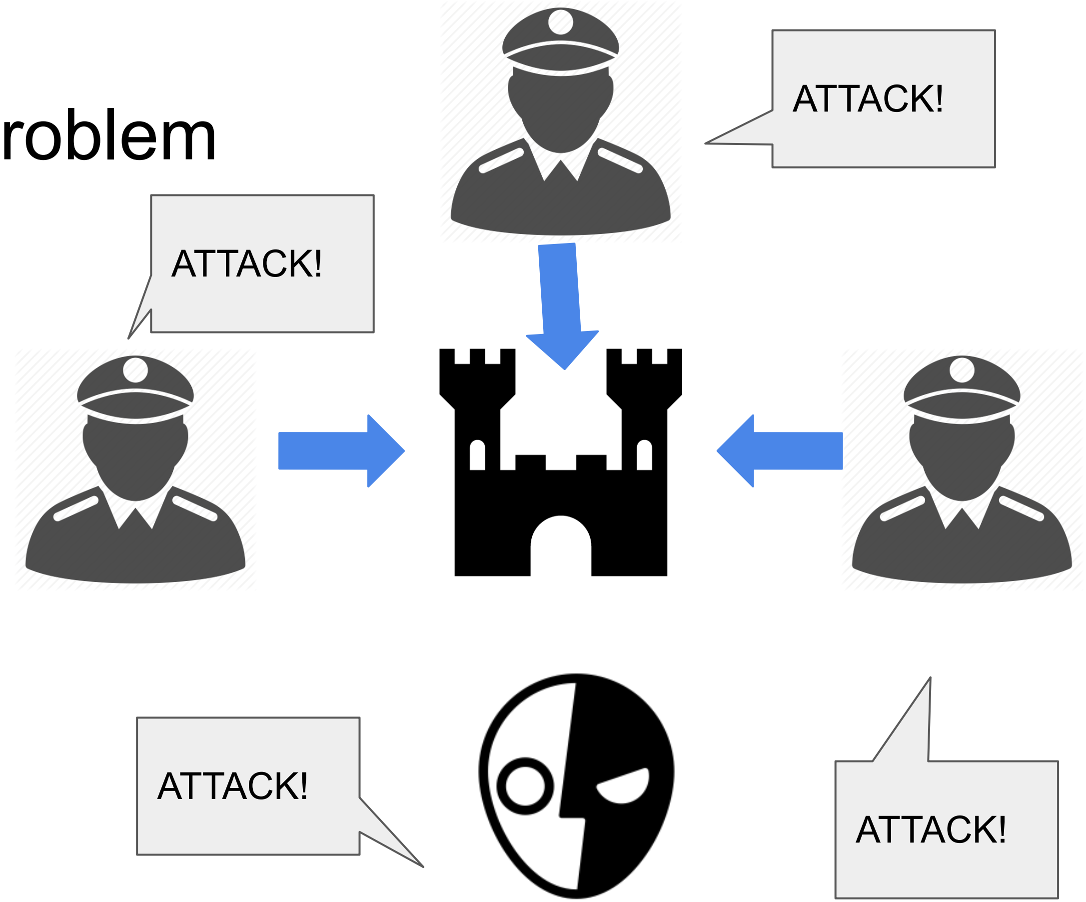
Byzantine generals problem

- But there might be traitors
- All loyal generals should reach a consensus



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Byzantine generals problem

- But traitors can act arbitrarily
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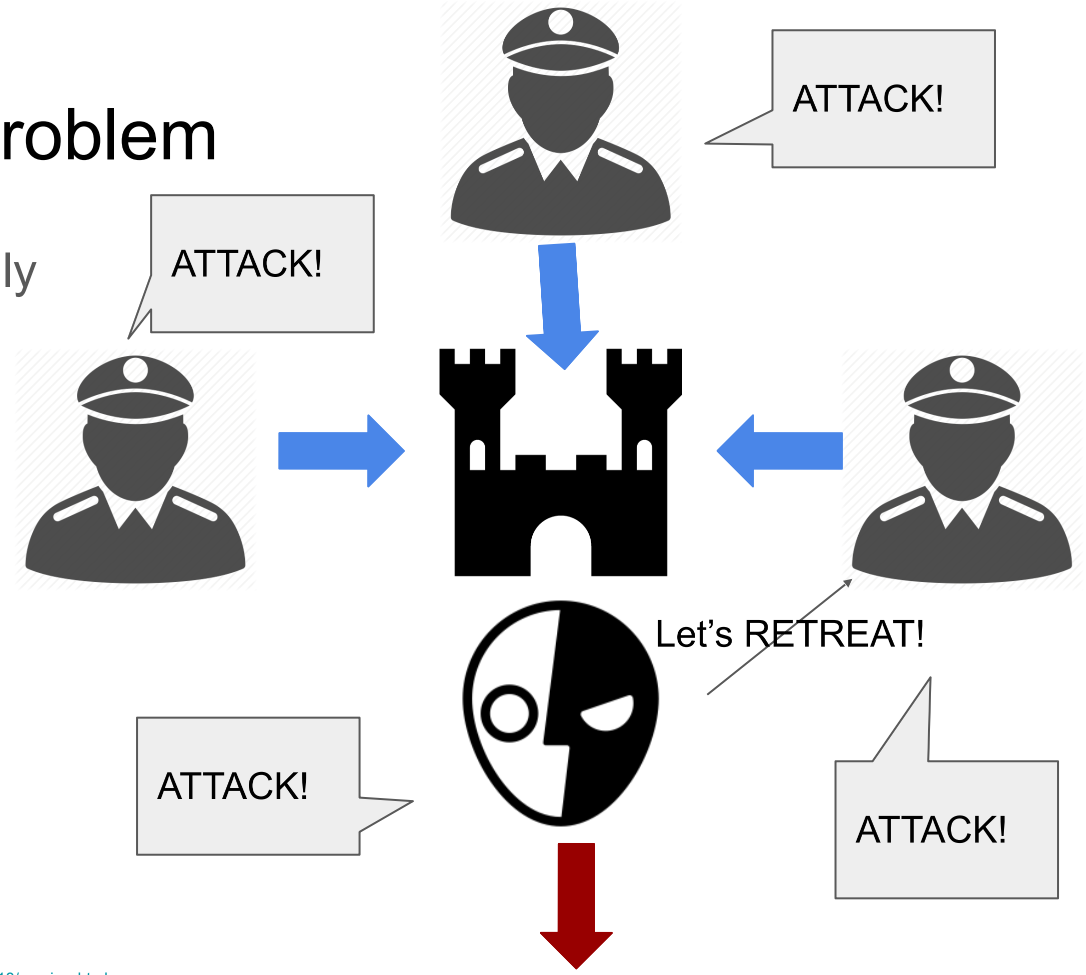

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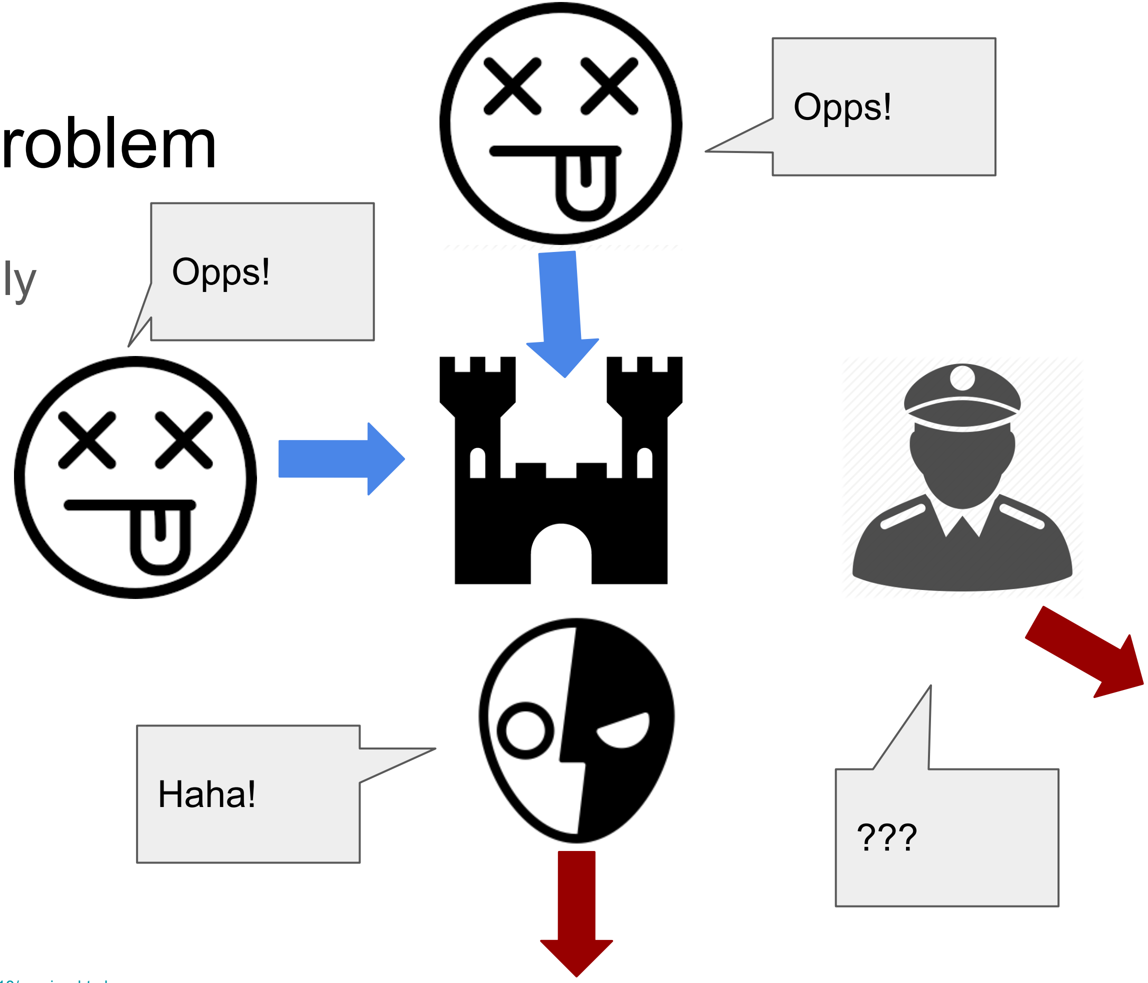

