CS577: Introduction to Blockchain and Cryptocurrency

Introduction to Distributed Systems

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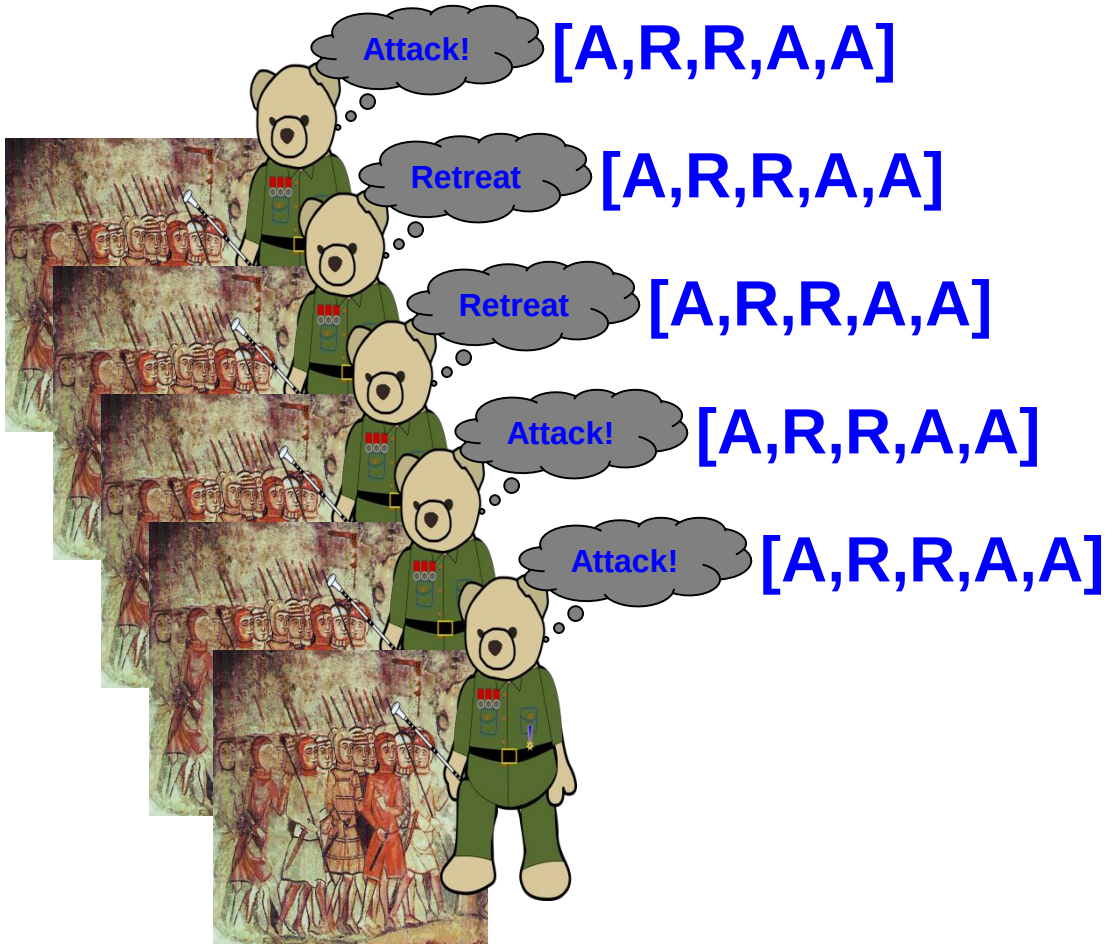
Byzantine Failures

- The network includes faulty processes that do not terminate but continue to participate in the execution of the algorithm.
- The behavior of the processes may be completely unpredictable.
- The internal state of a faulty process may change during the execution of a round arbitrarily, without receiving any message.
- A faulty process may send a message with any content (i.e., fake messages), independently of the instructions of the algorithm.
- We call such kind of failures as Byzantine failures.
- We use byzantine failures to model malicious behavior (e.g. cyber-security attacks).

Why study Byzantine Fault Tolerance?

- Does this happen in the real world?
  The "one in a million" case.
  - Malfunctioning hardware,
  - Buggy software,
  - Compromised system due to hackers.

