CS 60002: Distributed Systems

T9: Byzantine Agreement

Department of Computer Science and Engineering

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Byzantine Generals Problem

Lieutenant - 1

Commander

Lieutenant - 2

Byzantine Generals Problem

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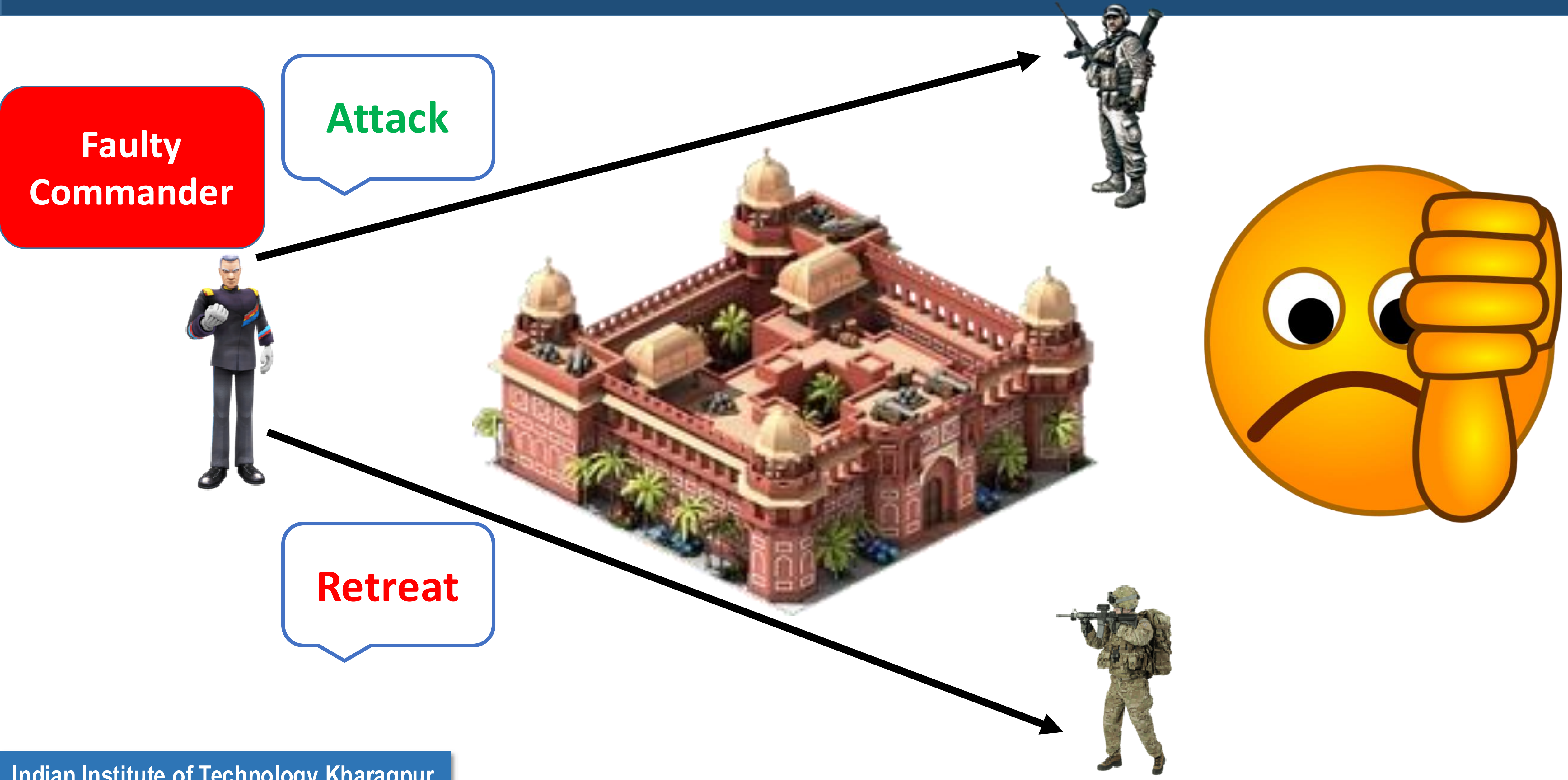

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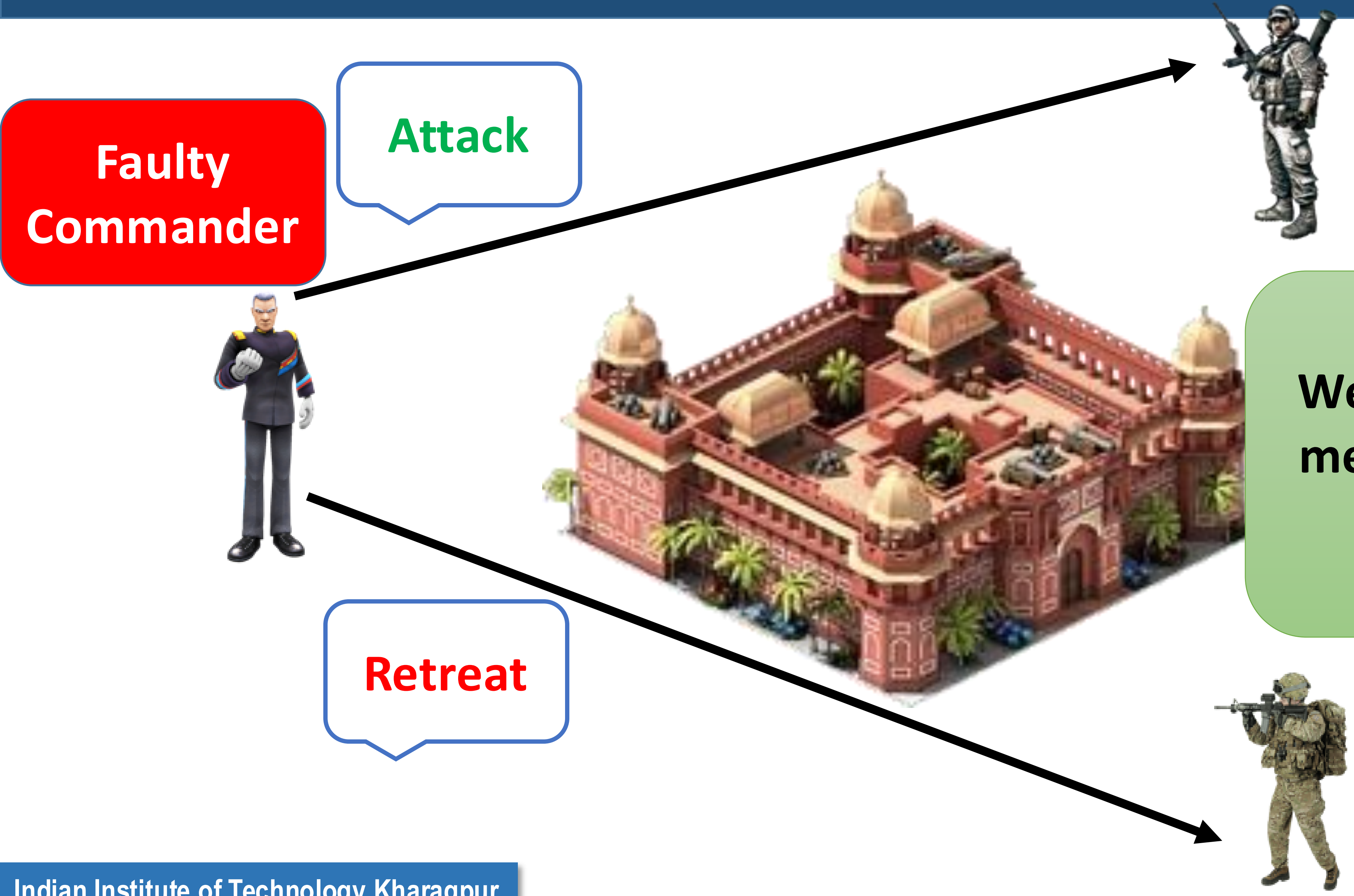

We need a consensus mechanism to decide who is faulty

Byzantine Generals Problem

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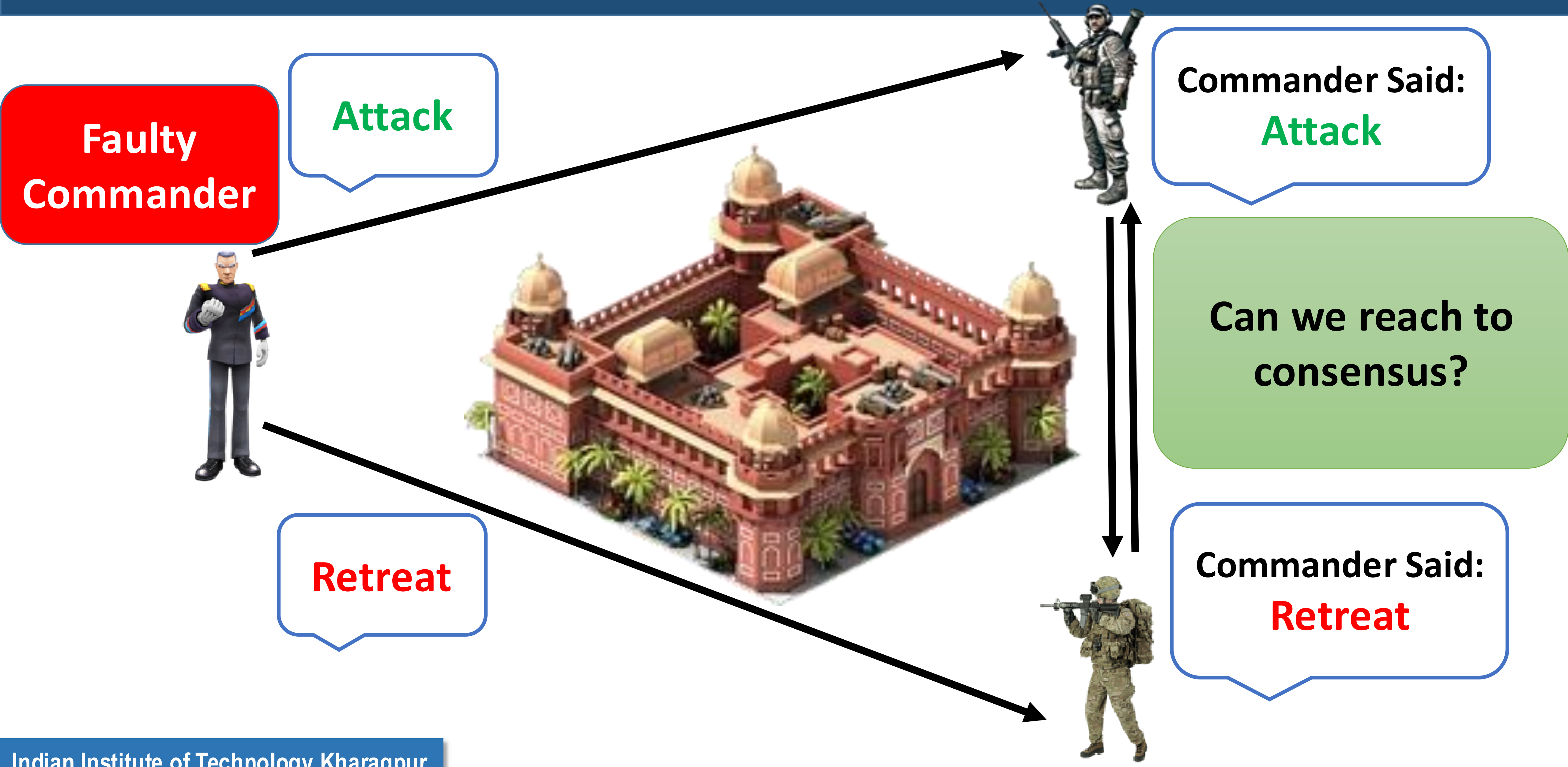

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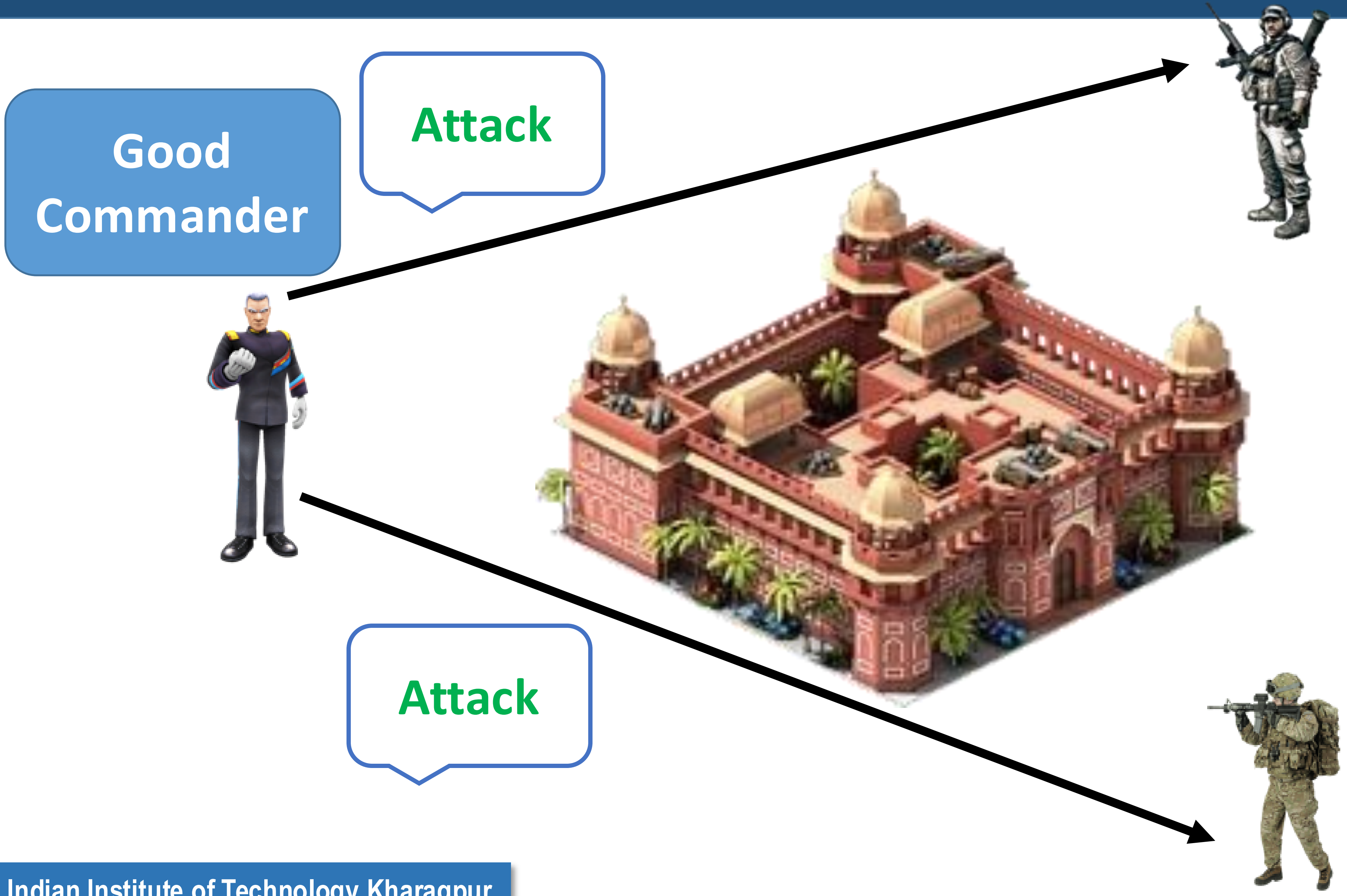