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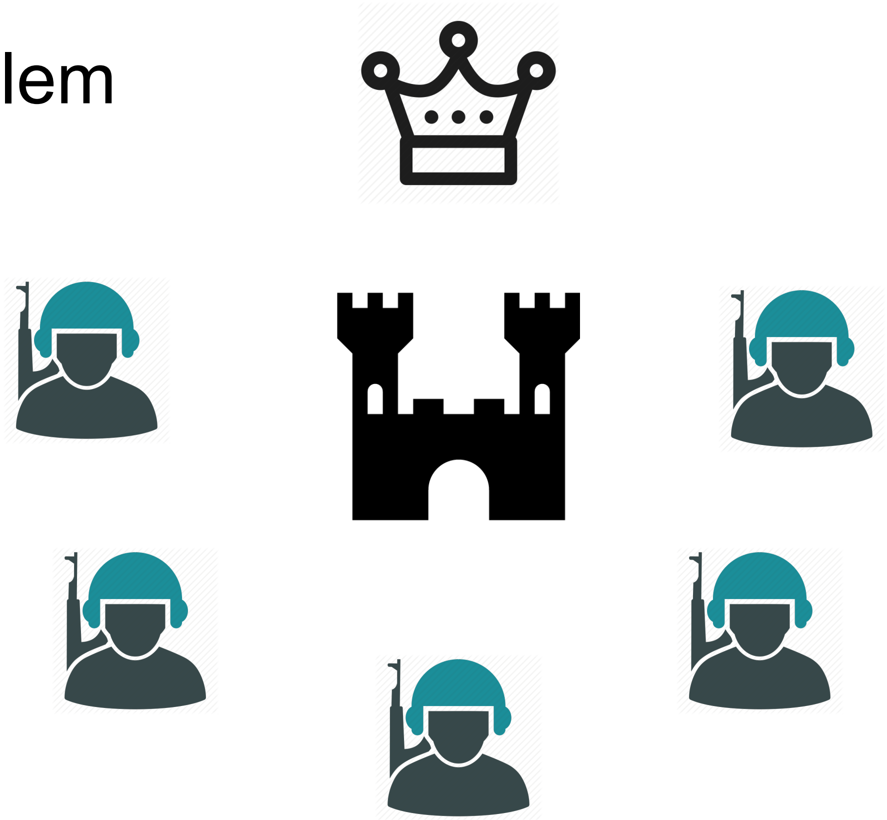
Byzantine generals problem

- A simplified version

“A commanding general sends 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.”



What is the byzantine generals problem

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

(Lamport calls it *Interactive Consistency*)

What is the byzantine generals problem

- Consistency/Agreement
- IC2. If the commanding general is loyal, then every loyal lieutenant obeys the order he sends.

What is the byzantine generals problem

- Consistency/Agreement
- Validity

What is the byzantine generals problem

- Consistency/Agreement
- IC2. If the commanding general is loyal, then every loyal lieutenant obeys the order he sends.

What is the byzantine generals problem

- Consistency/Agreement
- Validity
- Liveness/Termination?

Impossibility Result

Impossibility result

“if the generals can send only oral messages, then no solution will work unless more than ⅔ of the generals are loyal.”

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what are oral messages?

Impossibility result

oral messages:

- every message that is sent is delivered correctly
- the receiver of a message knows who sent it
- the absence of a message can be detected

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Impossibility result

oral messages:

- every message that is sent is delivered correctly
- authenticated channel
- synchronous network

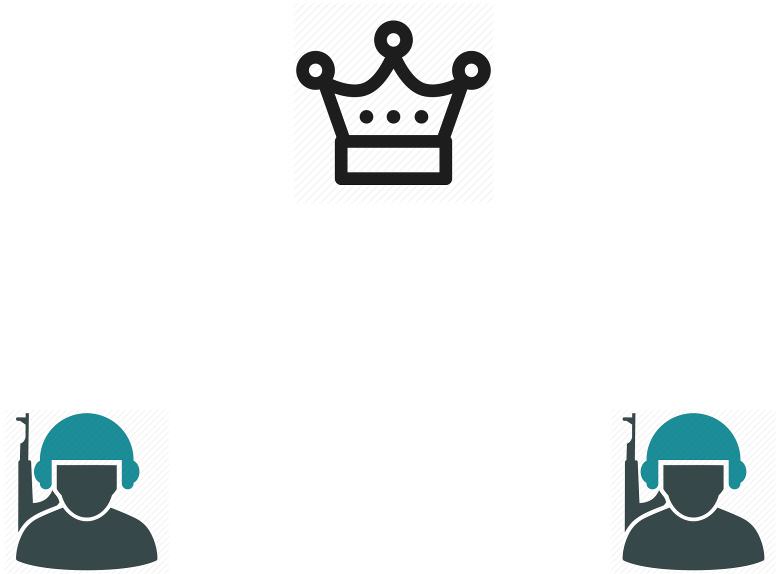
Impossibility result

"if the generals can send only oral messages, then no solution will work unless more than ⅔ of the generals are loyal."

in a synchronous network, with authenticated channel, when m generals are traitors, no solution will work unless there are more than $3m$ generals

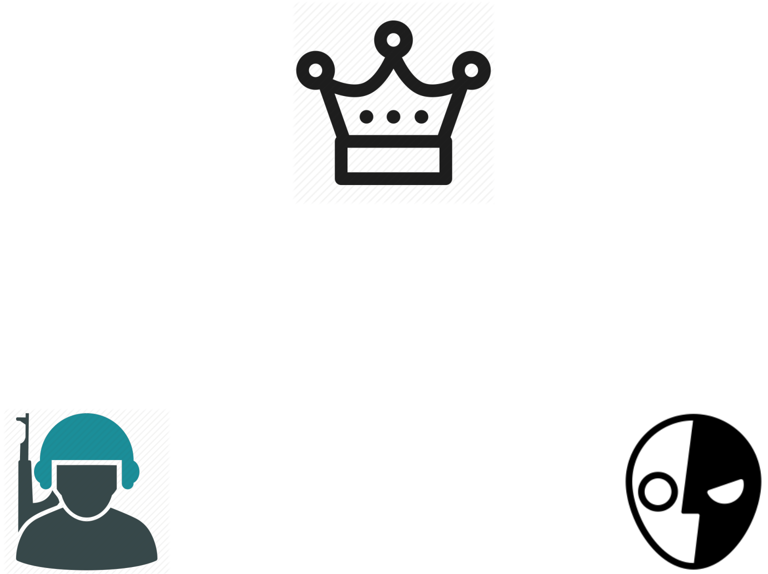
impossibility result - proof

- case $m = 1$:



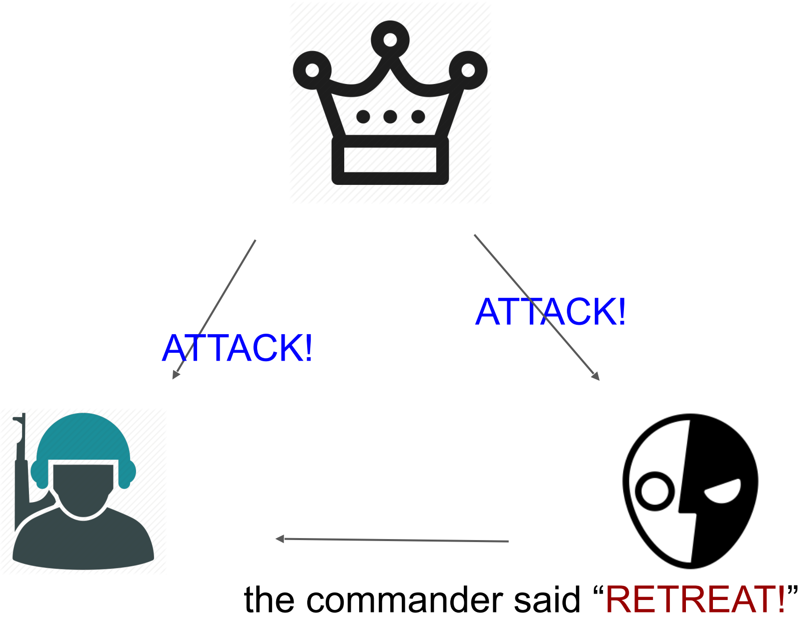
impossibility result - proof

- case m = 1:
    - scenario 1:
        - the commander is loyal
        - one lieutenant is a traitor