The problem


Attack!
[A,R,R,A,A]
Retreat
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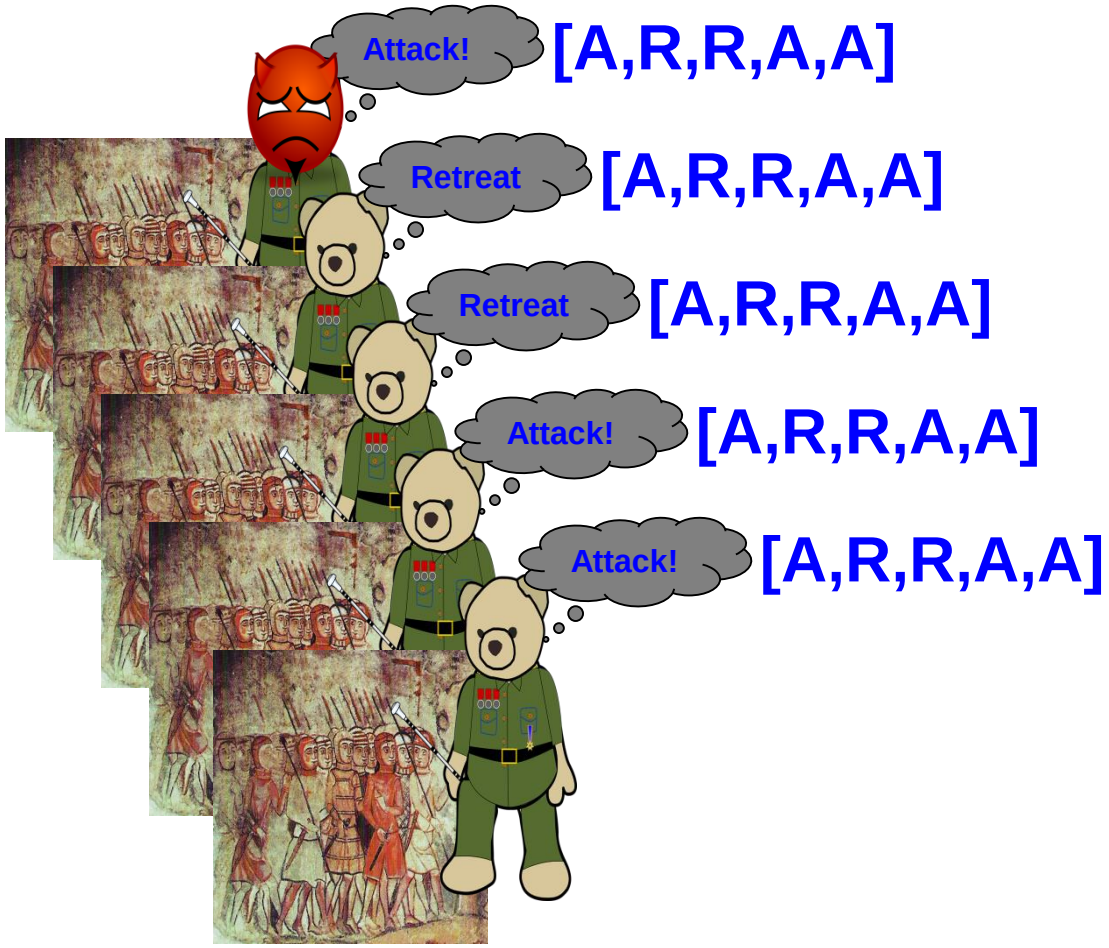
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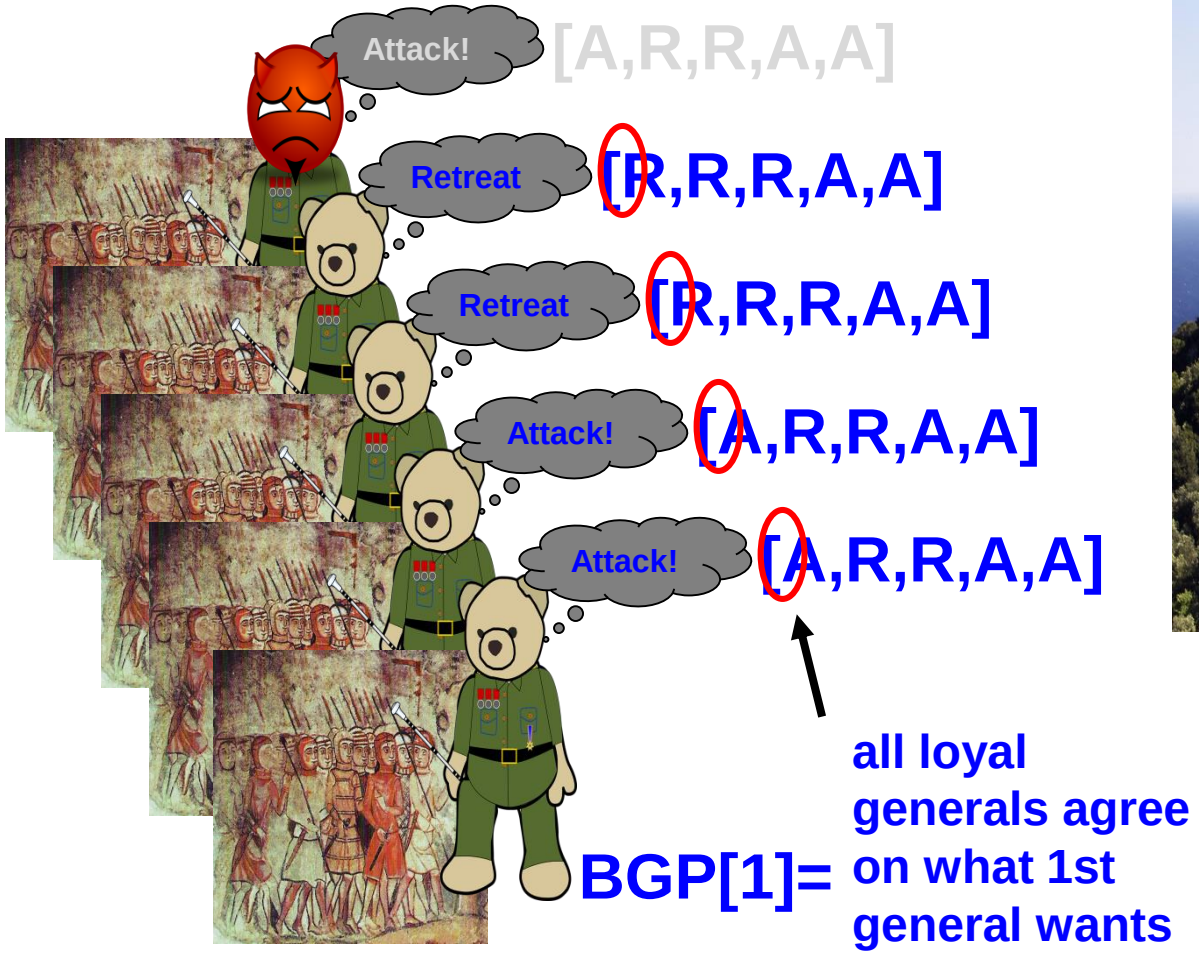
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BGP[1]=
all loyal generals agree on what 1st general wants

Solving Byzantine Generals Problem

How many traitors can you have and still solve BGP?

Lamport, Shostak and Pease Algorithm

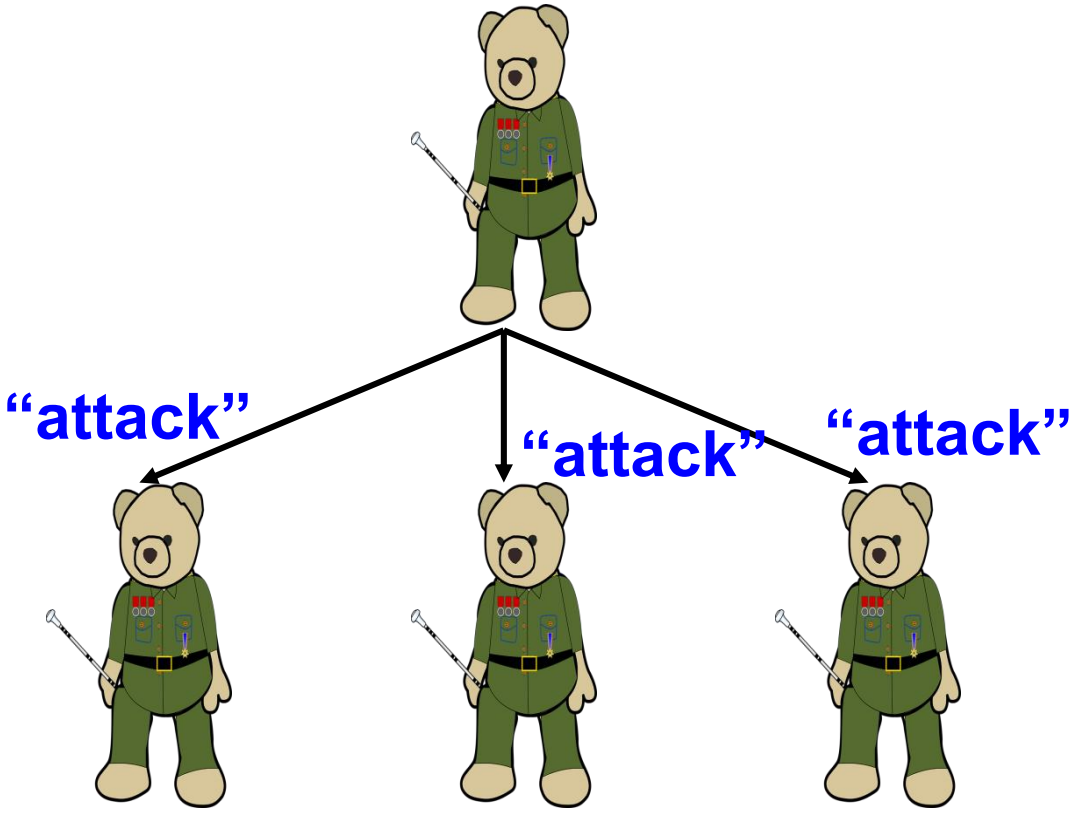
L. Lamport, R. Shostak, M. Pease: "The Byzantine Generals Problem", ACM Transactions on Programming Languages and Systems, 4(3): pp 382-401, 1982.