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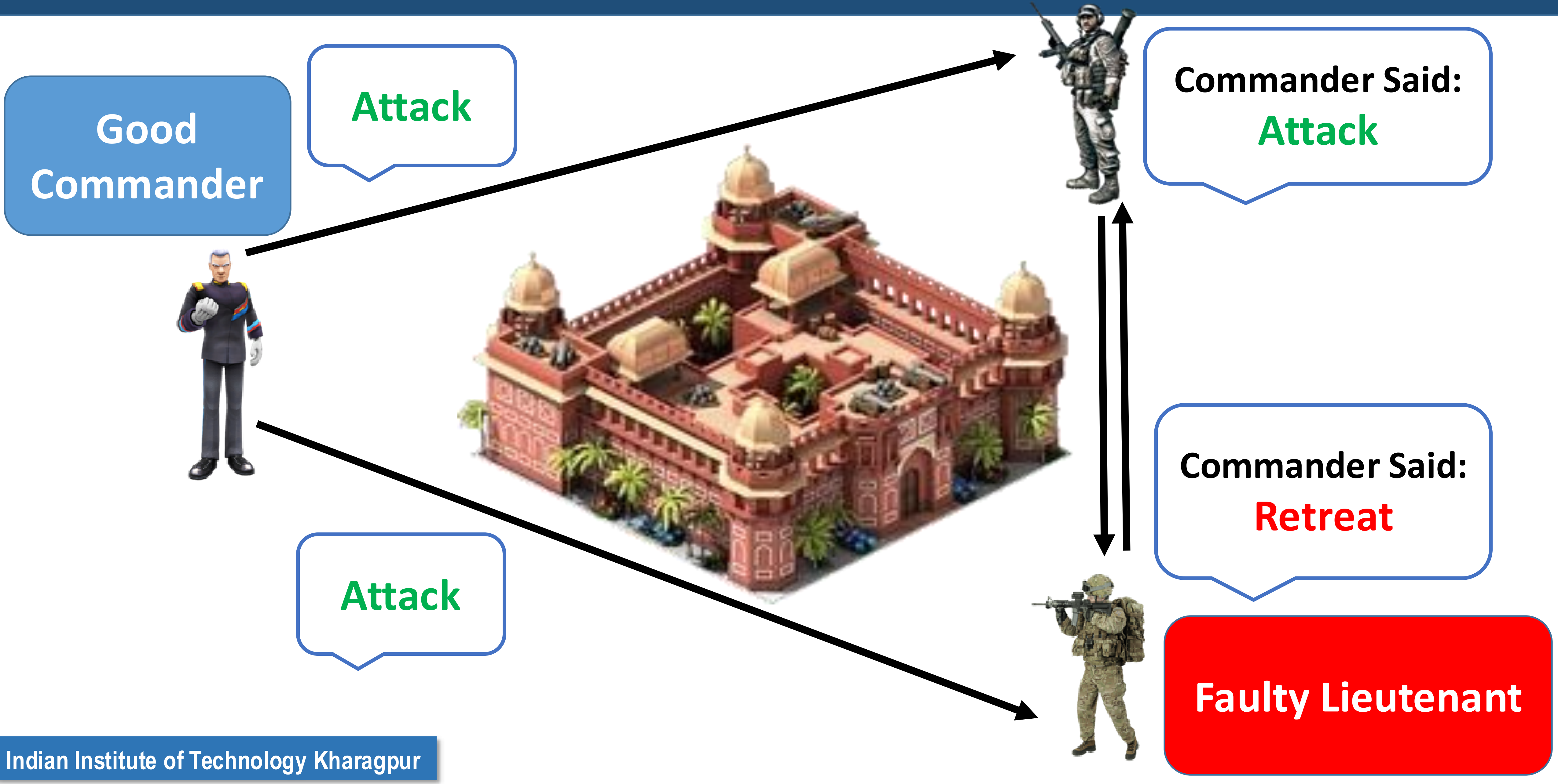

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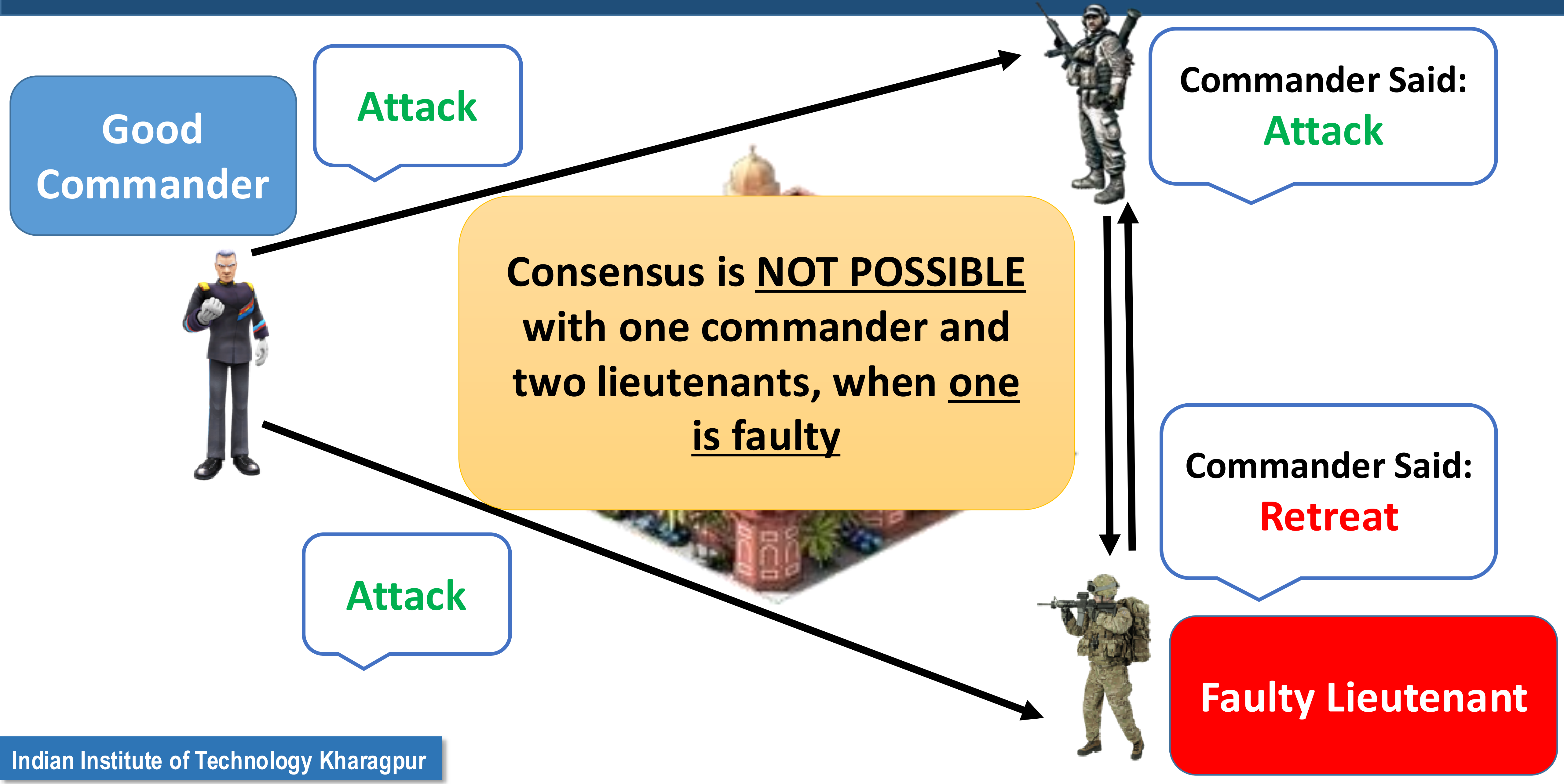

Byzantine Generals Problem – Three Lieutenants

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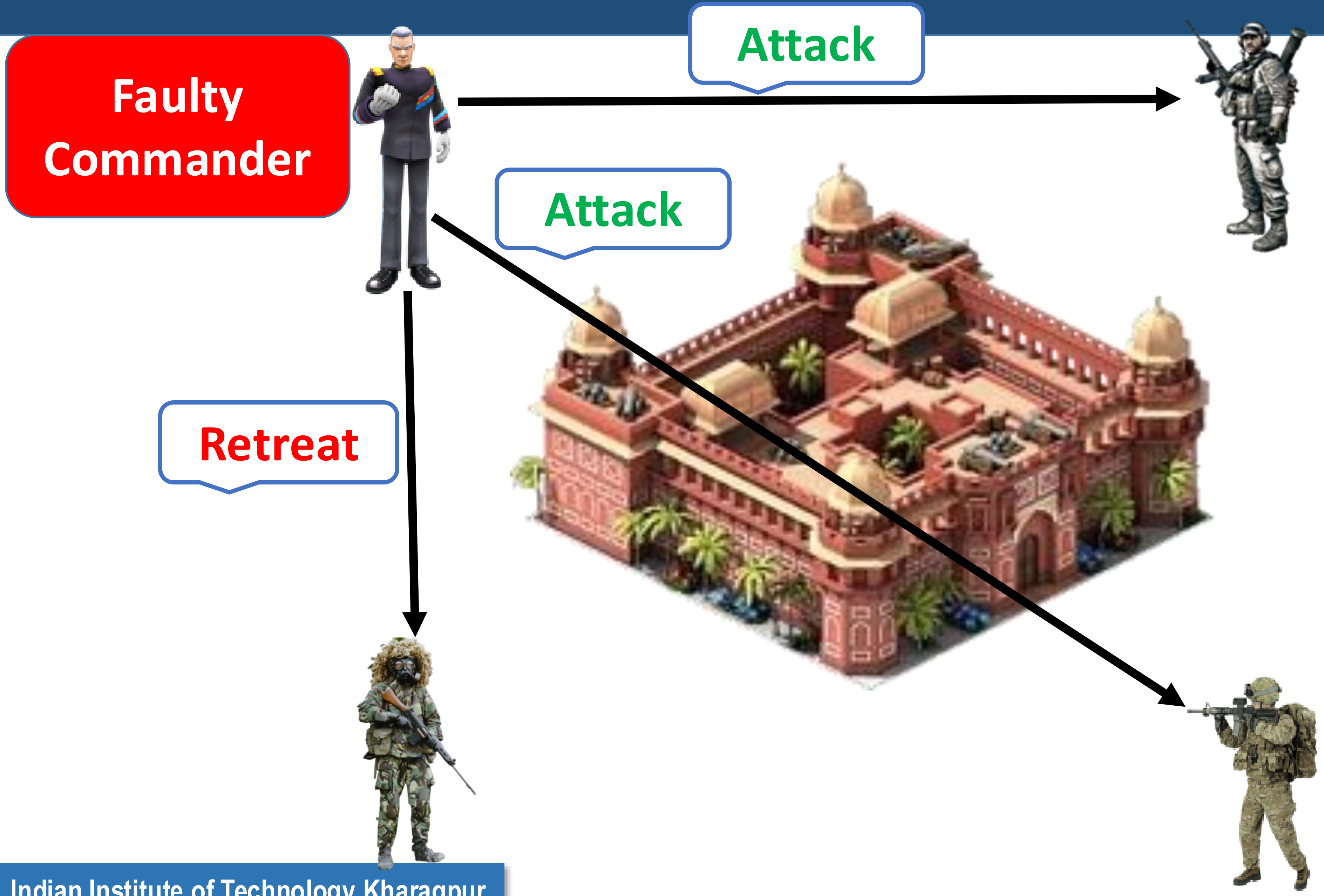

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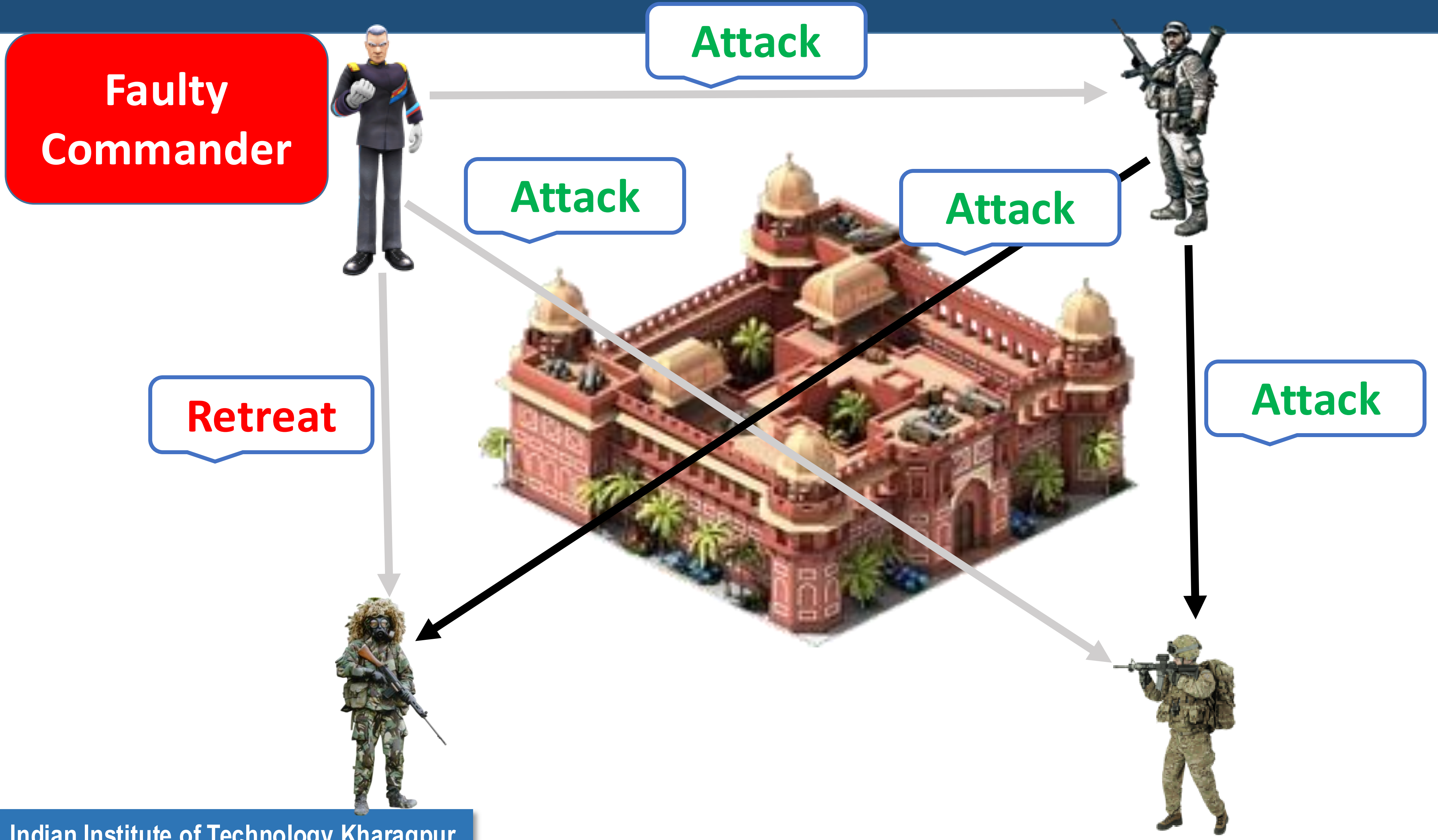