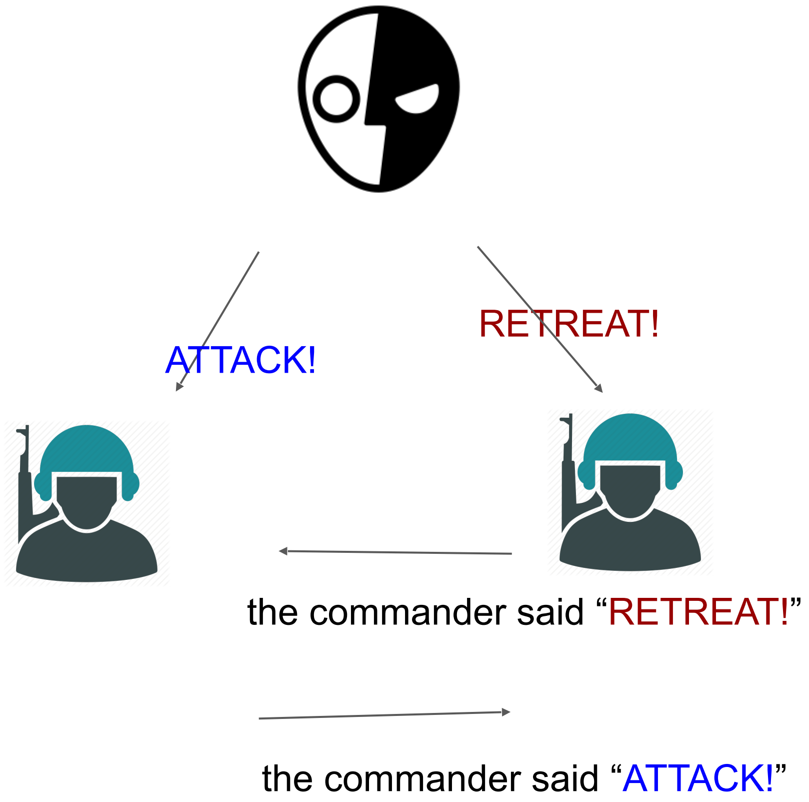
impossibility result - proof

- case $m = 1$:
  - scenario 1:
    - the commander is loyal
    - one lieutenant is a traitor
    - the left lieutenant should ATTACK

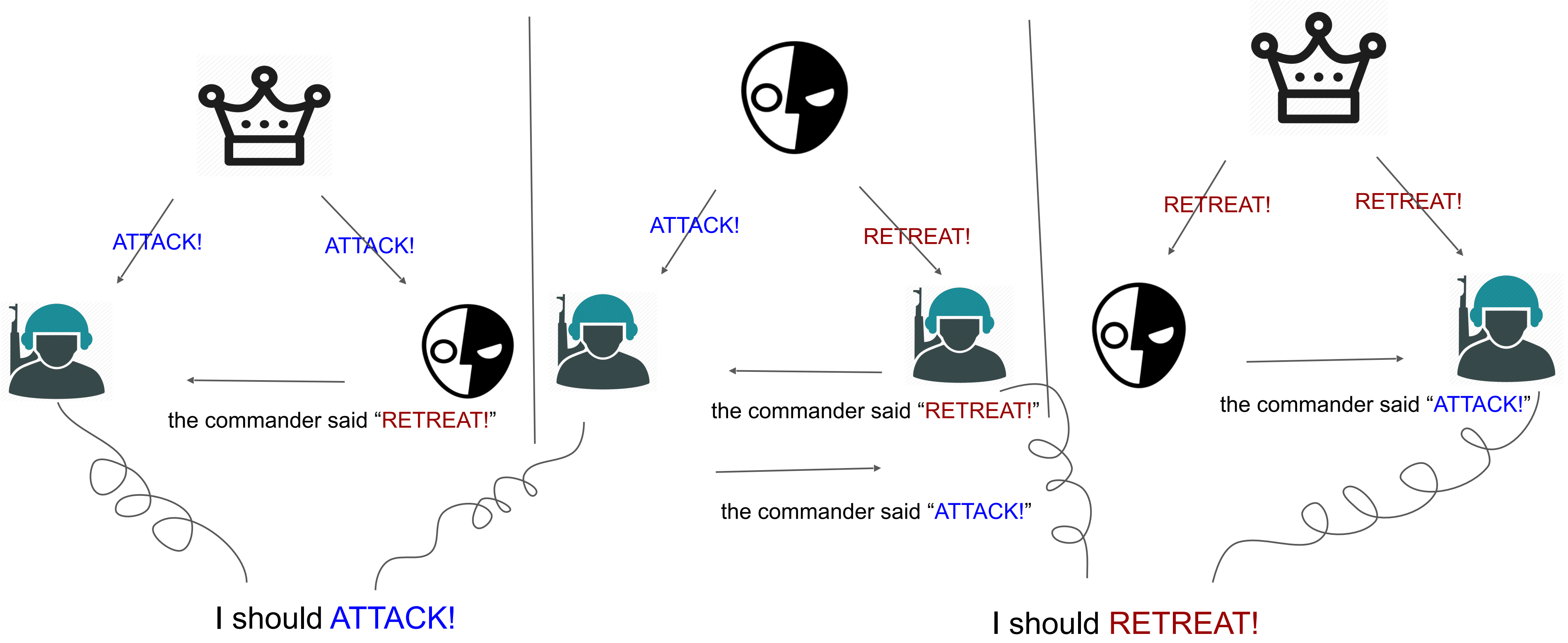


impossibility result - proof

- case m = 1:
    - scenario 2:
        - the commander is a traitor



Three scenarios



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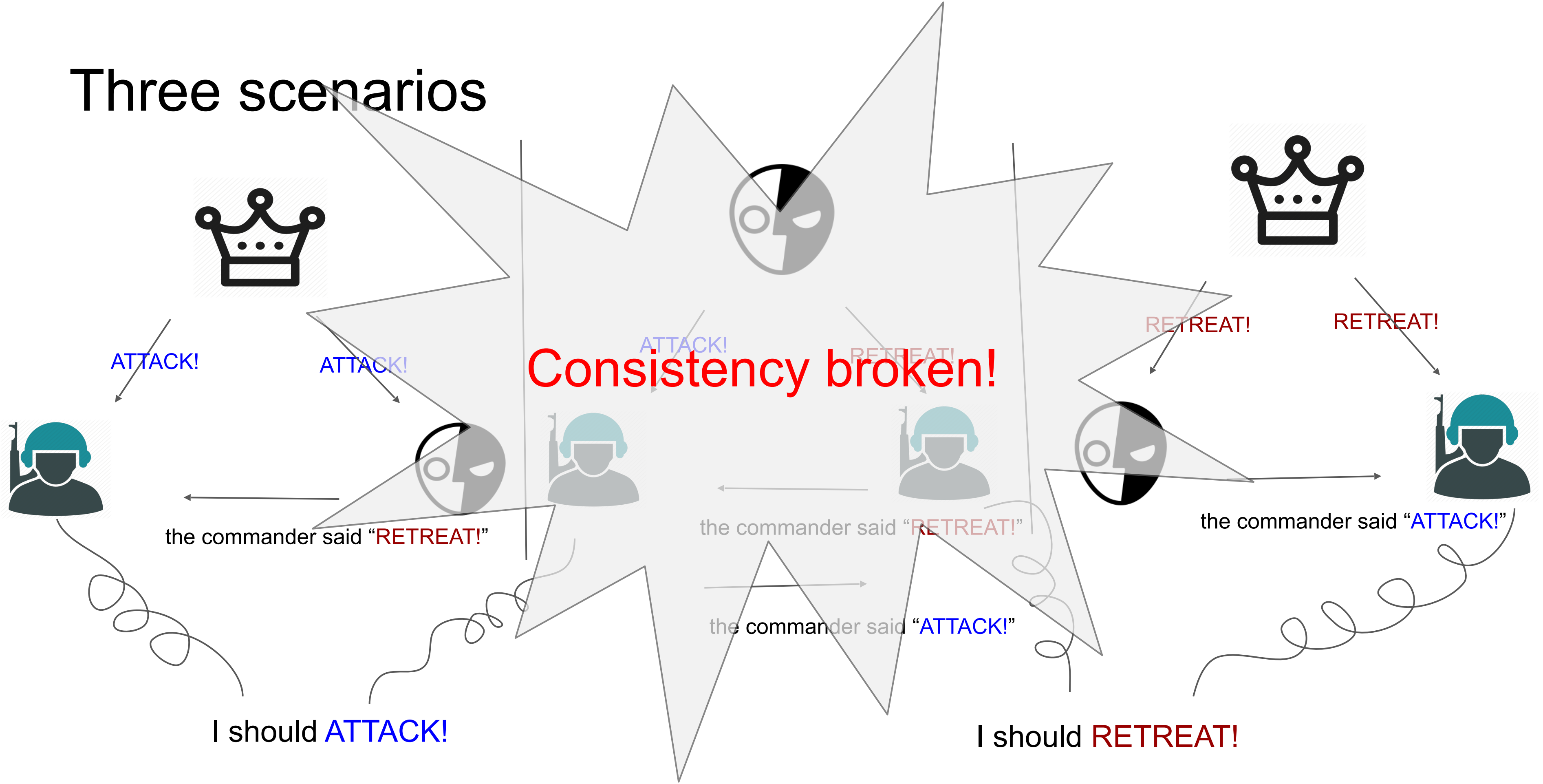


Consisntency: All loyal lieutenants obey the same order

impossibility result

prove $m > 1$ by contradiction

- assume we have a solution protocol f for $3m$ generals when $m > 1$
- we can solve $m = 1$ case by leveraging f

prove $m > 1$ by contradiction

- assume the three generals are x, y, z, and x is the commander;
- according to protocol f
  - x simulates one commander and m-1 lieutenants
  - each of y and z simulates m lieutenants

impossibility result

prove m > 1 by contradiction

- assume the three generals are x, y, z, and x is the commander;
- according to protocol f
  - x simulates one commander and m-1 lieutenants
  - each of y and z simulates m lieutenants
- at most one of x, y, z is a traitor
  - at most m simulated traitors
  - protocol f can solve the case when there are at most m traitors

impossibility result

prove $m > 1$ by contradiction

- if we can solve case $m > 1$ then we can solve $m = 1$
- we proved case $m = 1$ cannot be solved
- contradiction!