- The algorithm makes three assumptions regarding communication:
  1. All message transmissions are delivered correctly.
  2. The receivers knows the identity of the sender.
  3. The absence of a message can be detected.
- The 1st and 2nd assumptions limit the traitor from interfering with the transmissions of the other generals.
- The 3rd assumptions prevents the traitor to delay the attack by not sending any message.
- In computer networks conditions 1 and 2 assume that the processors are directly connected and communication failures are counted as part of the β failures.

Problem Statement

- On general achieves the role of Chief of Staff.
- The Chief of Staff has to send an order to each of the $n-1$ generals such that:
  1. All faithful generals follow the same order
     (all non faulty processes receive the same message)
  2. If the Chief of Staff is faithful, then all faithful generals follow his orders
     (if all processes are non-faulty then the messages received are the same with the transmitting process)
- The above conditions are known as the conditions for "consistent broadcast".
- Note: If the Chief of Staff is faithful, then the 1st condition derives from the 2nd. But he may be the traitor.

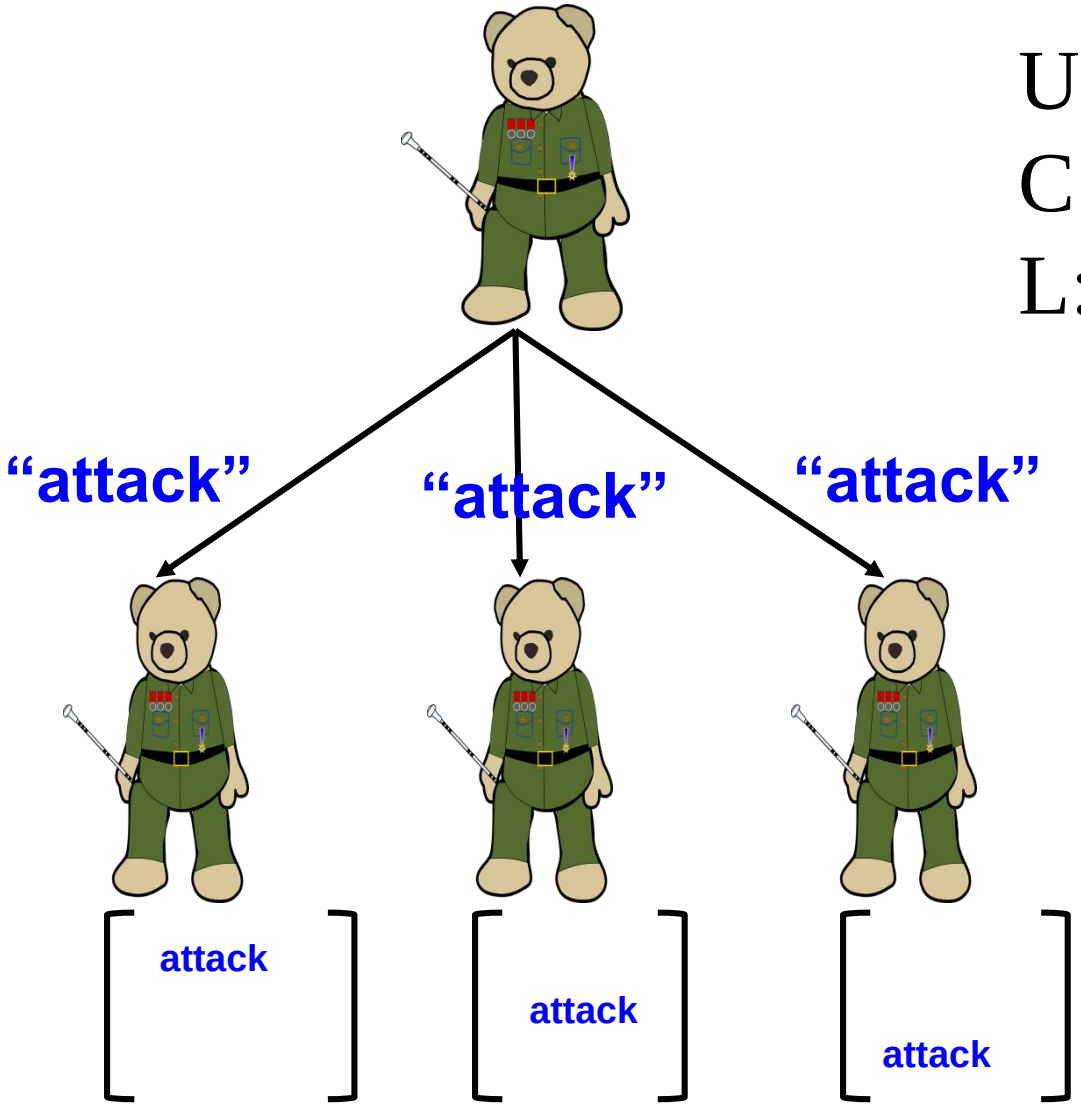
Inductive Solution for Oral Messages



m=0 (no. of traitor)

UM(4,m):
C: Sends order.
L: Follows if received.

Inductive Solution for Oral Messages



UM(4,m), m>=0:

C: Sends order.