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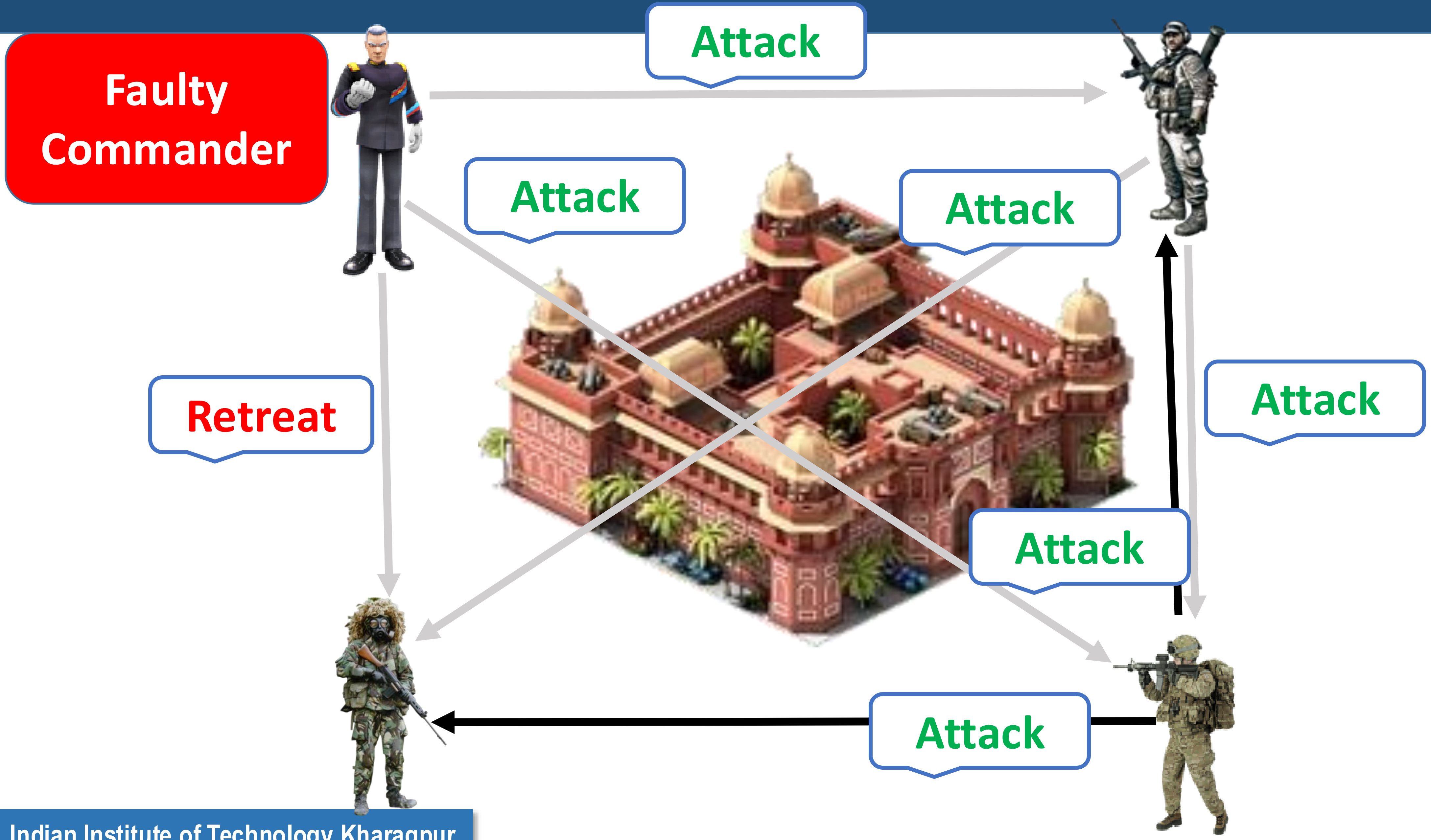

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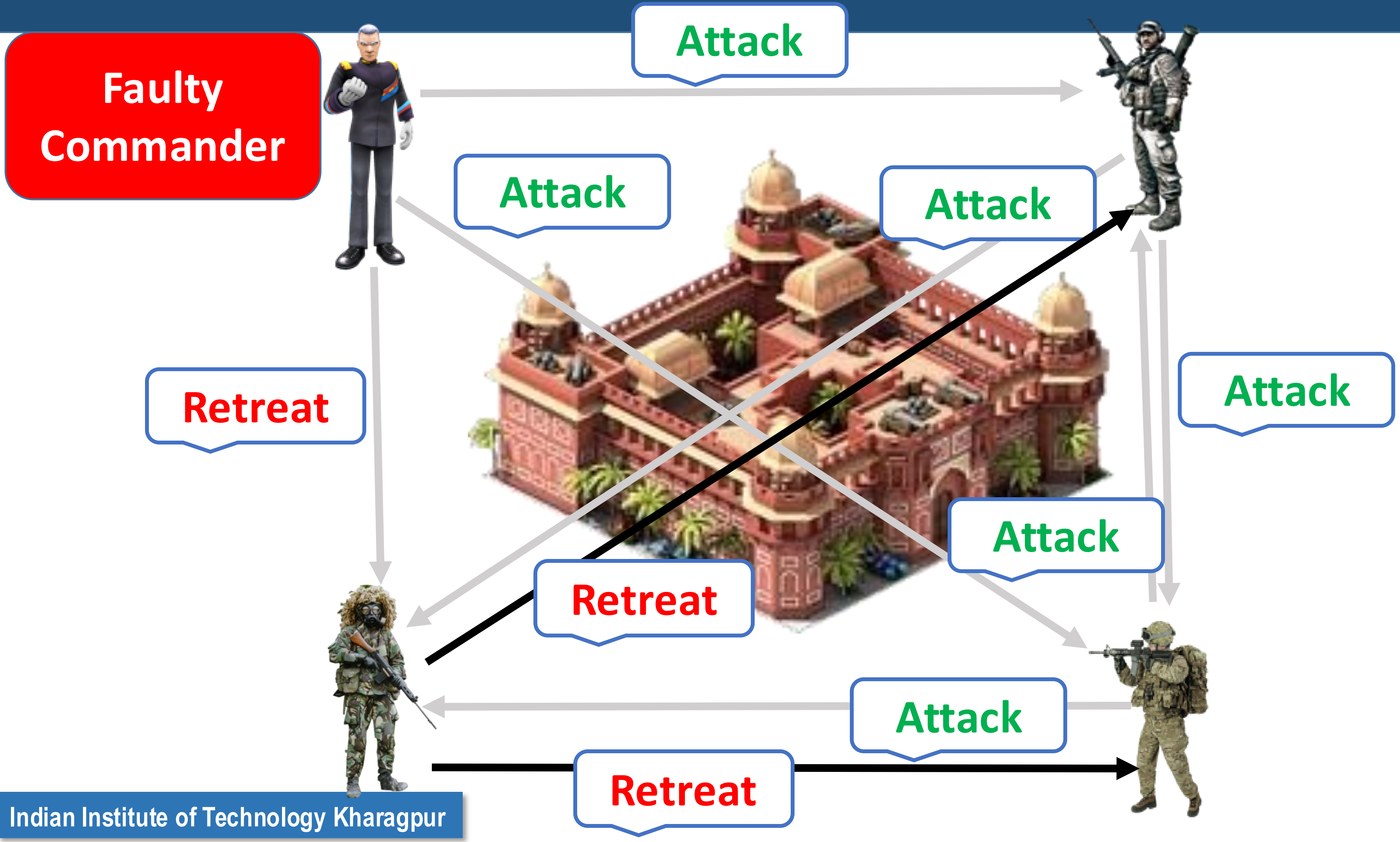

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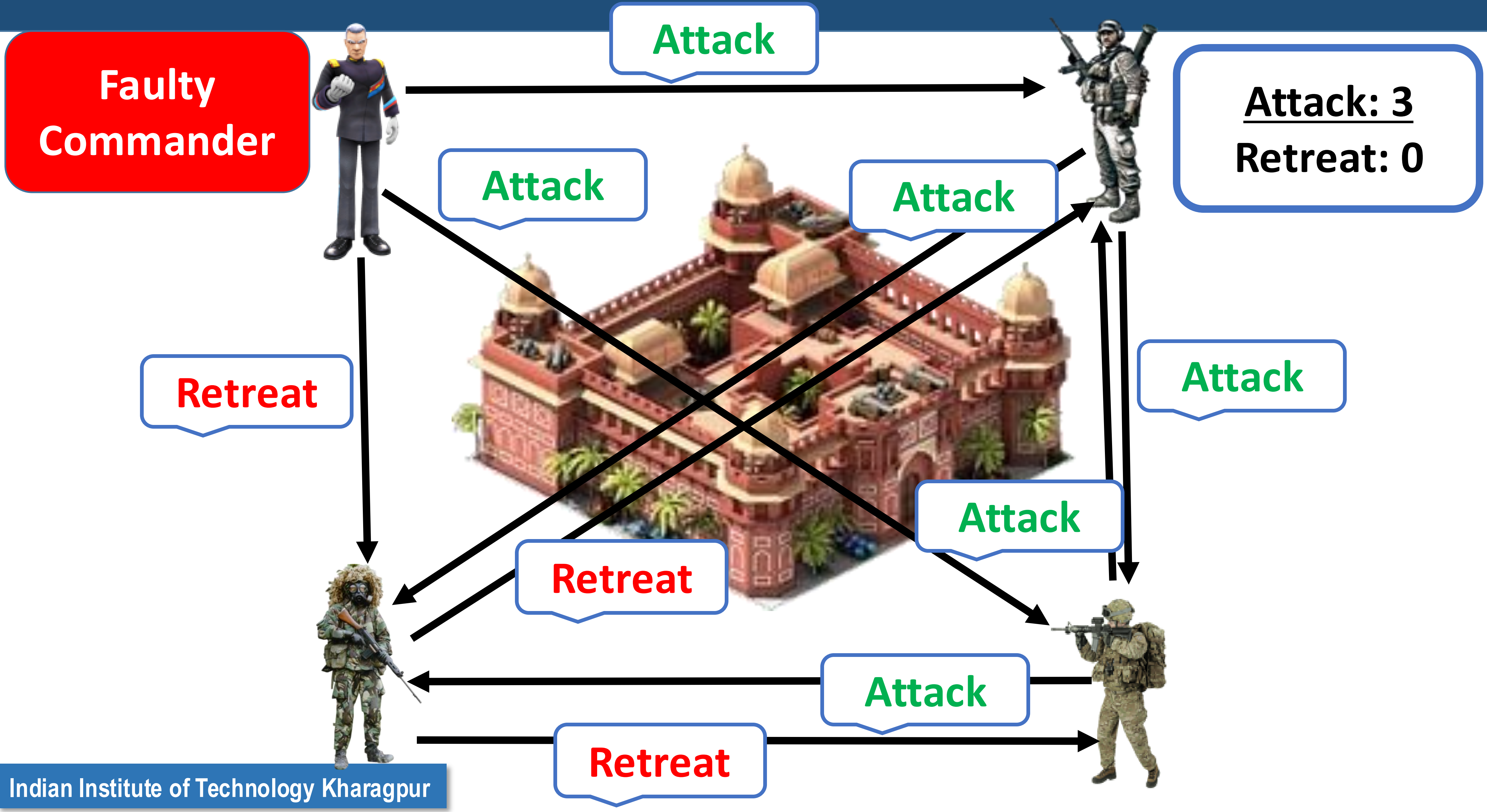

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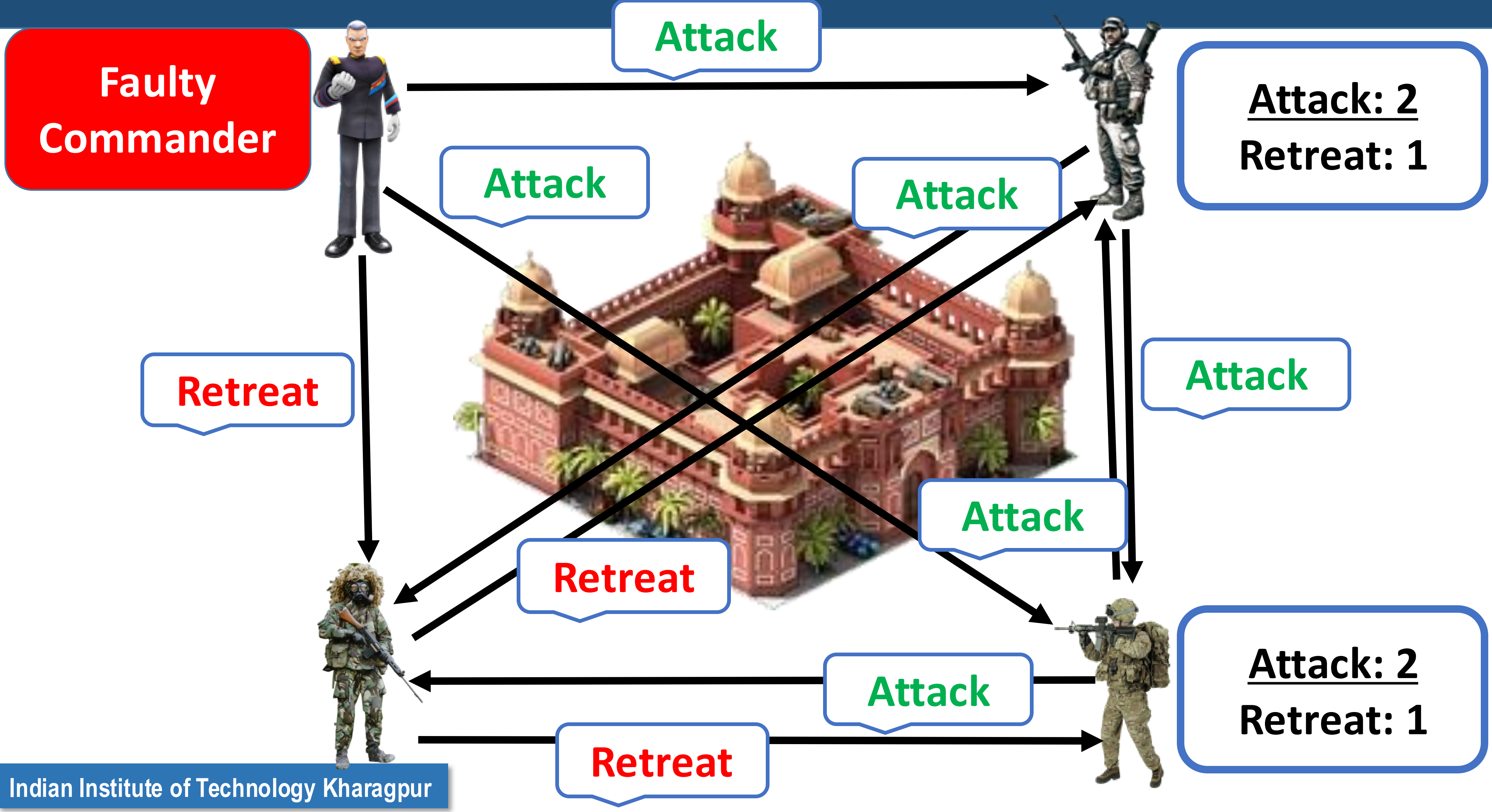

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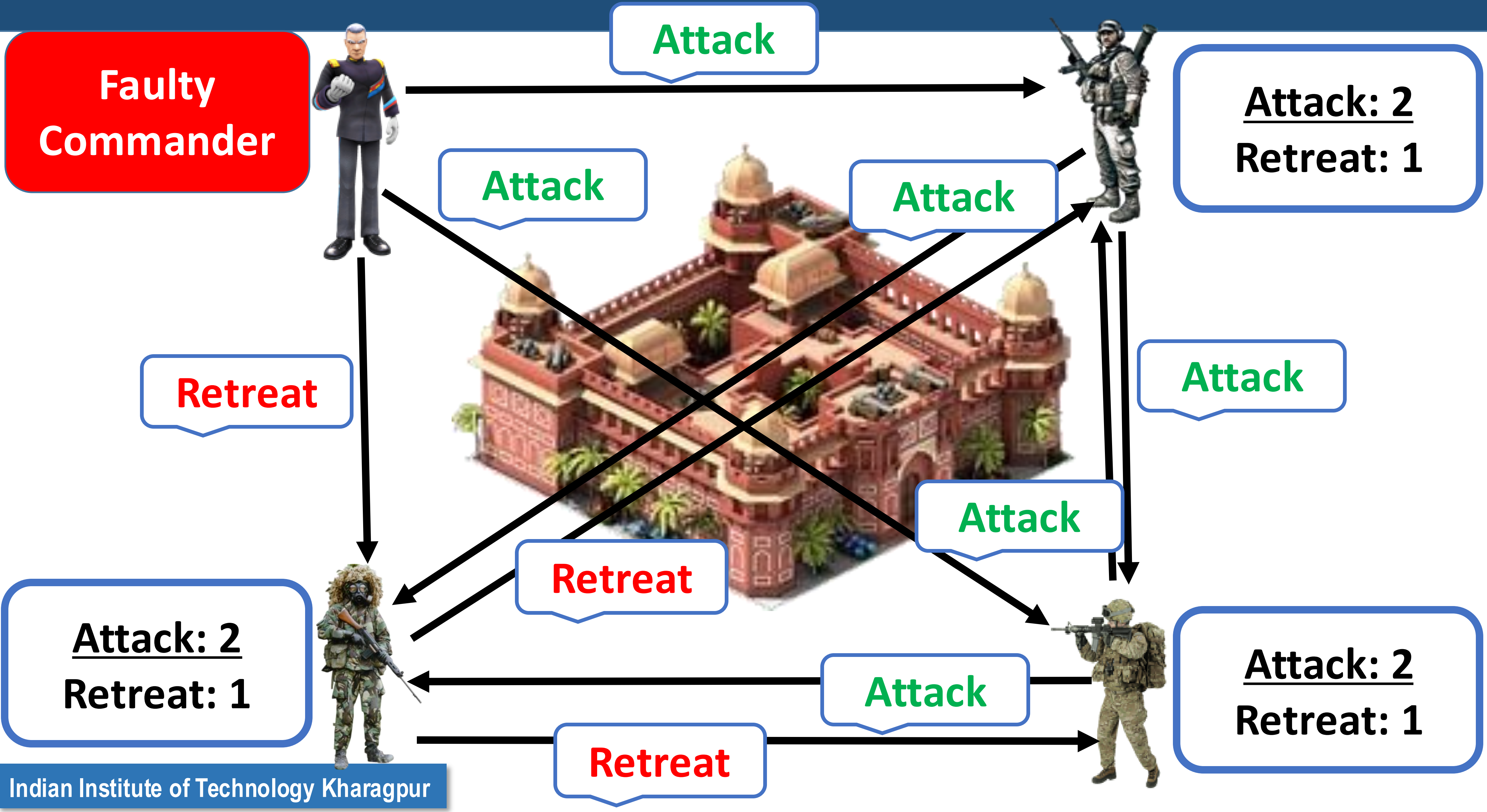