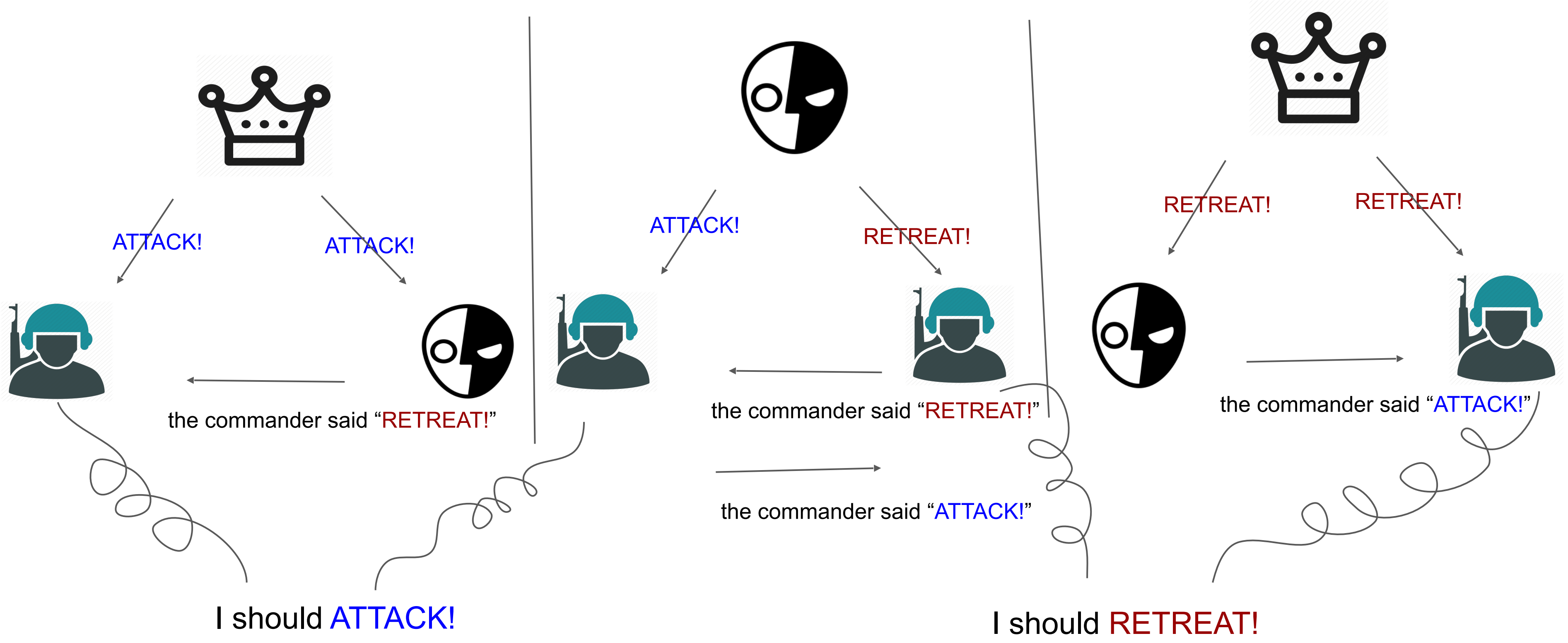
Oral messages' fault

oral messages:

- every message that is sent is delivered correctly
- the receiver of a message knows who sent it
- the absence of a message can be detected

- With only oral messages, traitors can lie by telling the wrong command they received

Three scenarios



Signed message

- With only oral messages, traitors can lie by telling the wrong command they received

- Signed messages
  - cannot be forged
  - anyone can verify the authenticity

Solutions:
oral messages and signed messages

Solutions - with oral messages (k - number of traiters)

- OM(k)
  - k == 0
    - commander sends the value to every one
    - everyone return the value they received

Solutions - with oral messages

- OM(k)
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    - commander sends the value to every one
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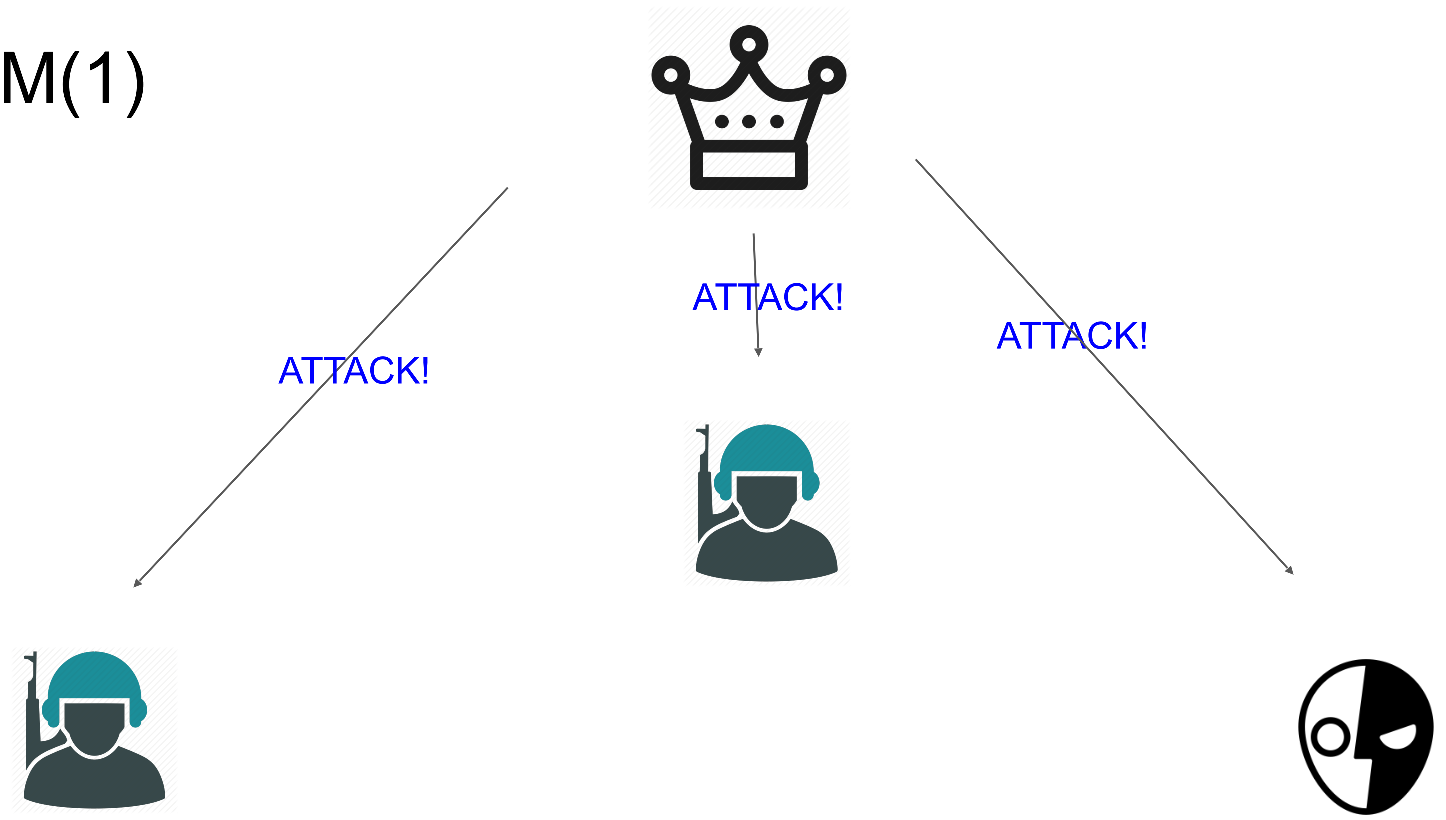
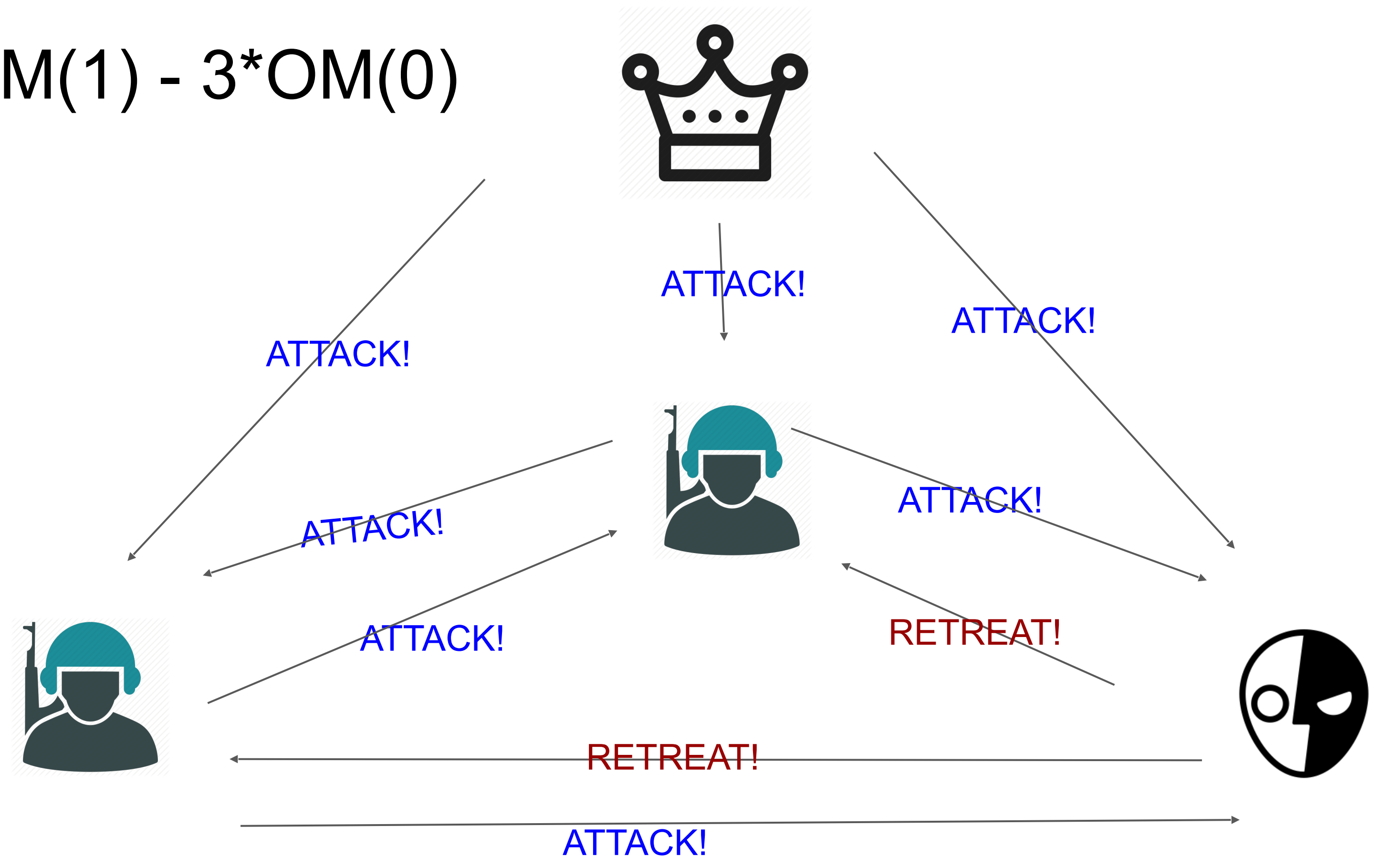
  - k > 0
    - commander sends the value to every one
    - everyone start a smaller bgp OM(k-1) containing all ones but the current commander and become the new commander
    - everyone participated n-1 OM(k-1) and get n-1 values, return the majority