L:

1. **Records if received.**
2. **Use UM(3,m-1) to tell others.**
3. **Follows majority() order.**

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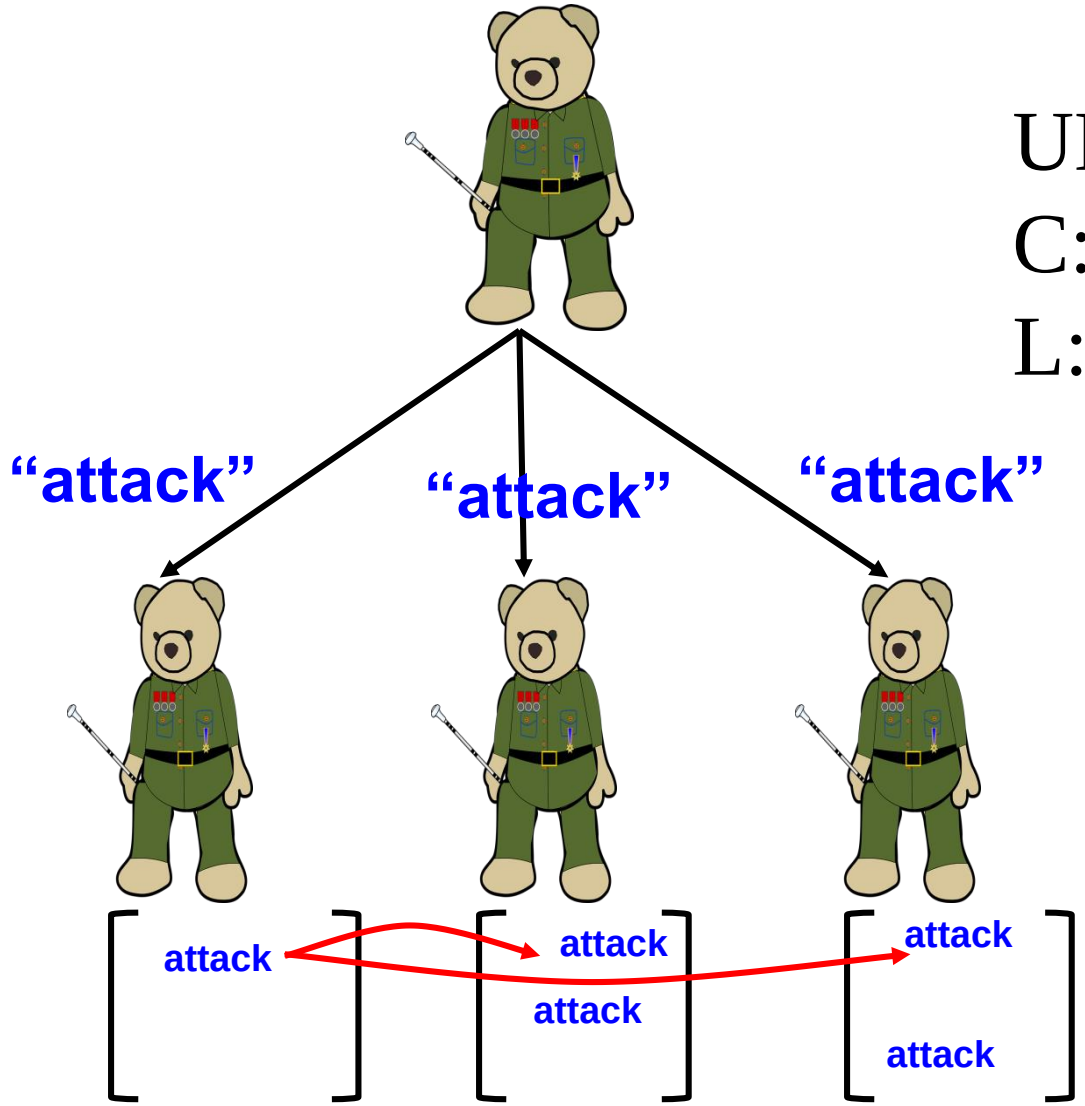

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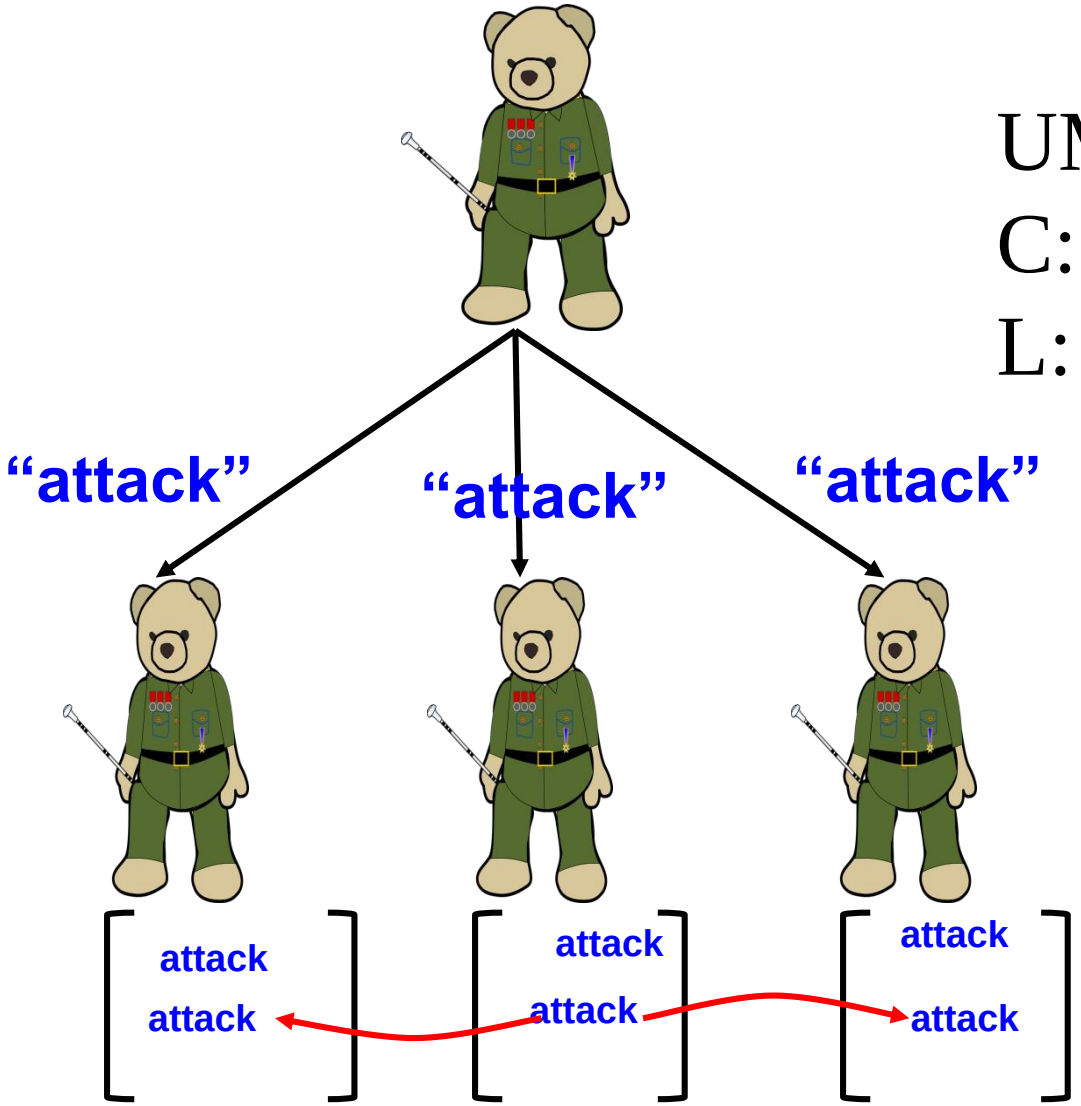