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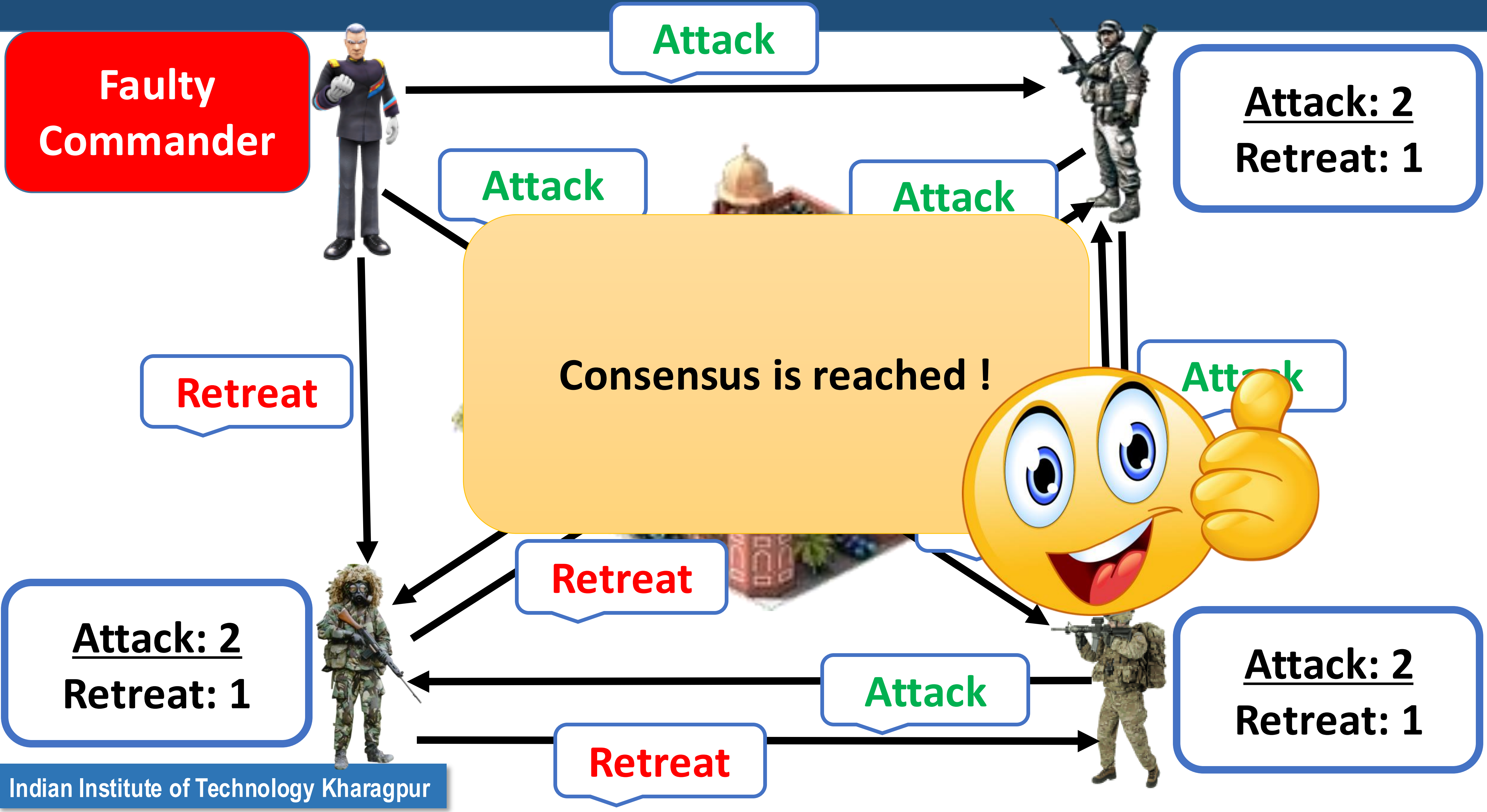

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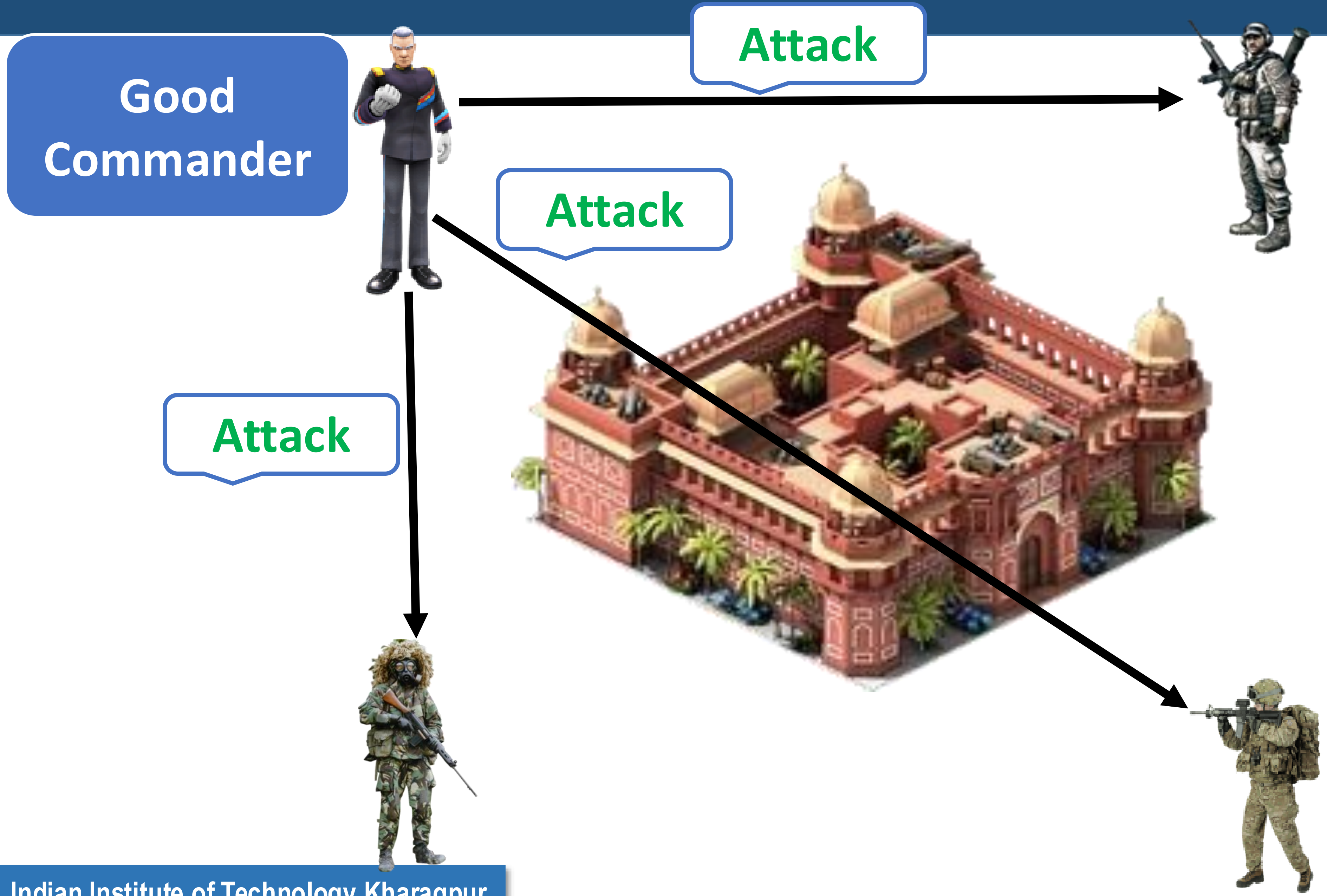

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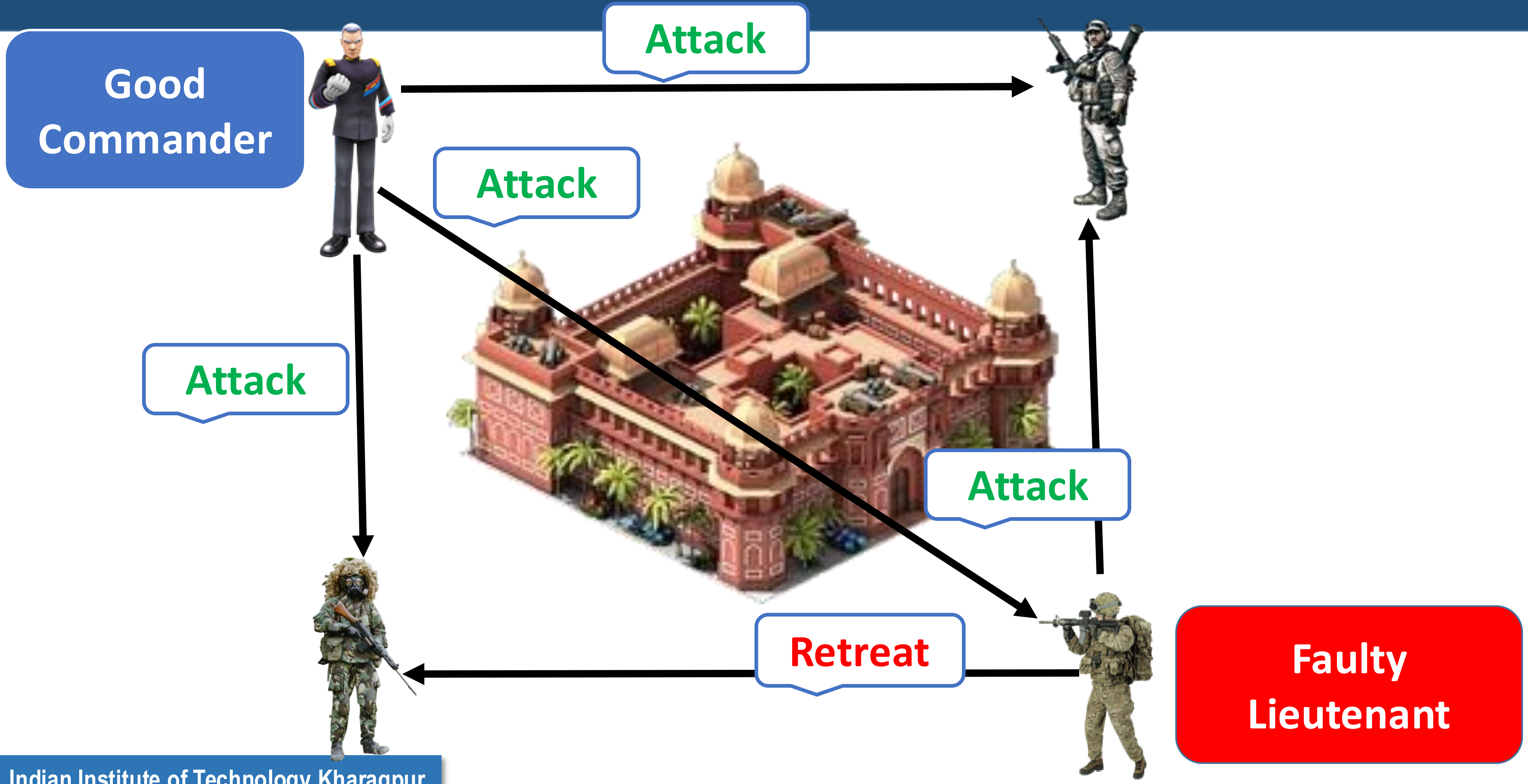

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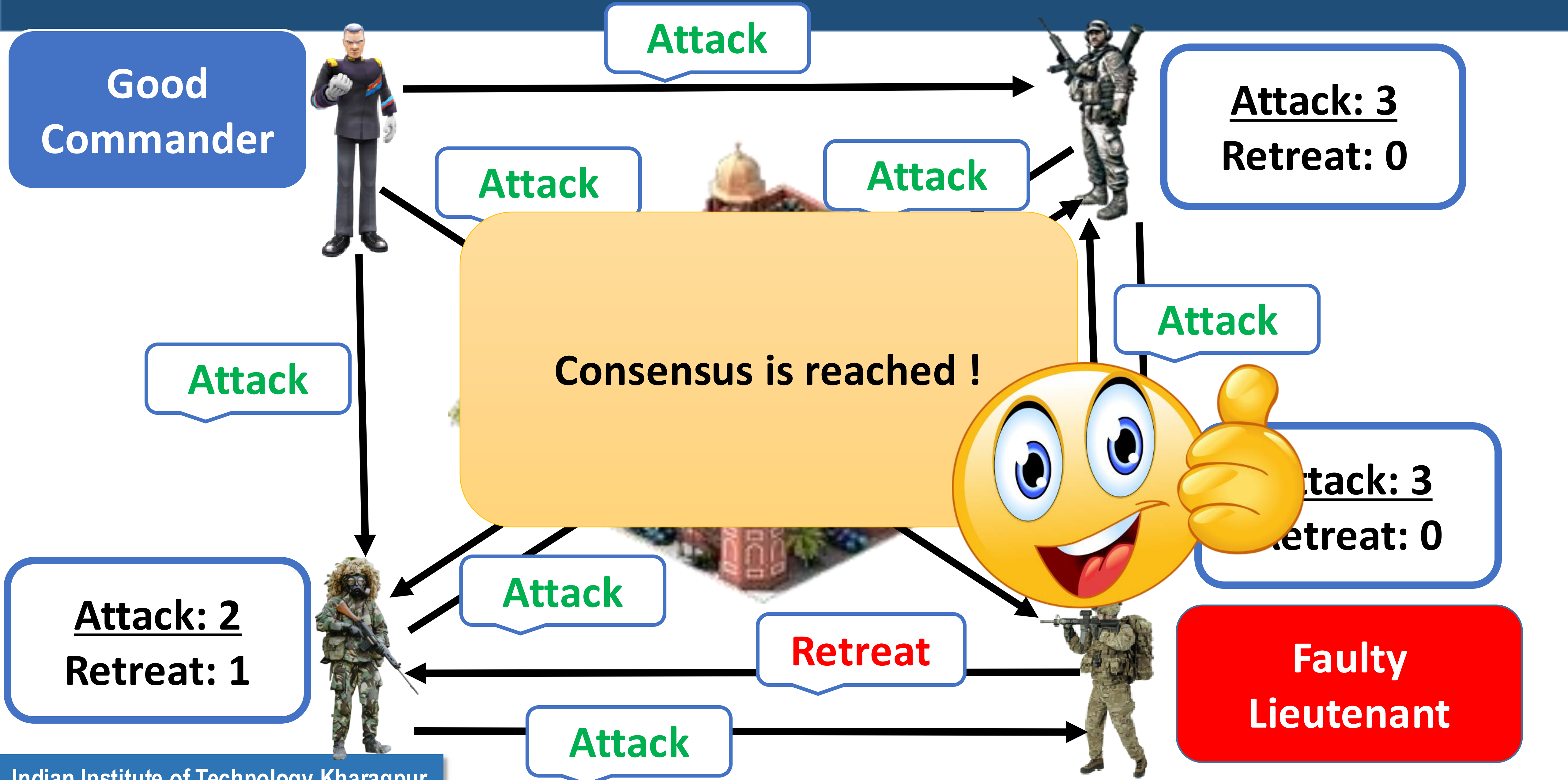