OM(1)



OM(1) - 3*OM(0)



ATTACK!
ATTACK!
ATTACK!
ATTACK!
ATTACK!
ATTACK!
RETREAT!
RETREAT!
ATTACK!

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- Intuition: for every message M received, solve a smaller bgp containing all but the current commander to tell others you received M

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- OM(m) for m traitors when $3m < n$

Solutions - with oral messages

- OM(k) - Message complexity: (n-1)*MC(OM(k-1)) + n-1 = O(n^m)
  - k == 0
    - commander sends the value to every one
    - everyone return the value they received
  - k > 0
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- OM(m) for m traitors when 3m < n (a Theorem, see Lamport's paper)

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  - every lieutenant maintains a value set V(i)
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  - when there will be no more messages, return choice(V(i))
  - choice(V)
    - if V = {v} return v
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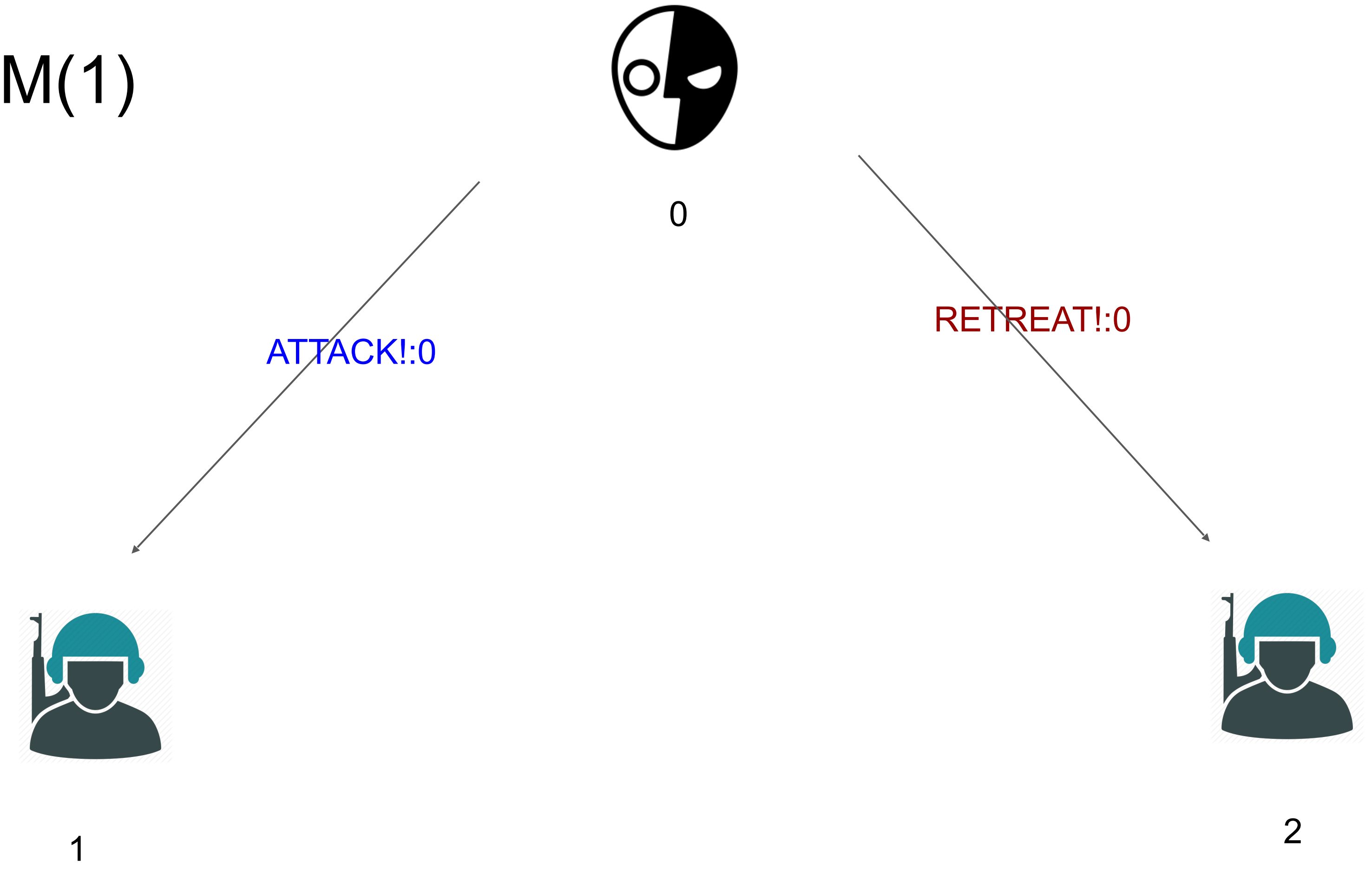
SM(1)



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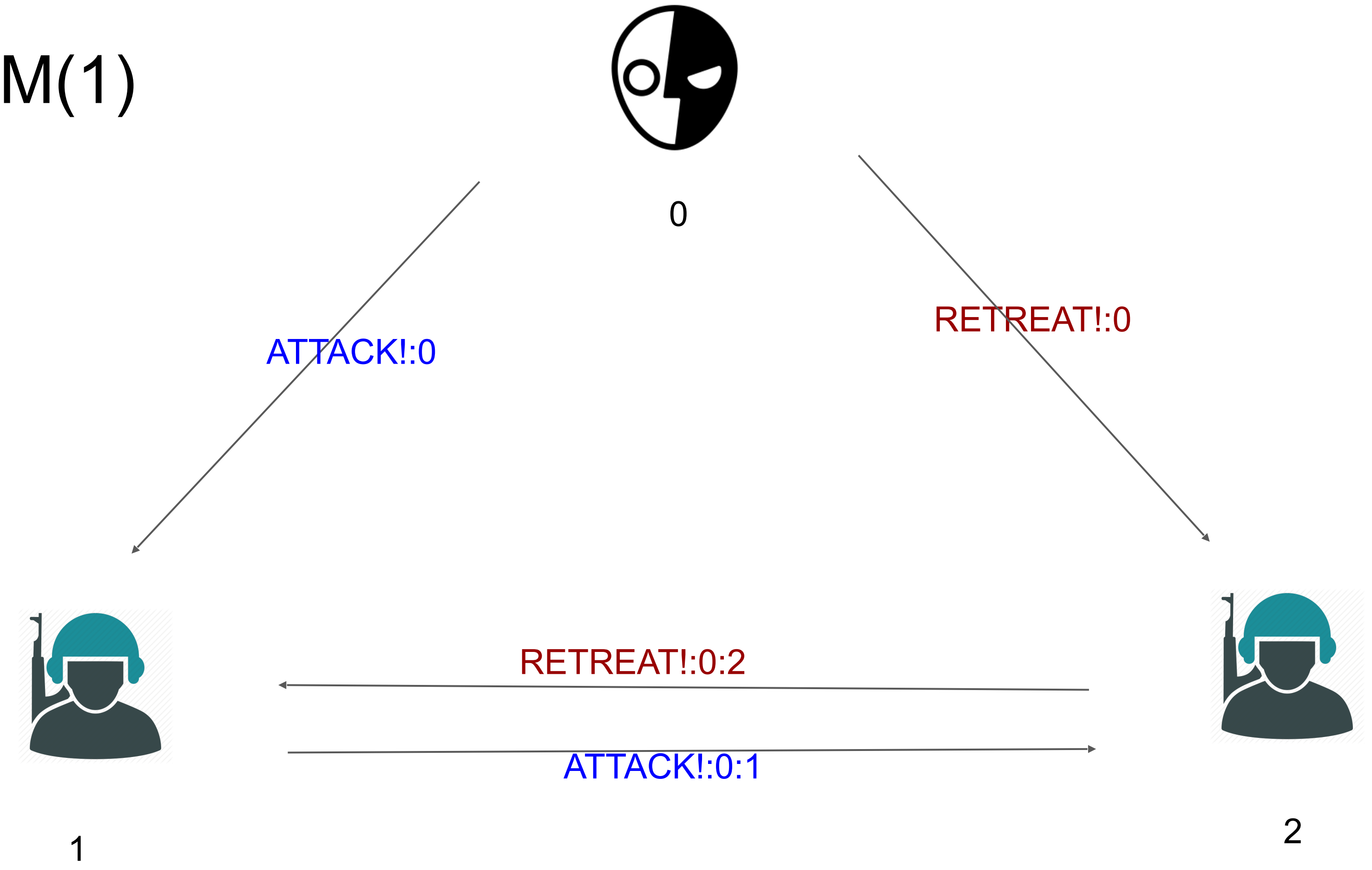