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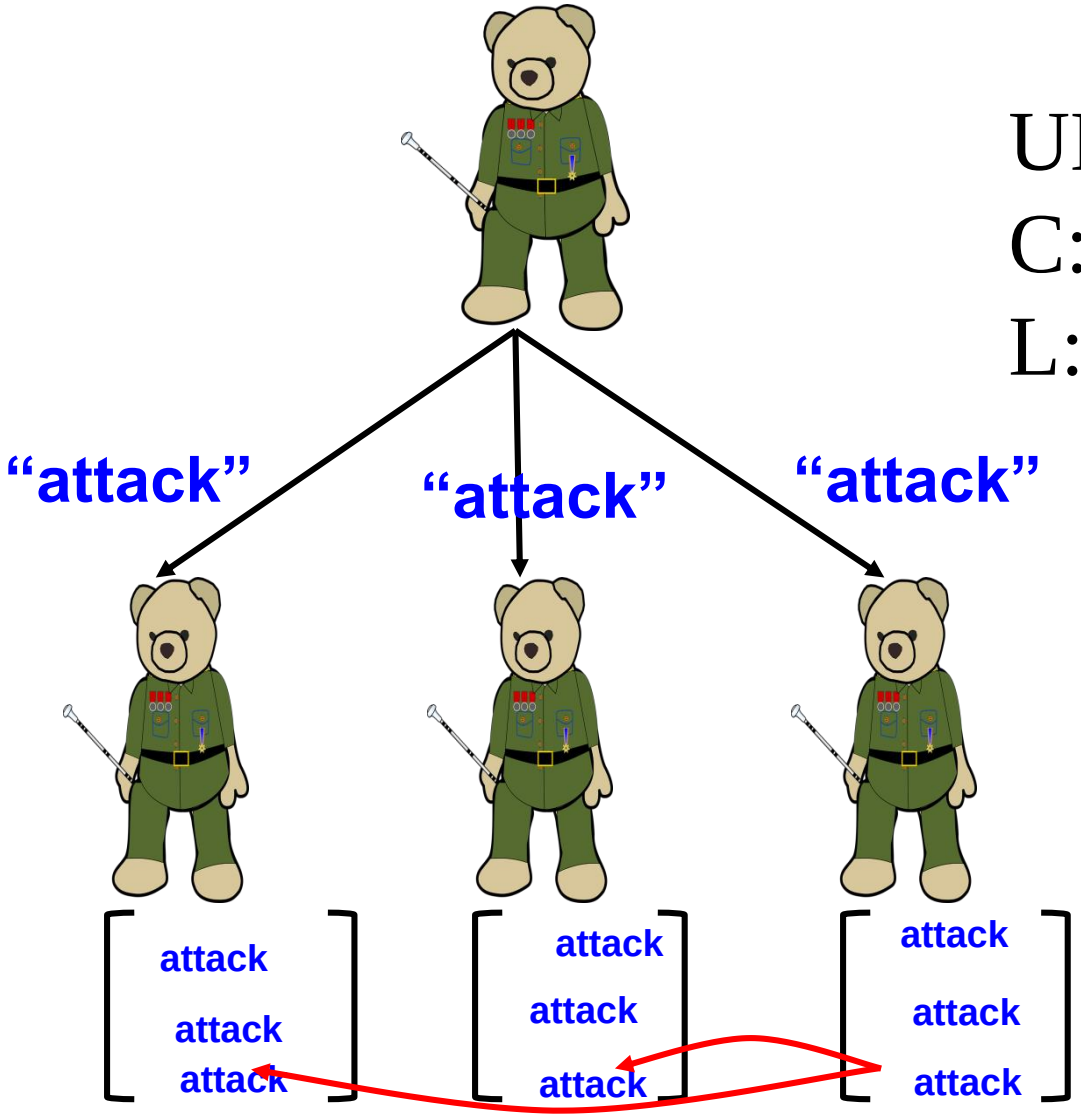