A Formal Definition

- A commander must send an order to his *n-1* lieutenants so that the following two conditions are met
  - **IC1:** All loyal lieutenants obey the same order
  - **IC2**: If the commander is loyal, then every loyal lieutenants obey the order that he sends

- IC1 and IC2 are called ***interactive consistency*** conditions

Impossibility Results

- Let F be the maximum number of faulty processes that the protocol can tolerate – **Byzantine agreement is not possible with fewer than 3F+1 processes**

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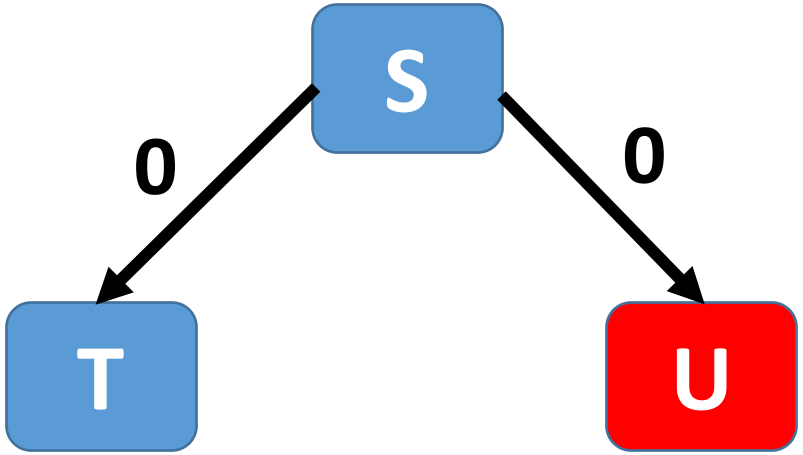

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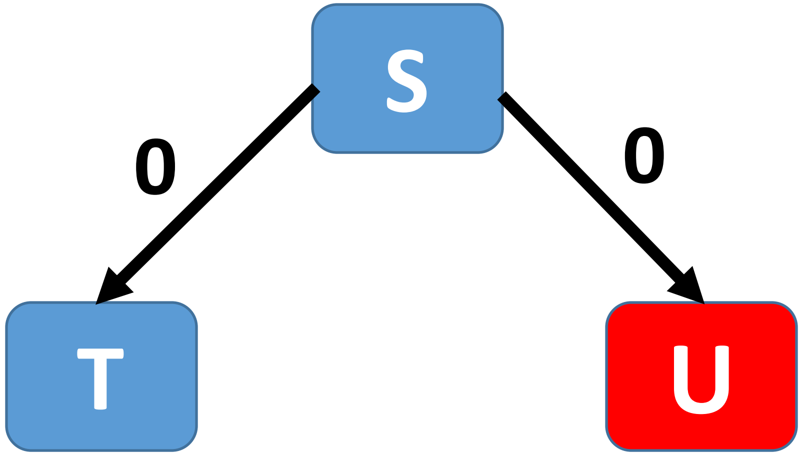

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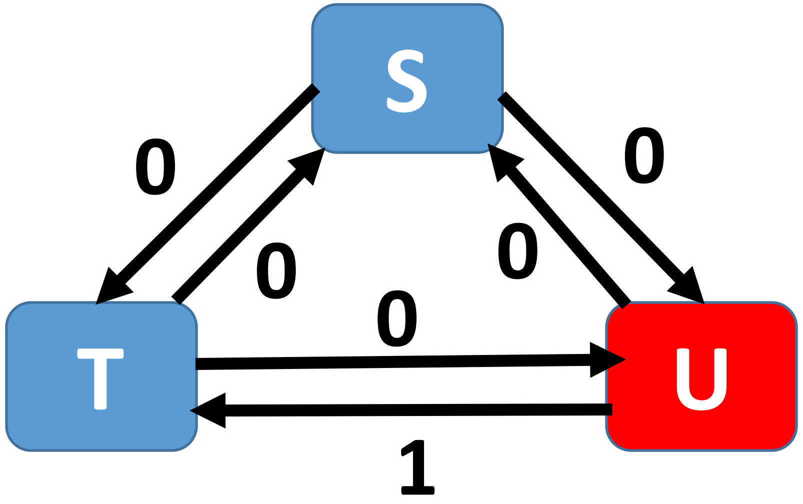

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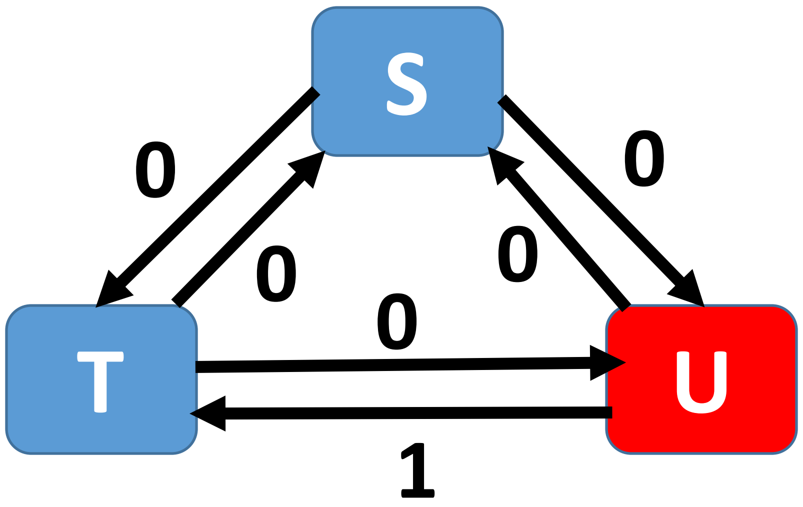

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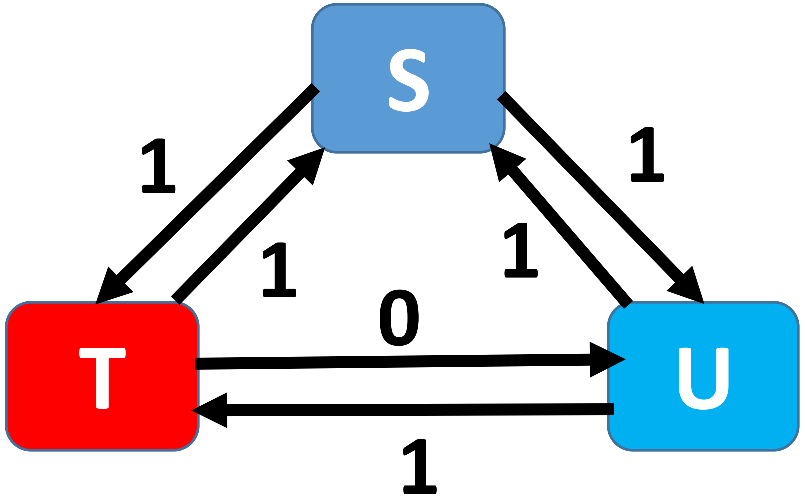

Case 1: S is a correct process that sends 1
U is correct, U must decide 1 (**validity)**

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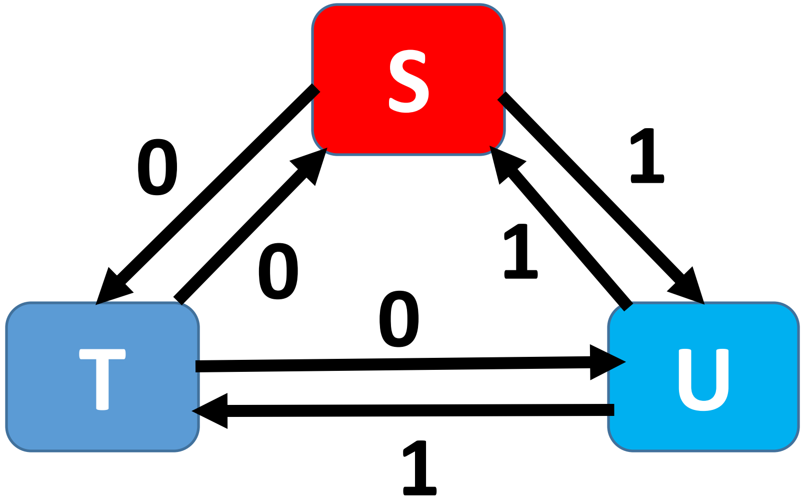

Case 2: S is faulty

For T: Same as Case-0

For U: Same as Case-1

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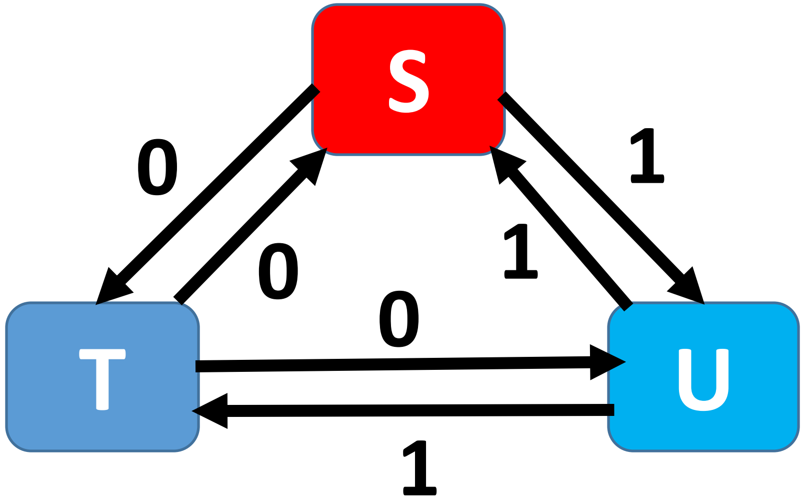

A correct process cannot distinguish between the two cases!

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- **NOTE:** Byzantine faults can be detected with fewer than 3F+1 processes
  - Needs F+1 processes to detect Byzantine faults – a correct node can reliably detect faults irrespective of the fraction of faulty nodes.
  - Check the following for a formal proof and the design of a Byzantine fault detector -- https://www.usenix.org/legacy/event/hotdep06/tech/prelim_papers/haeberlen/haeberlen_html/index.html

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  - **This is indeed interesting, many works have taken an alternate approach of BFT consensus – detect the faulty nodes and then throw them out – less number of rounds but implementation is sometime complex.**

Asynchronous Byzantine Agreement

- F faulty nodes – need 3F + 1 nodes to reach consensus

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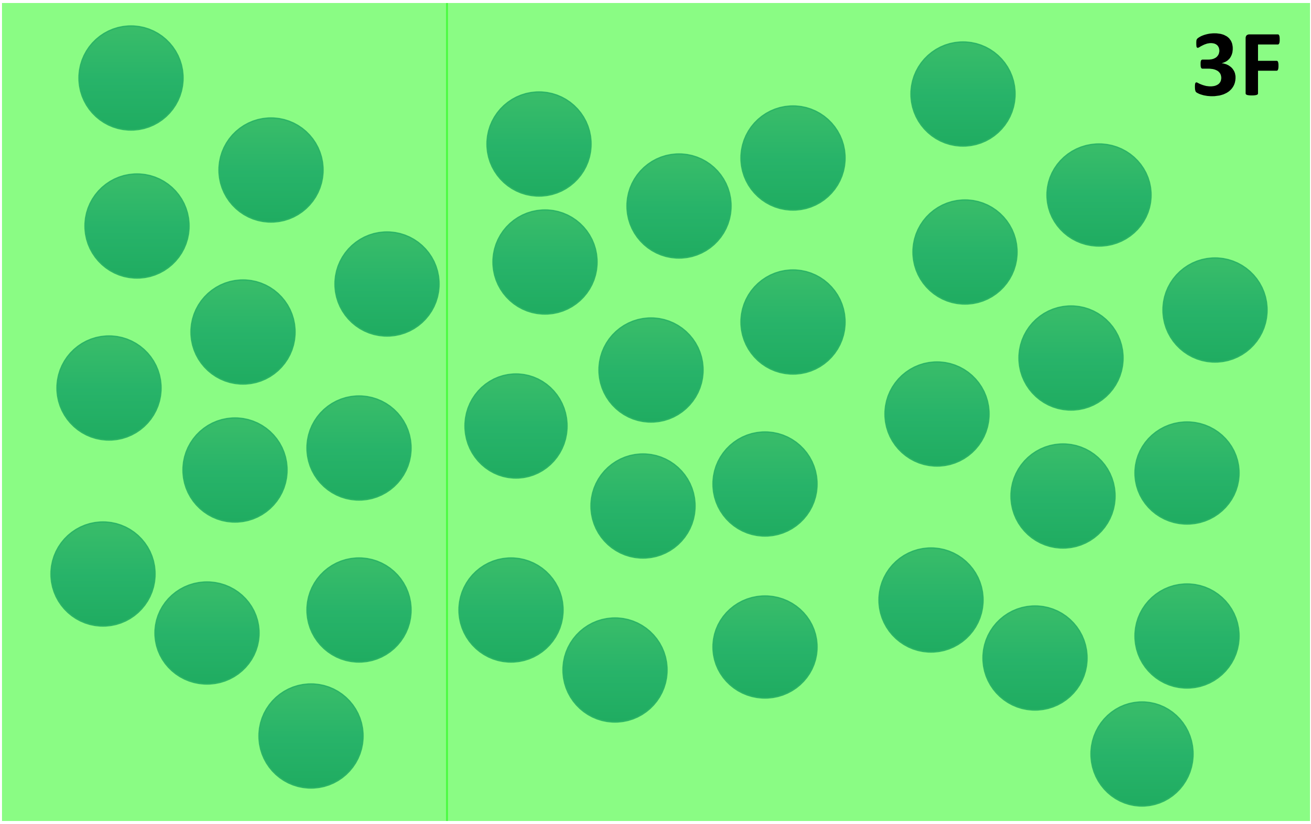

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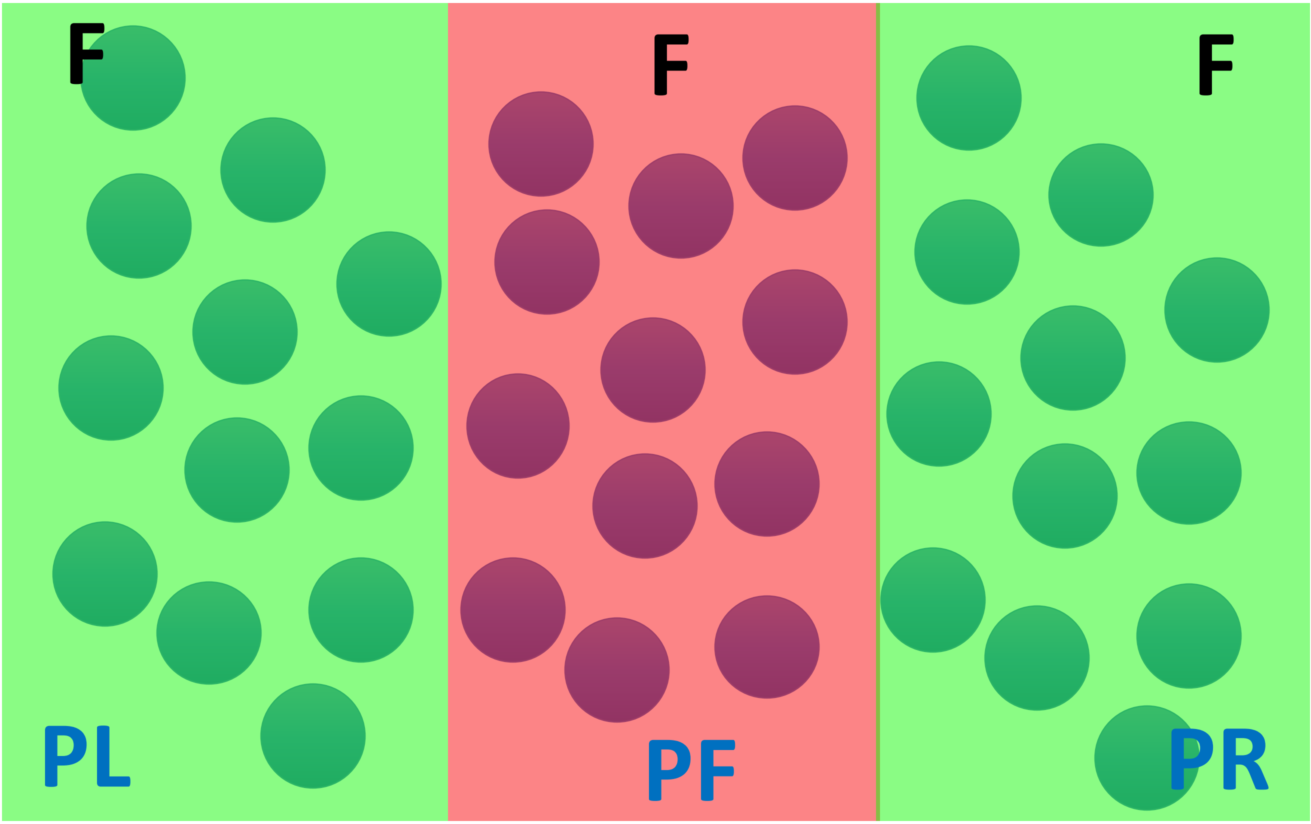