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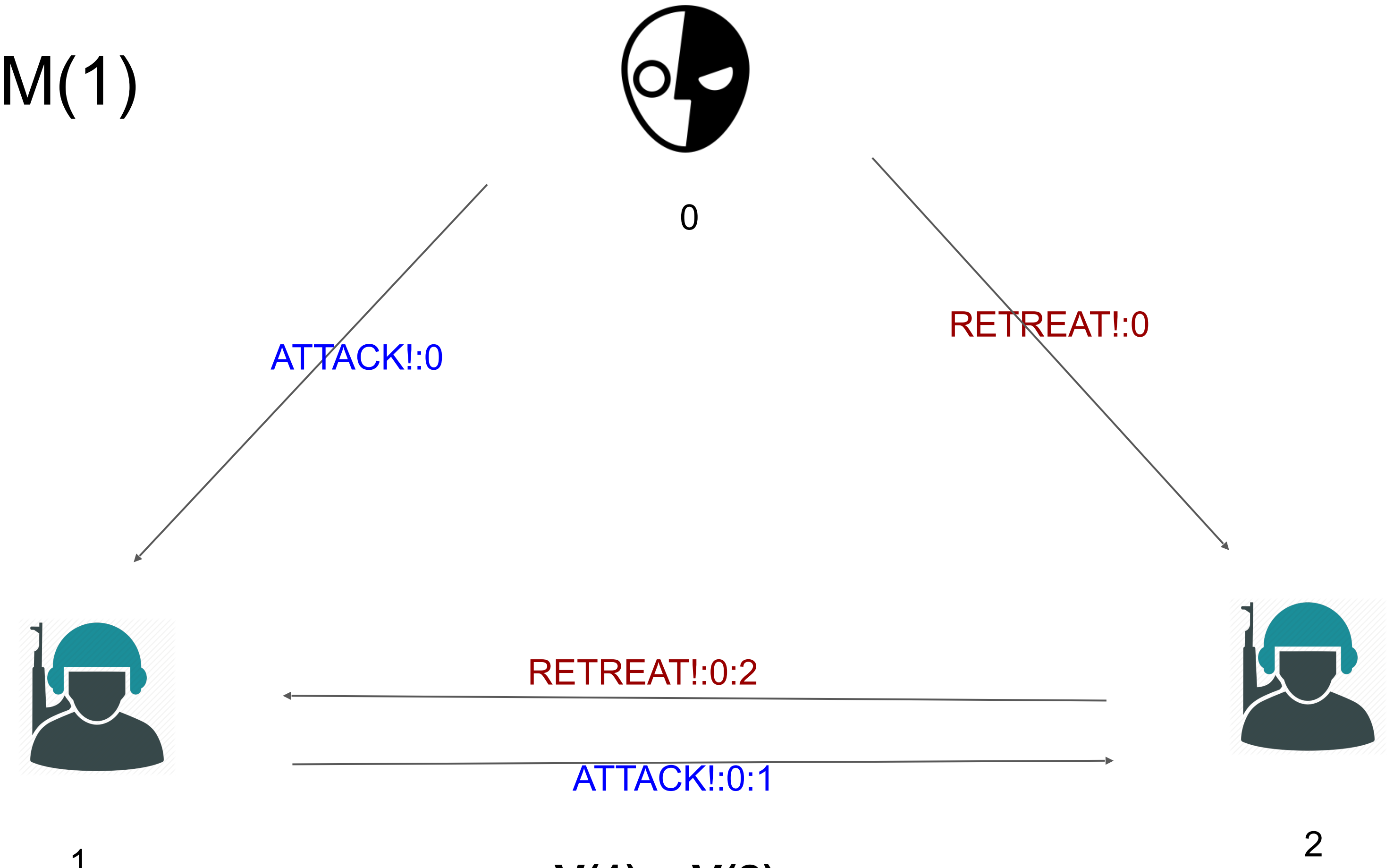
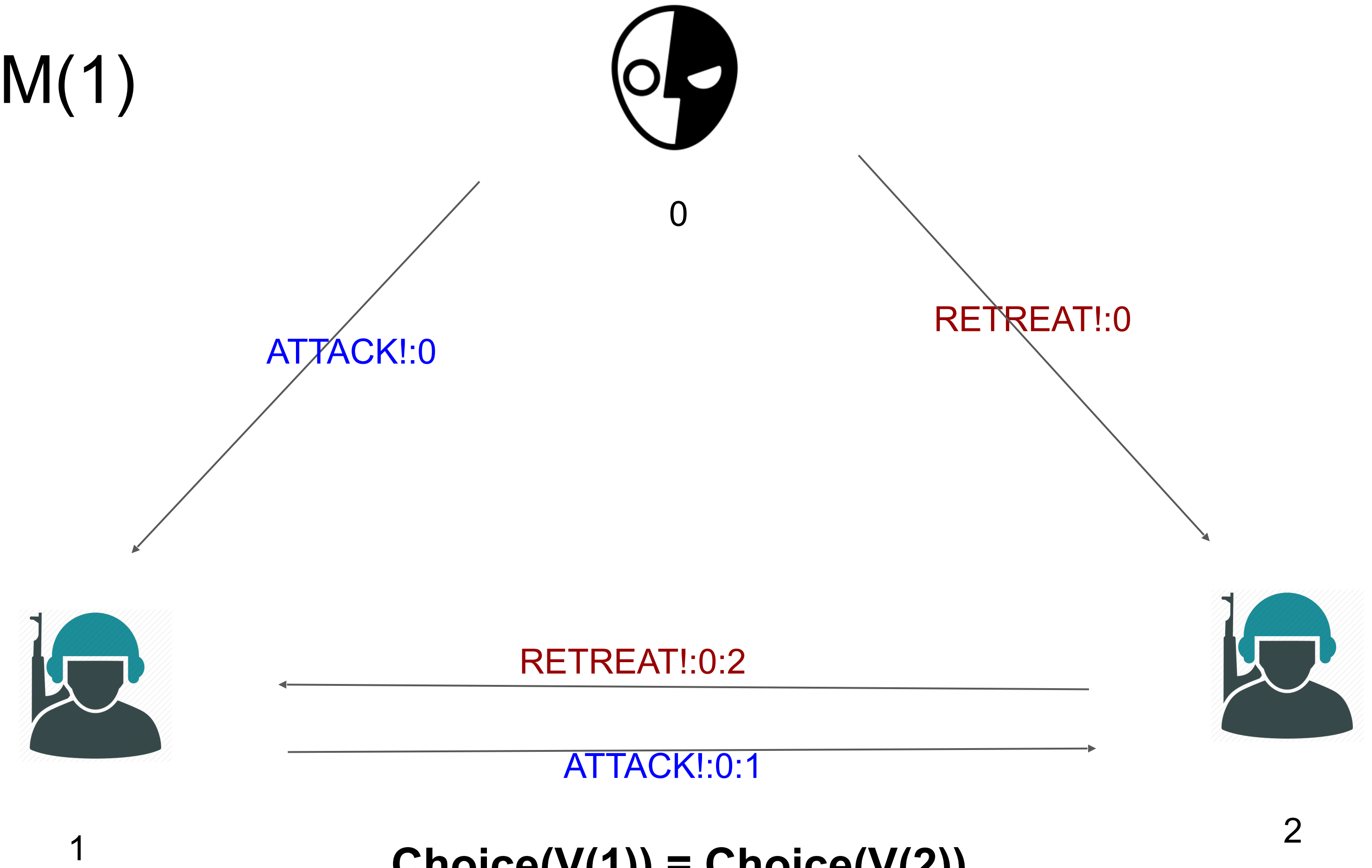


V(1) = V(2)

SM(1)



Choice(V(1)) = Choice(V(2))

Solutions - with signed messages

- SM(m) - message complexity: O(n^2)
  - every lieutenant maintains a value set V(i)
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- Intuition: ensure every message received by a loyal lieutenant is sent to every loyal lieutenant
- The protocol is safe as it is now stuck

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Minimum number required for which
an *f*-resilient consensus protocol exists

	synchrony	asynchrony	partial synchrony
fail-stop	f+1	inf	2f+1
crash	f+1	inf	2f+1 (Paxos)
byzantine with digital signature	f+1 (SM(f+1))	inf	
byzantine with authenticated channel	3f+1 (OM(f))	inf	

Partial synchrony:
fixed bounds on processor speed and message delays exist but they aren’t known a priori.