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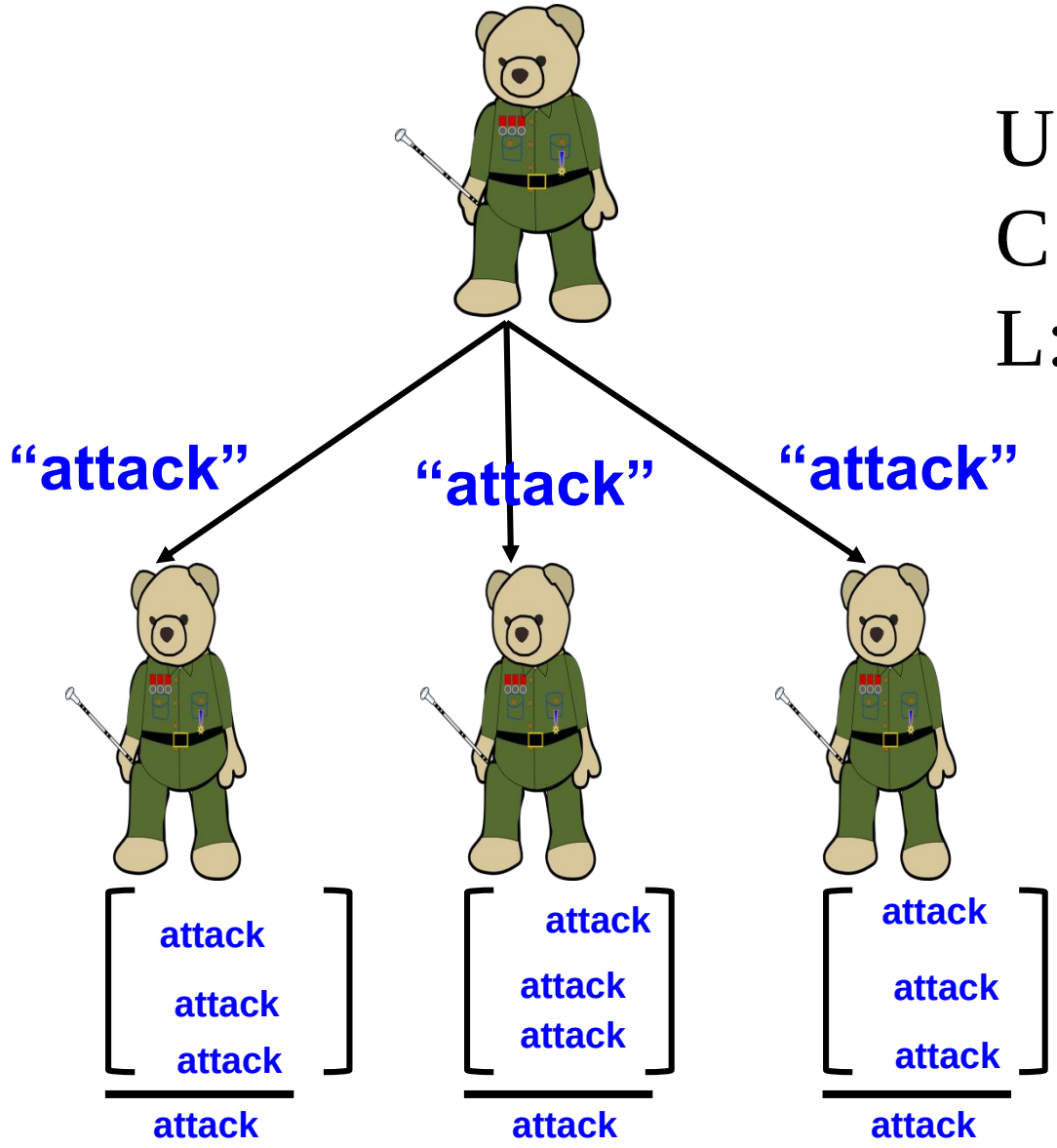

UM(m), m>=0:

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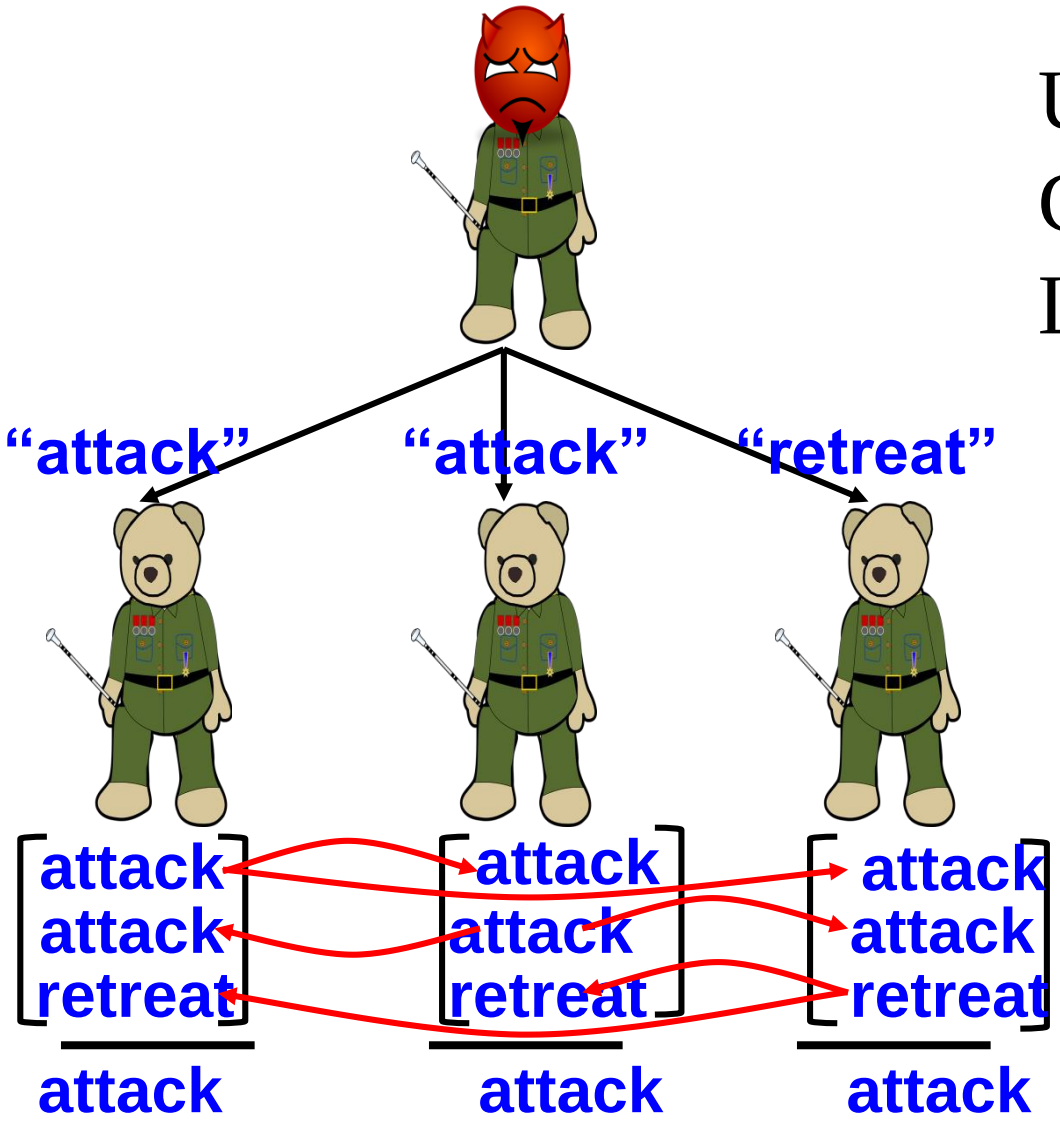
How this works with m=1