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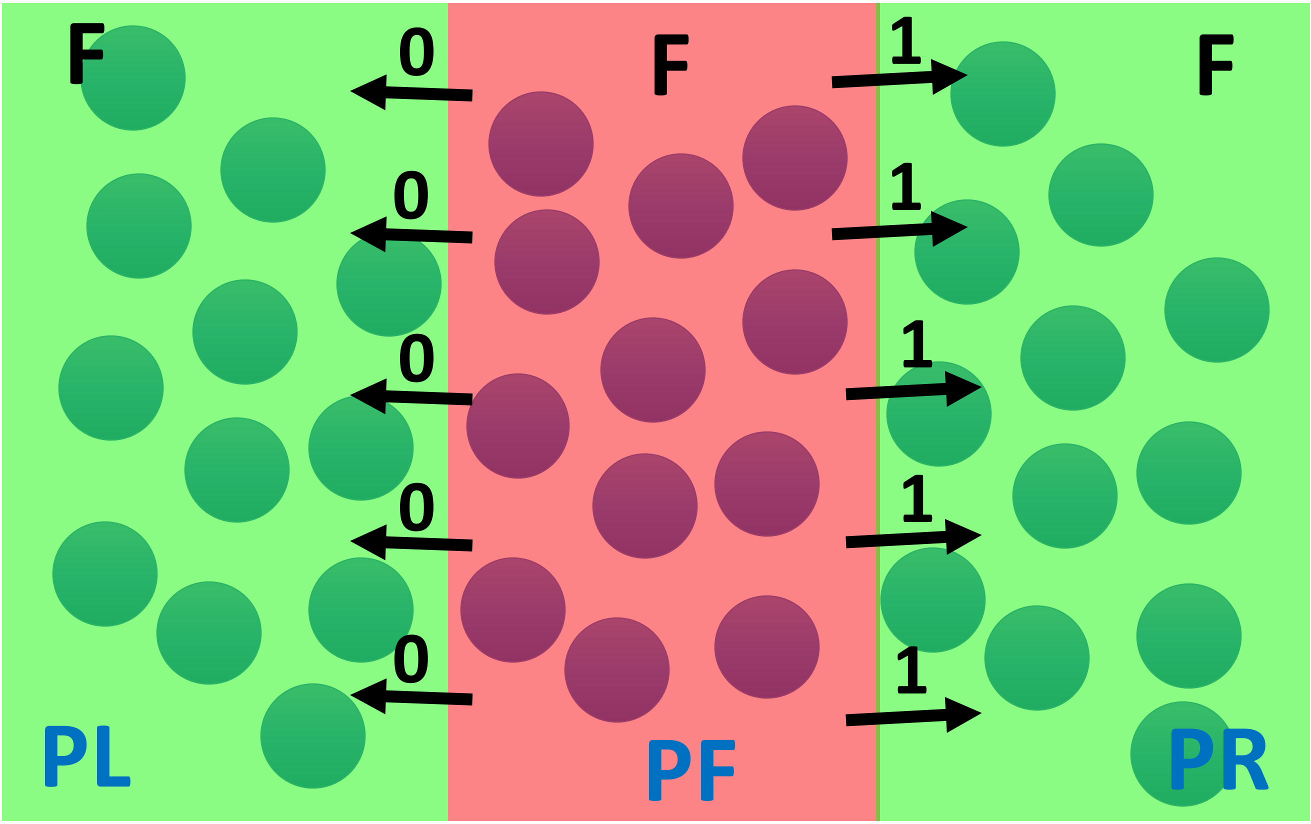

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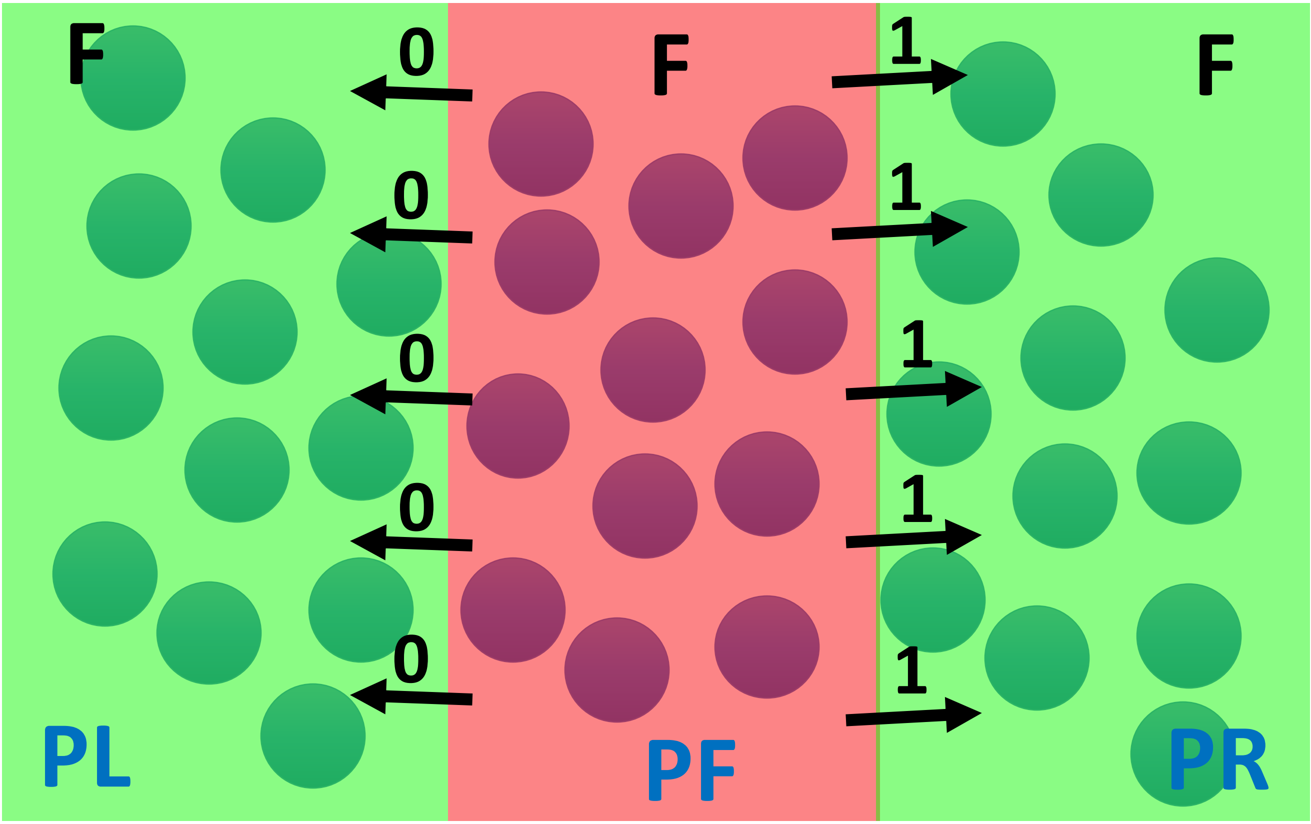

Either PL or PR must break the tie

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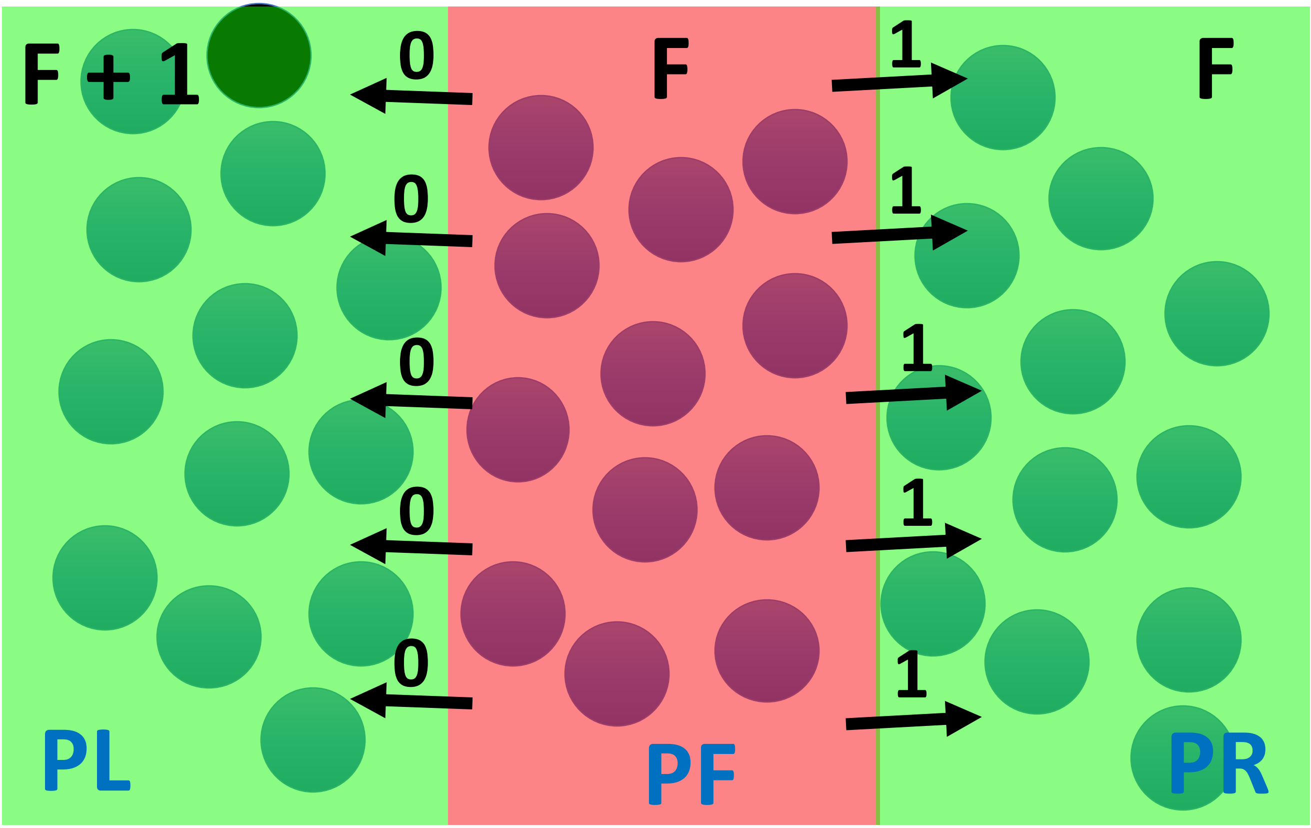

Put one additional node to PL / PR

Asynchronous Byzantine Agreement

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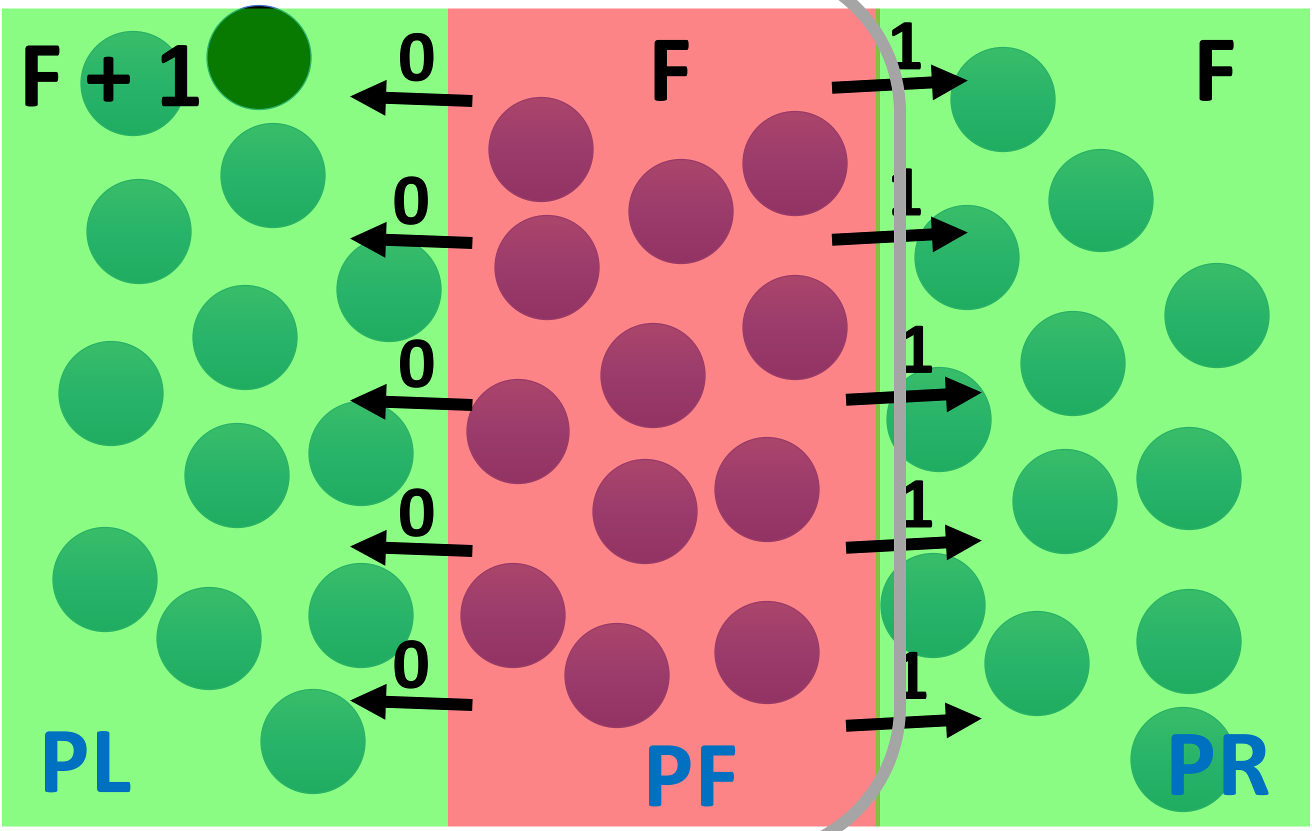
Breaks the tie to reach consensus



Put one additional node to PL / PR

Broad Idea of Agreement Protocols

- **Assumptions**: Synchronous, Completely connected, reliable communication, crash faults (crash-stop), maximum f faults

- (f+1) rounds for each process

- **Round 1:**
  - Broadcast own value to other processes
- **Round 2 to Round f+1:**
  - Broadcast any new received values
- **At the end of Round f+1:**
  - Decide on the minimum value received

Broad Idea of Agreement Protocols

- With f+1 rounds, there is at least one round with no faults
  - At the end of this round, all non-faulty processes have the values of all other non-faulty processes

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- However, we do not know a priori when that round will come, so we have to go for f+1 rounds – **this minimum bound is also applicable for Byzantine faults, try the proof!**

BFT Consensus

- **Lamport-Shostak-Peas Algorithm***
  - Synchronous environment
  - Reliable communication channel
  - Fully Connected Network
  - Receivers always know the identity of the Senders

* LAMPORT, LESLIE, ROBERT SHOSTAK, and MARSHALL PEASE. "The Byzantine Generals Problem." *ACM Transactions on Programming Languages and Systems* 4.3 (1982): 382-401.