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Partial synchrony:
fixed bounds on processor speed and message delays exist but they aren't known a priori.

Byzantine with digital signature in partial synchrony

- No partial synchronous protocols can tolerate ⅓ faults.
- Sound familiar?
- But there is a protocol that achieves safety for (3f + 1)

Practical Byzantine Fault Tolerance (PBFT)

- Introduced by **Miguel Castro & Barbara Liskov** in 1999
  - almost 10 years after Paxos
- Addresses real-life constraints on Byzantine systems:
  - *Partially-synchronous* network
  - *Byzantine* failure
  - Message senders *cannot be forged* (via public-key crypto)

PBFT Terminology and Layout

- Replicas — nodes participating in a consensus (no more *acceptor/proposer* dichotomy)
- A *dedicated replica* (**primary**) acts as a commander
  - A primary can be re-elected if suspected to be compromised
  - Backups — other, non-primary replicas (lieutenants)
- Clients — communicate directly with primary/replicas
- The protocol uses *time-outs* (partial synchrony) to *detect faults*
  - *E.g.*, a primary not responding *for too long is considered compromised*

Practical Byzantine Fault Tolerance

- Commander sends the value to every lieutenant
- Every lieutenant
  - if it receives a new value v, broadcast (prepare, v)
  - if it receives 2f+1 (prepare, v), broadcast (commit, v)
  - if it receives 2f+1 (commit, v), broadcast (committed, v)
  - if it receivers f+1 (committed, v), broadcast (committed, v)

Practical Byzantine Fault Tolerance

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- Ensure agreement
- Ensure liveness under an loyal commander

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- Ensure agreement
- Ensure liveness under an loyal commander
- What if the commander is faulty?
  - we need view change

Overview of the Core PBFT Algorithm

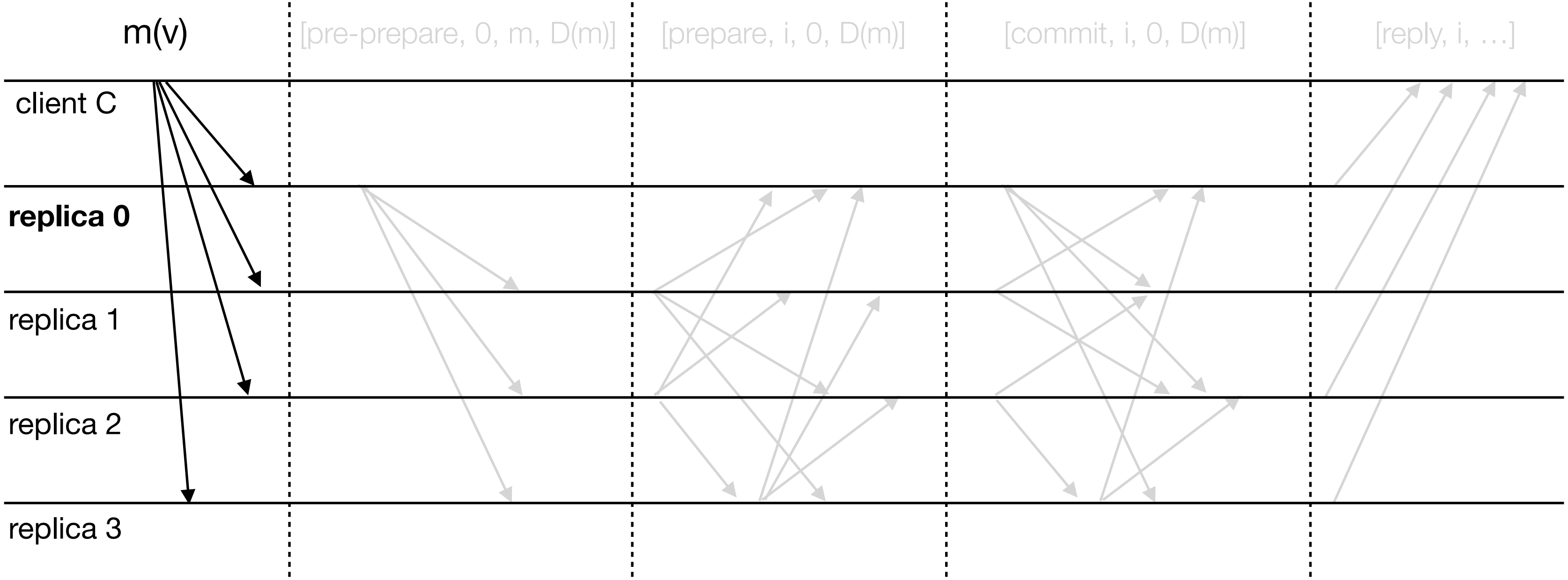
Request → **Pre-Prepare → Prepare → Commit** → Reply

Executed by Client

Executed by Replicas

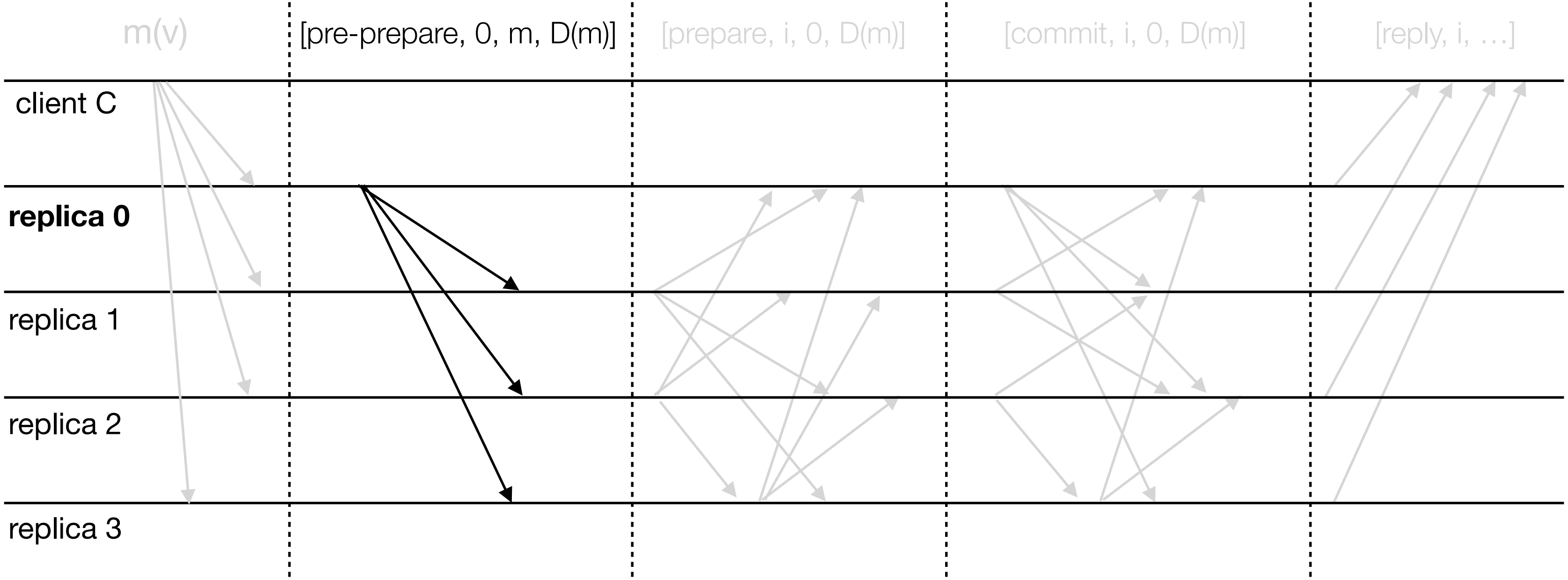
Request

Client C sends a message to *all* replicas



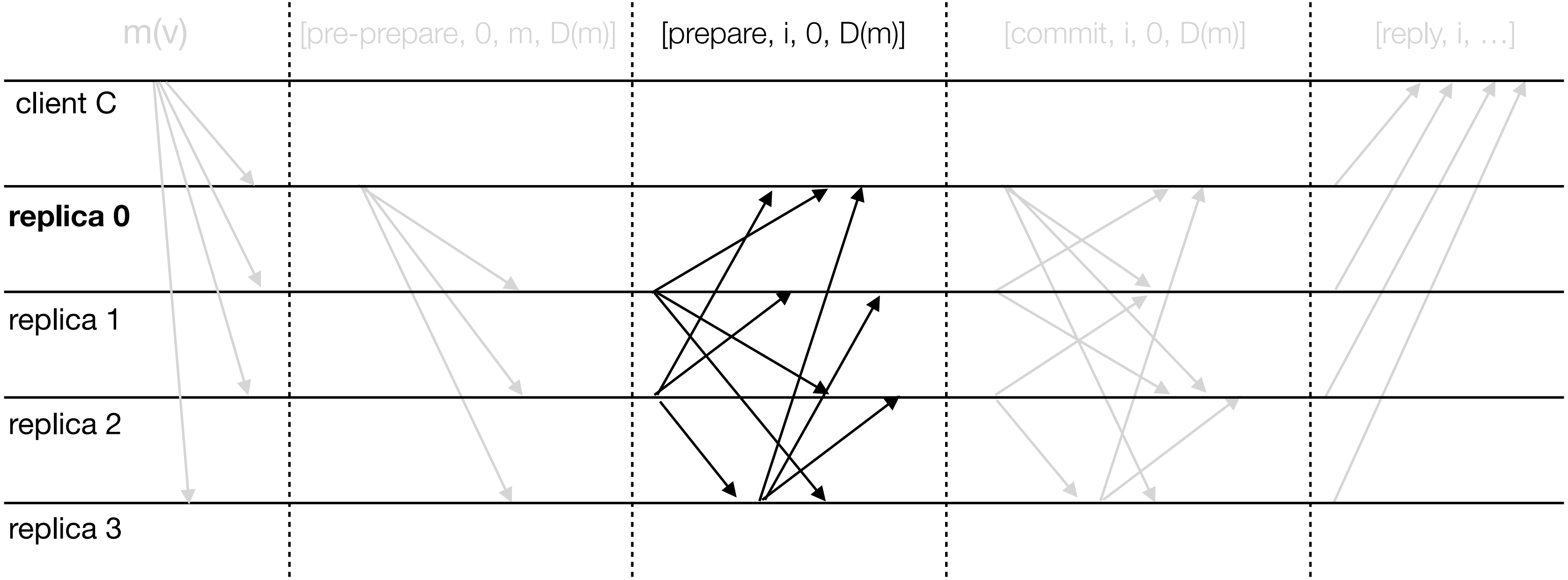
Pre-prepare

- Primary (0) sends a signed pre-prepare message with the to *all backups*
  - It also includes the *digest (hash)* D(m) of the original message