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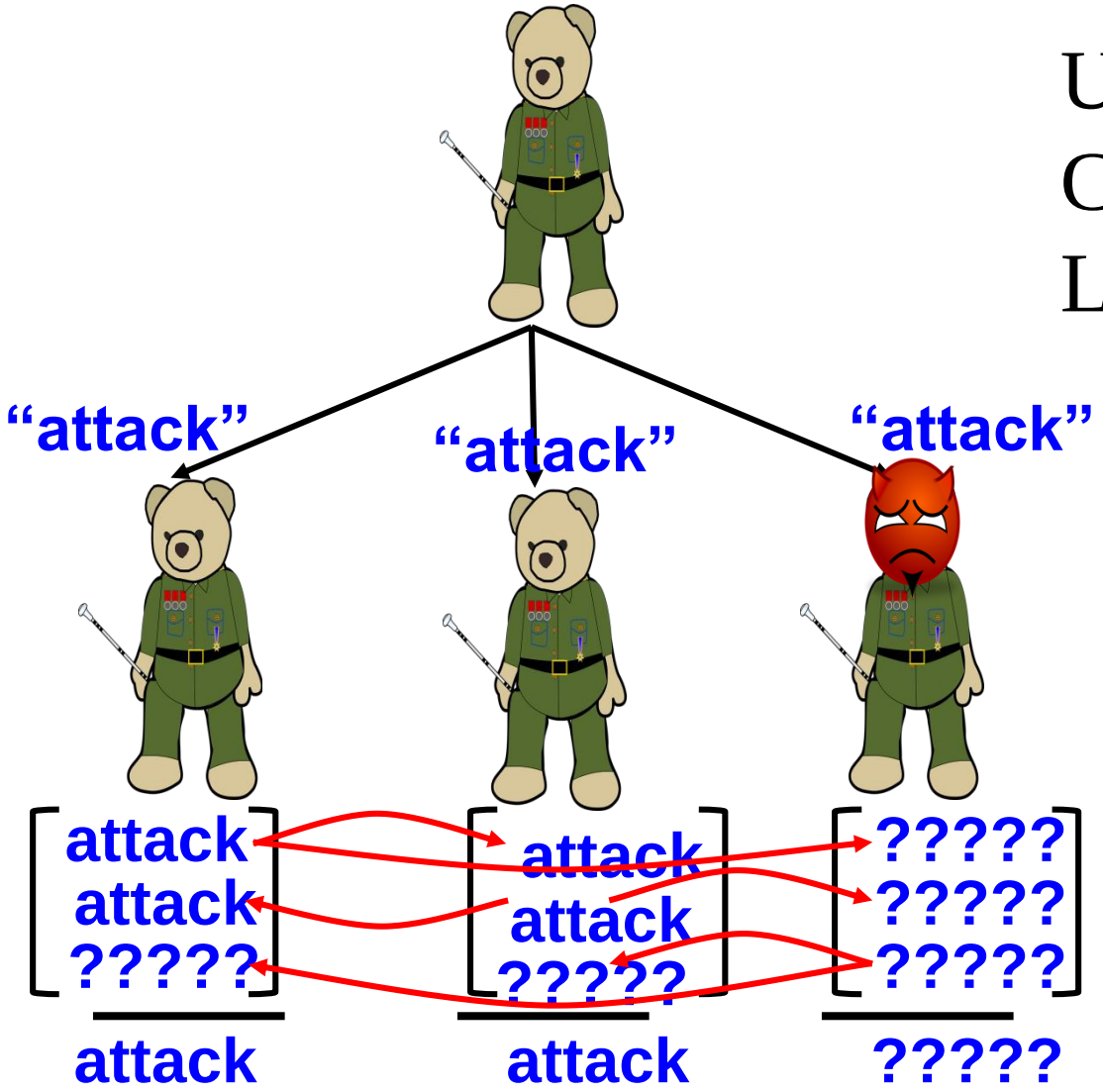

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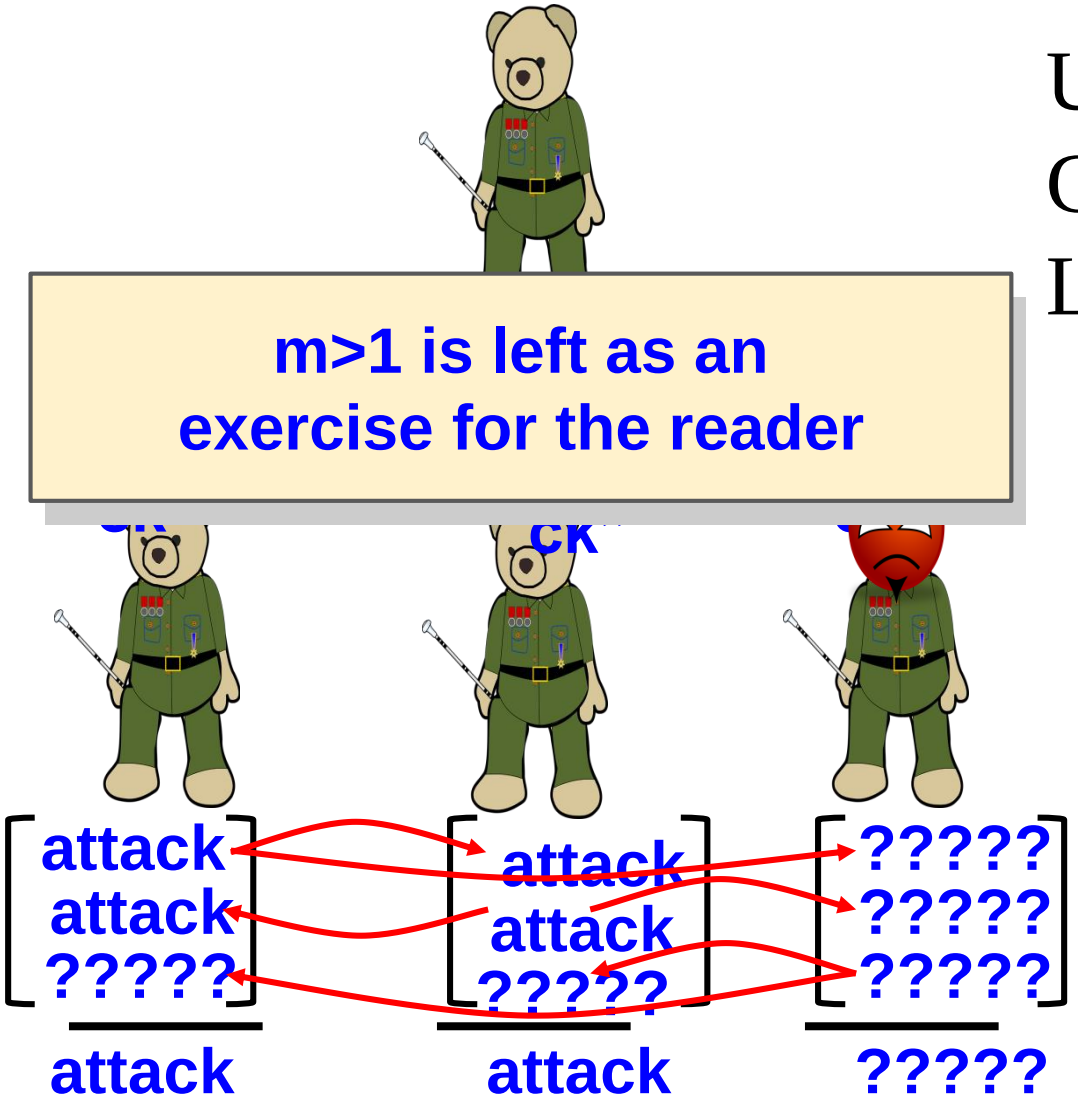

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Lamport, Shostak and Pease Algorithm

- Let n processes and β failures.
- Processes have a predefined decision o_{def} that is used when the Chief of Staff is a traitor (e.g., retreat).
- We define function majority$(o_1, \ldots, o_{n-1}) = o$ that computes the majority of decisions $o_u = o$

Algorithm UM(n,0) (for 0 traitors)

1. The Chief of Staff transmits decision o to all generals.
2. All generals decide o or if they do not receive a message, they decide o_{def}.