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Unrealistic assumptions for real networks

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- Many different variants of BFT Consensus have emerged

- **Practical Byzantine Fault Tolerance (PBFT)****
  - Use cryptographic techniques to release the **unrealistic** assumptions

** Castro, Miguel, and Barbara Liskov. "Practical byzantine fault tolerance." *USENIX OSDI*. Vol. 99. No. 1999. 1999.

Lamport-Shostak-Peas Algorithm

- **Oral messages –** messages can be forged or changed in any manner, but the receiver always knows the sender

- The algorithm has been defined in a recursive way

Lamport-Shostak-Peas Algorithm

OM(f) for f>0

- Source x broadcast values to all processes
- Let v_i = the value received by process i from source (0 if no value received). Process i acts as a new source and initiates OM(f-1), sending v_i to remaining f-2 processes
- For each I, j, i≠j, let v_j = value received by process i from process j in the previous step using OM(f-1). Process i uses the value majority (v_1, v_2, …, v_n)

Lamport-Shostak-Peas Algorithm

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- Source x broadcast values to all processes
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- Source x broadcast values to all processes
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- Time complexity: (f+1) rounds
- Message complexity: $O(n^f)$ where n is the total number of processes

Practical Byzantine Fault Tolerance

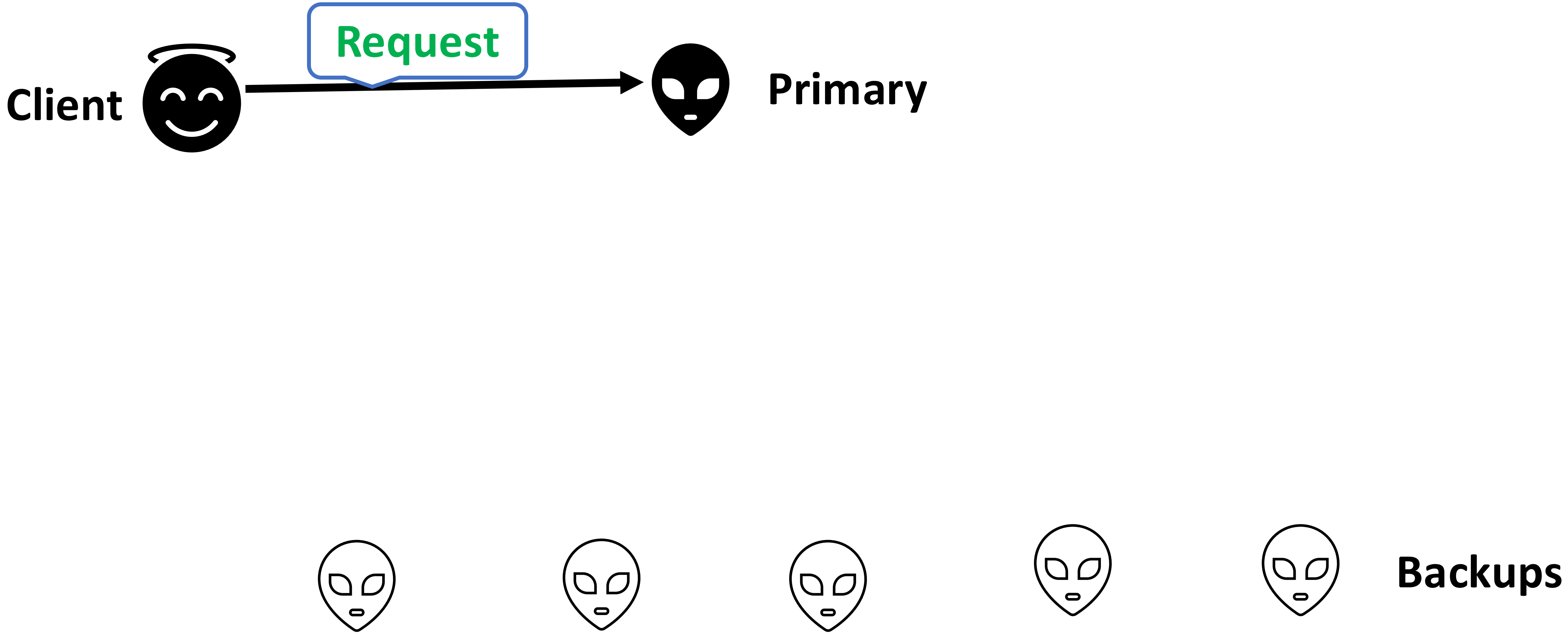
- **Why Practical?**
  - Considers an asynchronous environment (Gives priority to Safety over Liveness)
  - Utilizes digital signature to validate the identity of the senders
  - Low overhead
- Incorporated in many distributed applications including Blockchain
- Uses cryptographic techniques to make the messages tamper-proof

PBFT Overview

- Based on State Machine Replication
  - Considers 3F + 1 replicas where F can be the maximum number of faulty replicas

- The replicas move through a succession of configurations, known as ***views***
  - One replica in a view is considered as the <u>**primary**</u> (works like a leader), and others are considered <u>**backups**</u>
  - The primary proposes a value (similar to the Proposers in Paxos), and the backups accept the value (similar to the Paxos Acceptors)
  - When the primary is detected as faulty, the view is changed – PBFT elects a new primary and a new view is initiated
  - Every view is identified by a unique integer *v*
  - Only the messages from the current view is accepted

PBFT – Broad Idea



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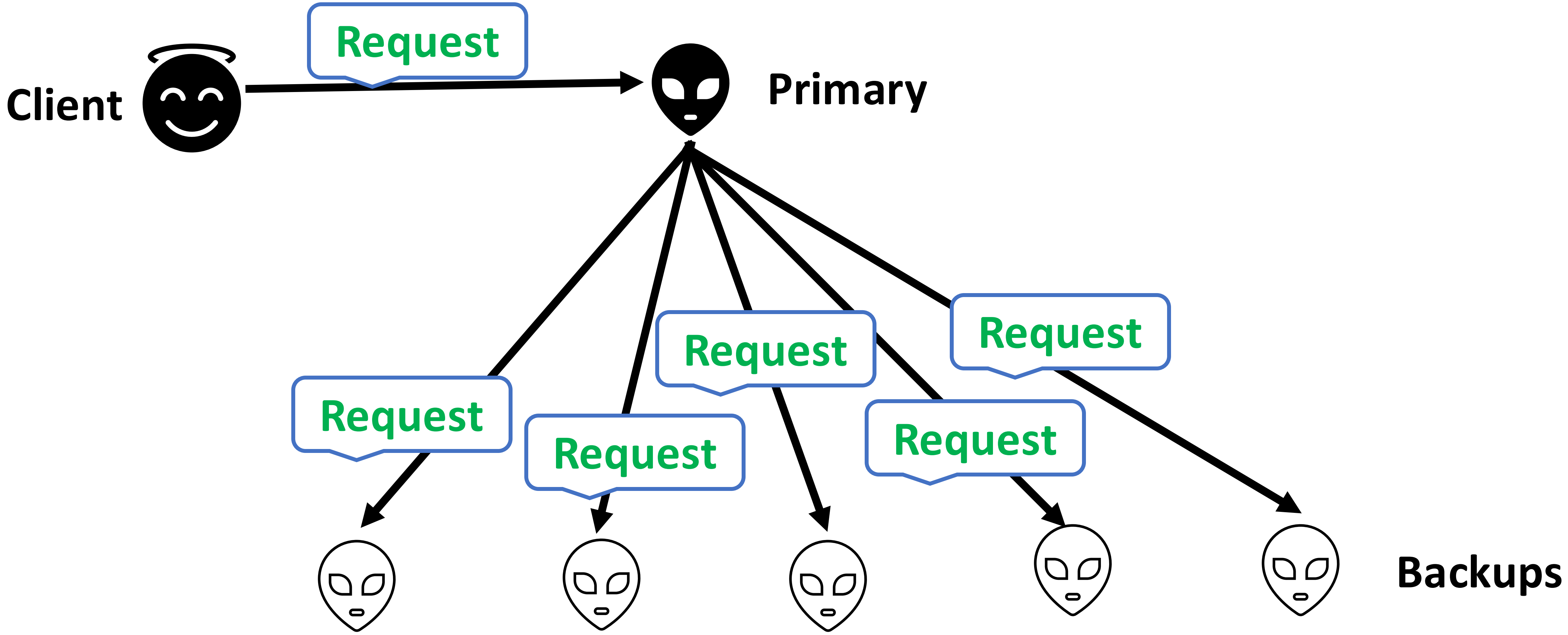

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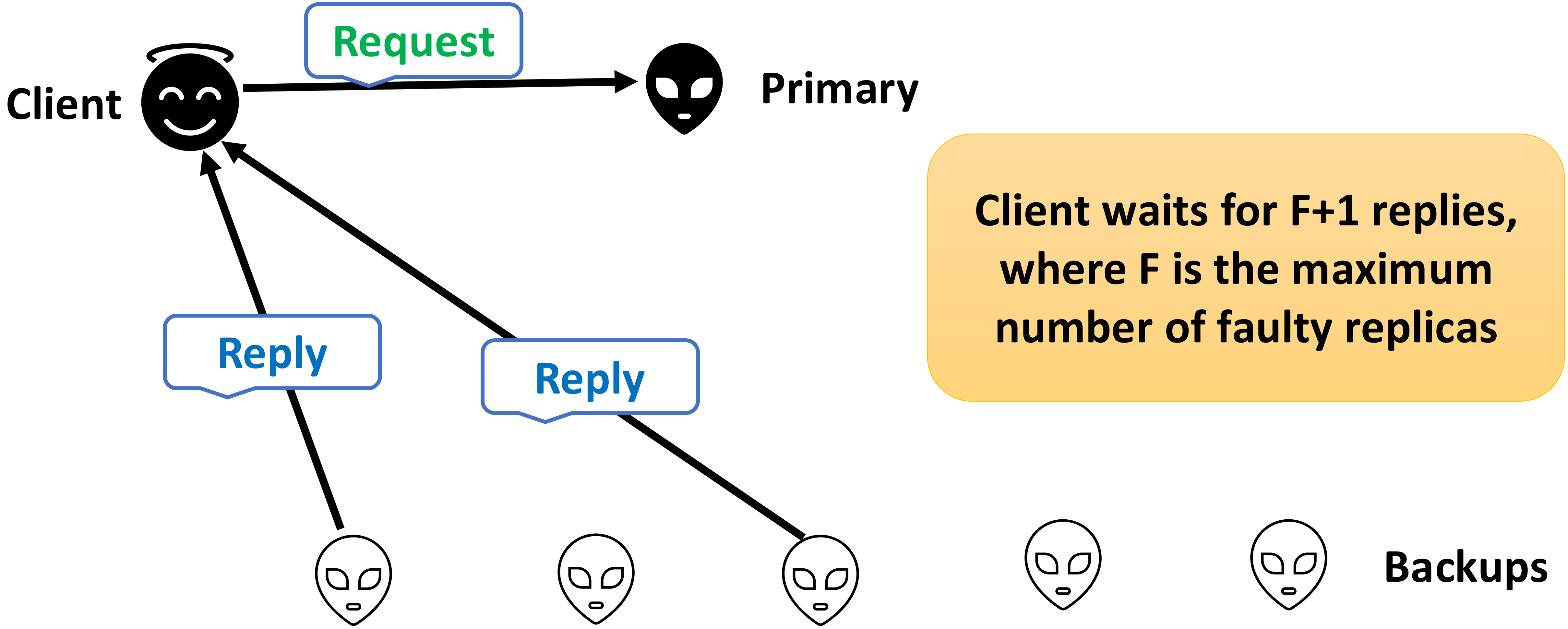
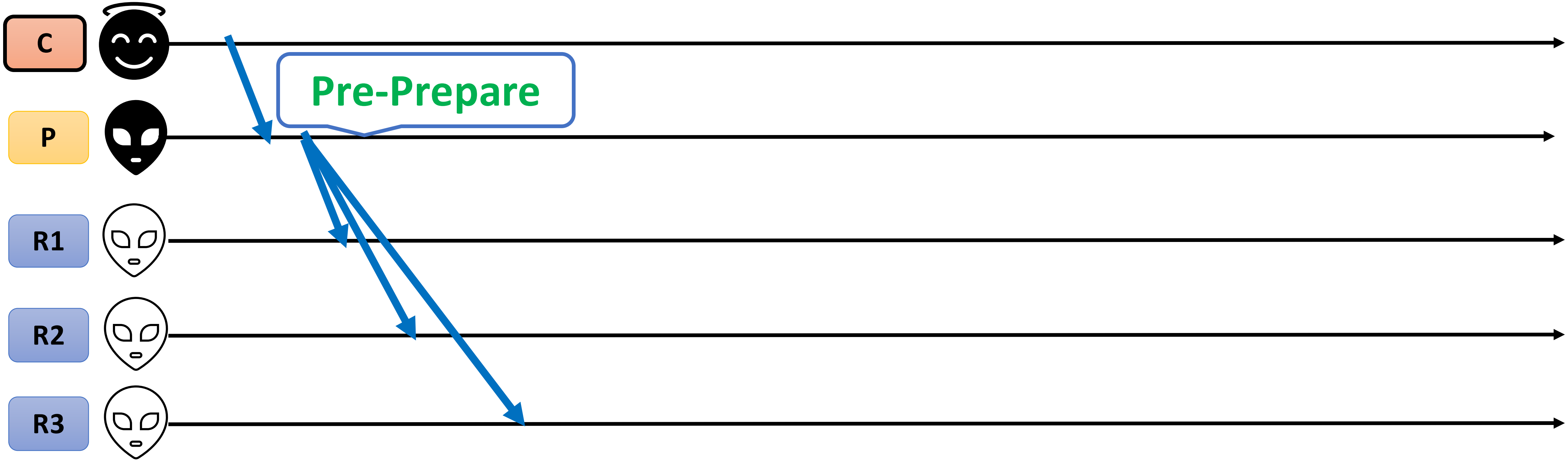


Client waits for F+1 replies, where F is the maximum number of faulty replicas

PBFT – The Algorithm

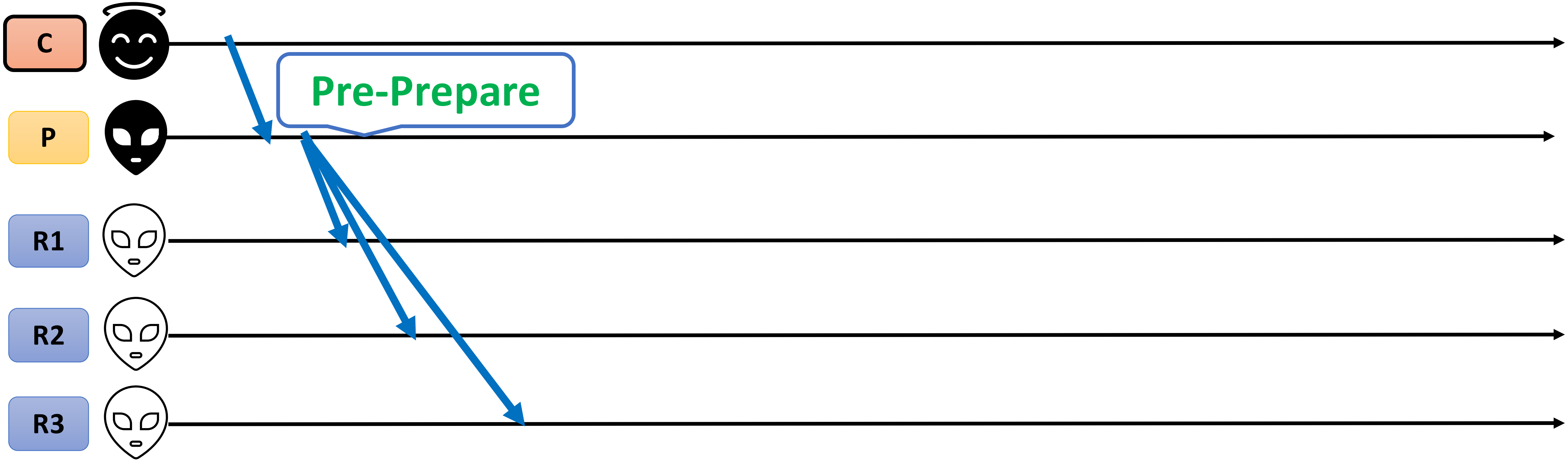
- The protocol starts by the client sending a Request message to the primary
- The primary collects all the Request messages from different clients and order them based on certain pre-defined logic

PBFT – The Algorithm



- Primary assigns a sequence number n to the Request (or a set of Requests) and multicast a message **<<PRE-PREPARE, *v*, *n*, *d*>$_{\beta\_p}$, *m*>** to all the backups
  - v is the current view number, d is the message digest, m is the message
  - β_p is the private key of the primary