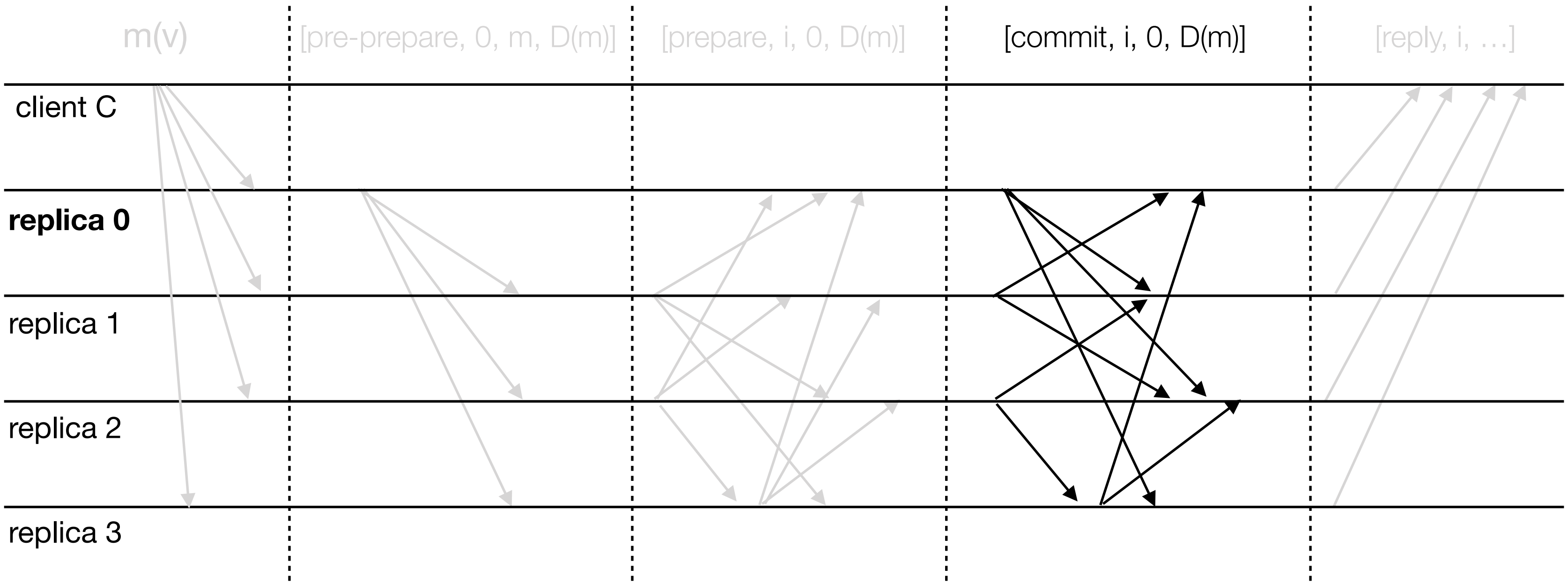
Prepare

- Each replica sends a prepare-message to all other replicas
- It proceeds if it receives 2/3*N + 1 prepare-messages *consistent* with its own



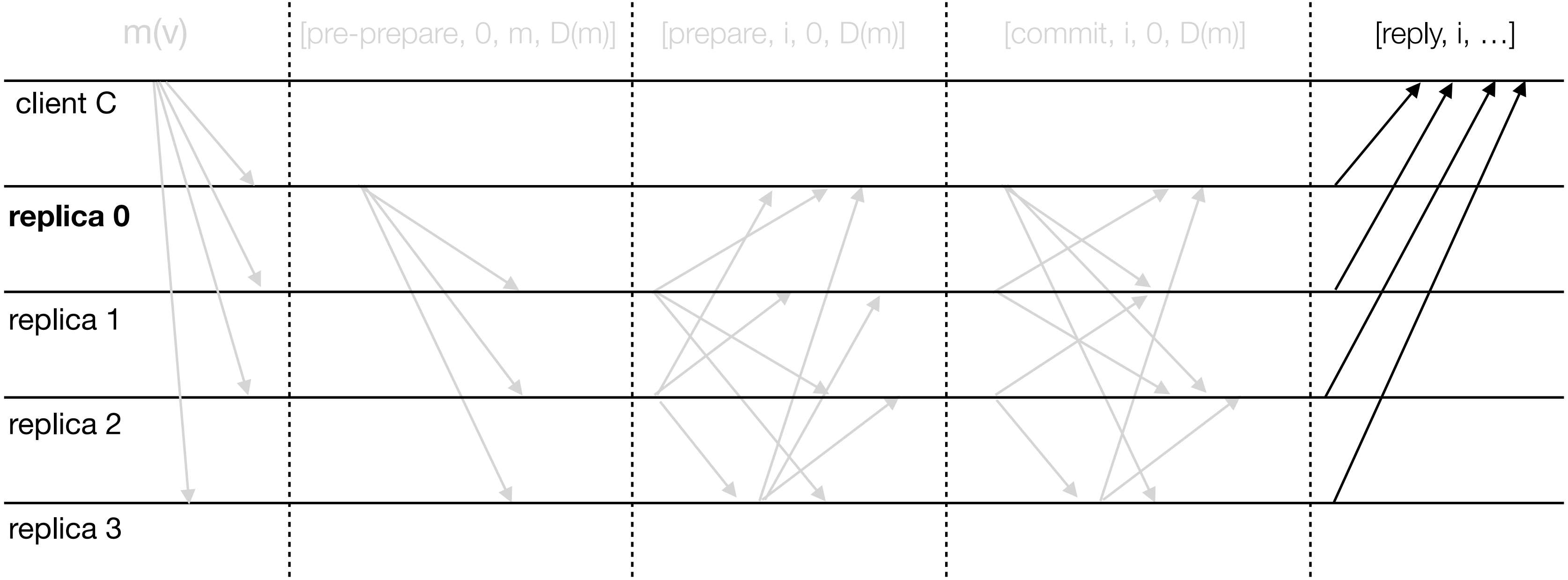
Commit

- Each replica sends a signed commit-message to all other replicas
- It commits if it receives 2/3*N+1 commit-messages *consistent* with its own



Reply

- Each replica sends a signed response to the initial client
- The client trusts the response once she receives N/3 + 1 matching ones



What if Primary is compromised?

- Thanks to large quorums, it *won't break integrity* of the good replicas
- Eventually, replicas and the clients will detect it *via time-outs*
    - Primary sending inconsistent messages would cause the system to *"get stuck"* between the phases, without reaching the end of **commit**
- Once a faulty primary is detected, backups-will launch a ***view-change***, *re-electing a new primary*
- View-change is *similar to reaching a consensus* but gets tricky in the presence of partially committed values
    - See the *Castro & Liskov '99 PBFT* paper for the details…

PBFT in Industry

- Widely adopted in practical developments:
    - Tendermint
    - IBM’s Openchain
    - Elastico/Zilliqa
    - Chainspace
- Used for implementing *to speed-up* blockchain-based consensus
- Many blockchain solutions build on similar ideas
    - Stellar Consensus Protocol, HotStuff

Minimum number required for which
an *f*-resilient consensus protocol exists

	synchrony	asynchrony	partial synchrony
fail-stop	f+1	inf	2f+1
crash	f+1	inf	2f+1 (Paxos)
byzantine with digital signature	f+1 (SM(f+1))	inf	3f+1(PBFT)
byzantine with authenticated channel	3f+1 (OM(f))	inf	

Conclusions

- Defined Byzantine generals problem
- Proved lower bound in synchronous environment with authenticated channel
- Introduced solutions in synchronous environment with authenticated channel and with digital signature
- PBFT Can be used only for a fixed set of replicas
    - Agreement is based on fixed-size quorums
    - Open systems (used in Blockchain Protocols) rely on alternative mechanisms of Proof-of-X (e.g., Proof-of-Work, Proof-of-Stake)
    - Also see Algorand

Timeline

1982

The Byzantine Generals Problem

OM() sync/authenticated channel

SM() sync/digital signature

1990

The part-time parliament

Paxos: async/non-byzantine(crash-failure)

1998

Practical Byzantine Fault Tolerance

PBFT: partial sync/
digital signature/
state machine replication

2008

Bitcoin: A peer-to-peer electronic cash system

Blockchain: partial sync/
proof of work/
state machine replication

2019

Lots of improvements on PBFT

HotStuff
Stellar
Algorand