Lamport, Shostak and Pease Algorithm

Algorithm UM(n, m) (for m traitors)

1. The Chief of Staff transmits decision o to all generals.
2. For each general u
   - Set o_u to the value received, or if no message received, set to o_{def}.
   - Send the value o_u to the $n-2$ generals by invoking UM($n-1, m-1$).
3. For each general u and each $v \neq u$
   - Set o_v to the value received from u at step 2, or if no message received set to o_{def}.
   - Decide on value majority($o_1, \ldots, o_{n-1}$).

n=1, or n=2?

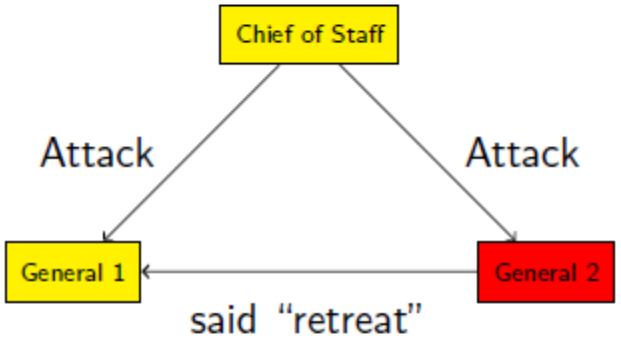
Trivial, no consensus required.

Impossibility Result n=3 and m=1

Impossibility result

Let's examine the following cases involving 3 generals:

Case #1



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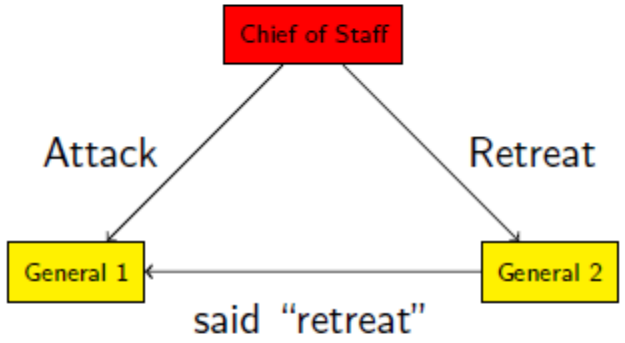

- In case #1, General 1 in order to meet the 2nd condition, he has to attack.

2nd Condition

If the Chief of Staff is faithful, then all faithful generals follow his orders.

Impossibility Result n=3 and m=1

Impossibility result

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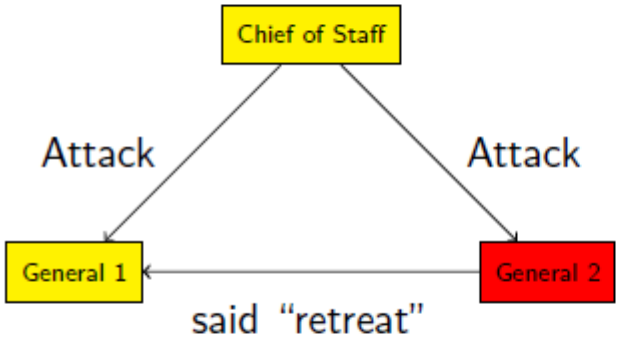

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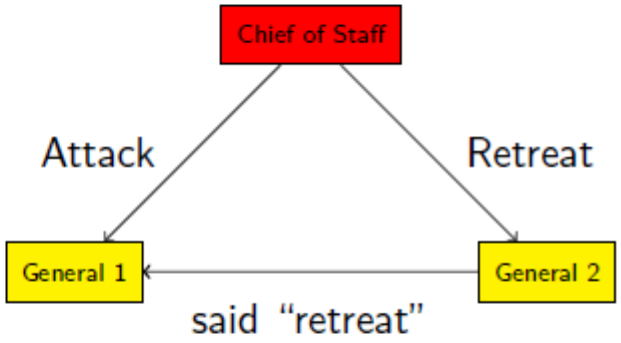

- In case #2, if General 1 attacks then he violates the 1st condition.

1st Condition

All faithful generals follow the same order

Impossibility result

- Given the messages received by General 1, each case looks symmetric.
- General 1 cannot break the symmetry.
- No solution exists for the Byzantine Generals in case of 3 generals and 1 traitor.
- Generalization of the impossibility result:
  No solution exists for less then $3\beta + 1$ generals if it has to deal with β traitors.

Properties of Algorithm

- By applying UM(n,β) we get $n-1$ messages
- For each message the UM(n,$\beta-1$) is activated that generates $n-2$ messages
- ...
- The total number of messages is $\mathcal{O}(n^{\beta+1})$
- The $\beta+1$ steps during which messages are exchanged between the processes is a mandatory feature of algorithms that need to reach consensus in the presence of β faulty processes.

Fischer-Lynch-Paterson [FLP'85] Impossibility Result

- It is impossible for a set of processors in an asynchronous system to agree on a binary value, even if only a single process is subject to an unannounced failure
  - We won't show any proof here – it's too complicated
- The core of the problem is asynchrony
  - It makes it impossible to tell whether or not a machine has crashed (and therefore it will launch recovery and coordinate with you safely) or you just can't reach it now (and therefore it's running separately from you, potentially doing stuff in disagreement with you)
- For synchronous systems, 3PC can be made to guarantee both safety and liveness!
  - When you know the upper bound of message delays, you can infer when something has crashed with certainty

Coordinated Attack of 4 Byzantine Generals

Four generals wish to coordinate the attack of their armies in an enemy city. Among the generals there exits a traitor. All loyal generals must agree to the same attack (or retreat) plan regardless of the actions of the traitor. Communication among generals is carried out by messengers. The traitor is free to do as he chooses.

- Consensus problem in a system with $n = 4$ processes under the presence of byzantine failures.
- Possible input/output values are "yes" or "no" – that is $S = \{\text{"yes"}, \text{"no"}\}$