PBFT – The Algorithm



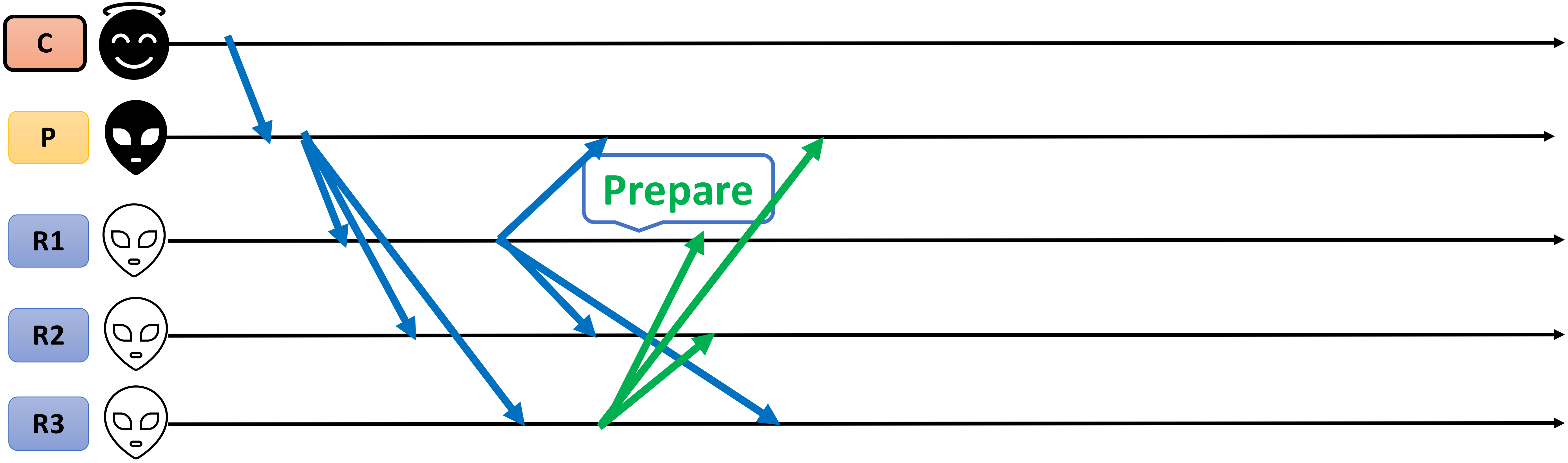
- Pre-prepare works as a proof that the Request was assigned a sequence number *n* for the view *v*

PBFT – The Algorithm

A backup accepts the Pre-prepare message, if

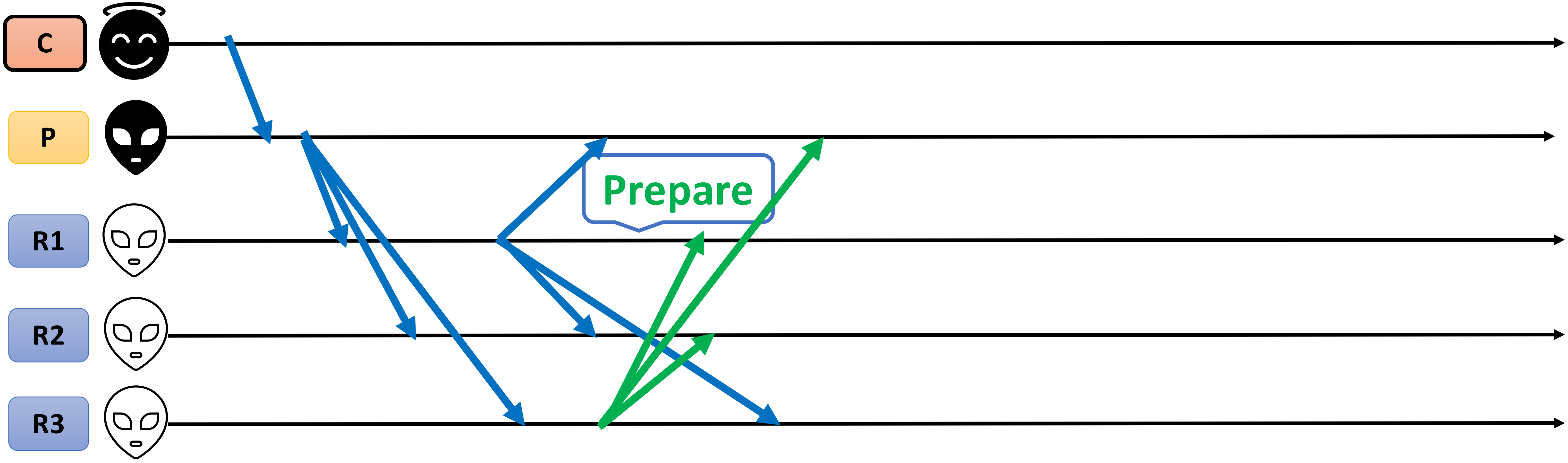
- The signature is correct and *d* is the digest of the message *m*
- The backup is in view *v*
- It has not received a different Pre-Prepare message with sequence *n* and view *v* with a different message digest
- The sequence number is within a threshold (the message is not too old – prevents a reply attack)

PBFT – The Algorithm



- The correct backups send a Prepare message to all other backups including the primary – works as proof that the backups agree on the message with the sequence number *n* under view *v*

PBFT – The Algorithm



- Message format for backup *k* : **<PREPARE, *v*, *n*, *d*, *k*>$_{\beta\_k}$**

PBFT – The Algorithm

Primary and backups accepts the Prepare message, if

- The signatures are correct
- View number is equal to the current view
- Sequence number is within a threshold (note that messages may be received **out of order** – so a backup may receive the Prepare message before the corresponding Pre-prepare message – so it needs to keep track of all the messages received)

PBFT – Three Phase Commit

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

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

- Assumptions for Commit:
  - Primary is non-faulty
  - You may have a maximum of f faults including Crash + Network + Byzantine

PBFT – Three Phase Commit

- A message is committed if
  - ***2f*** Prepare from different backups matches with the corresponding Pre-prepare
  - You have total ***2f + 1*** votes (one from the primary that you already have!) from the non-faulty replicas

PBFT – Three Phase Commit

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  - You have total ***2f + 1*** votes (one from the primary that you already have!) from the non-faulty replicas

- Note that all ***2f + 1*** votes may not be same
  - You have votes from Byzantine faulty replicas as well

Why *2f + 1* Votes? The idea of Quorum

- **Quorum:** Minimum number of votes a distributed transaction needs to obtained to get committed
  - Proposed by David Gifford in 1979 (Gifford, David K. (1979). *Weighted voting for replicated data*. SOSP '79)
  - Widely used in Commit protocols and Replica management

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- **Byzantine Dissemination Quorum:**
  - **Intersection:** Any two quorums have at least one correct replica in common
  - **Availability:** There is always a quorum available with no faulty replicas

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- **Quorum:** Minimum number of votes a distributed transaction needs to obtained to get committed
  - Proposed by David Gifford in 1979 (Gifford, David K. (1979). *Weighted voting for replicated data*. SOSP '79)
  - Widely used in Commit protocols and Replica management

- **Byzantine Dissemination Quorum:**
  - **Intersection:** Any two quorums have at least one correct replica in common
  - **Availability:** There is always a quorum available with no faulty replicas

- PBFT uses Byzantine Dissemination Quorum with $2f + 1$ replicas

Quorum in PBFT

- You have *f* number of faulty nodes – you need at least ***3f + 1*** replicas to reach consensus
  - But you do not know whether those are Crash faults, Network faults, or Byzantine Faults

Quorum in PBFT

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- **Case 1: All *f* are Crash or Network faulty – You'll not receive messages from them!**
  - You'll receive ***2f + 1*** Prepare messages from non-faulty nodes
  - All these ***2f + 1*** are non-faulty votes – you can reach to an agreement

Quorum in PBFT

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- **Case 2: All *f* are Byzantine faulty – they send messages!**
  - You may receive at most ***3f + 1*** Prepare messages (votes) -- ***f*** are from Byzantine nodes
  - Sufficient to wait till ***2f + 1*** Prepare messages – even if ***f*** are faulty, you still have ***f+1*** non-faulty votes
  - You cannot wait for ***f+1***, the first ***f*** might be all faulty

Quorum in PBFT

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  - You m om
    Byzan
  - Suffici you still
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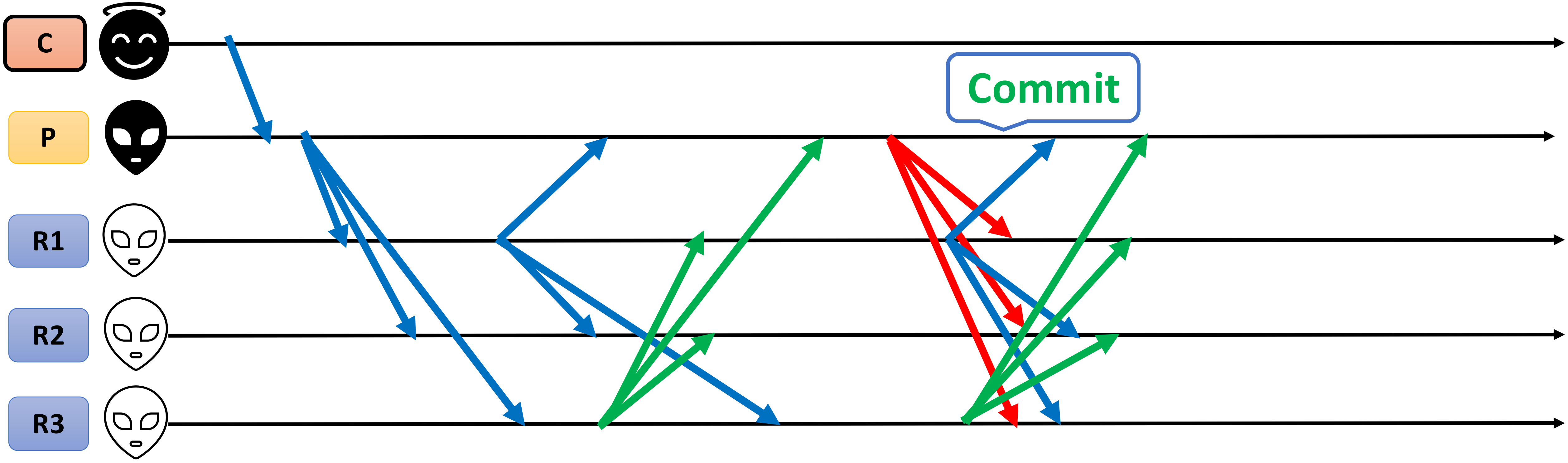
Remember, you are on an asynchronous channel – messages get delayed and can be received out of order

Wait untill you receive *2f + 1* Prepare messages – once you received *2f + 1* votes, you can safely take a decision based on majority voting

PBFT – The Algorithm



- Message format for replica k : <COMMIT, v, n, d, k>$_{\beta\_k}$

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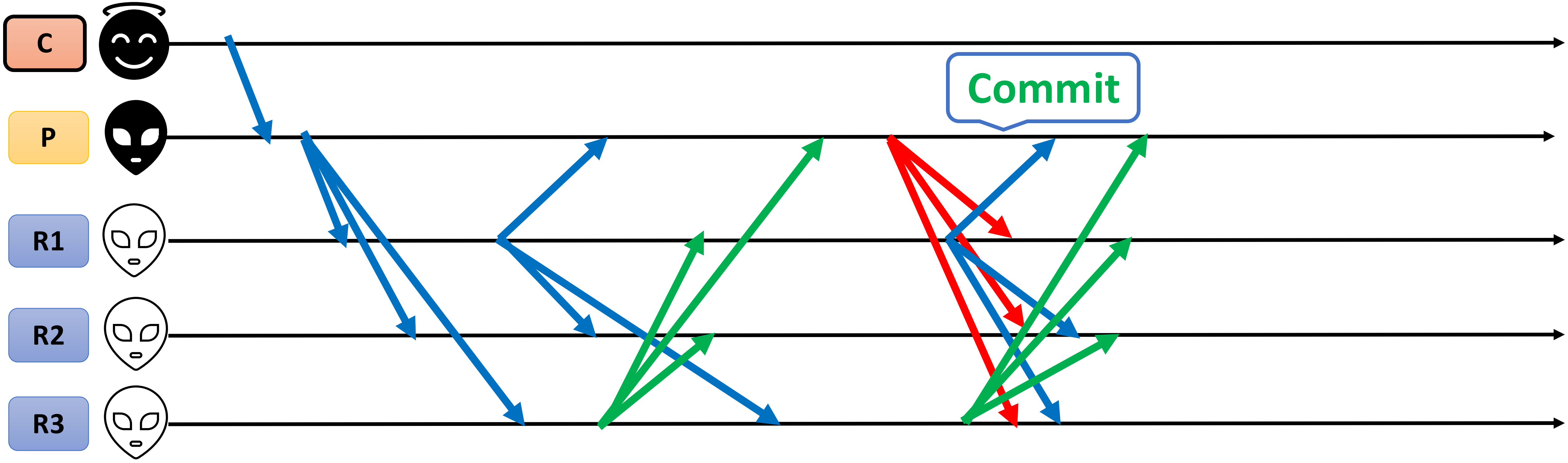

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  - It has sent the Commit message
  - It has received *2f* Commit messages from other replicas

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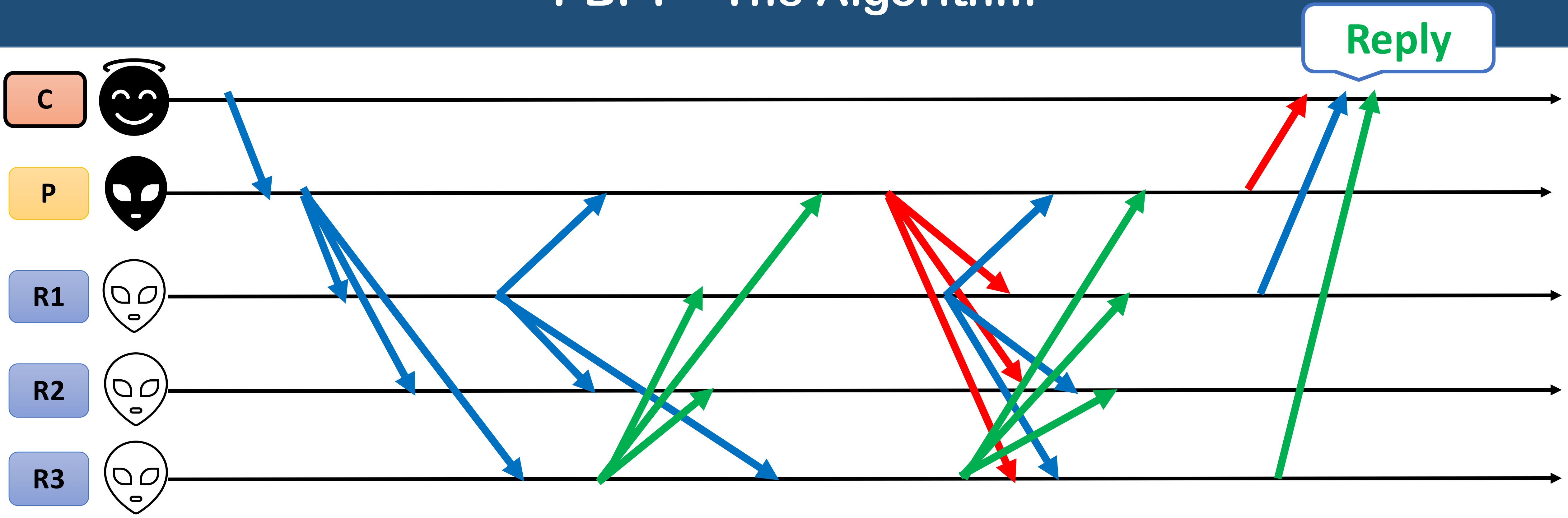

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Liveness and Weak Synchrony

- Unlike multiple Paxos proposers, PBFT works with a single Primary
  - Ping-pong does not arise from the proposals from multiple replicas
  - However, a replica needs to wait for ***2f + 1*** votes (Prepare and Commit messages)

- However, a primary may fail – the liveness gets hampered as the protocol cannot progress any further
  - Primary failure cannot be handled in a pure asynchronous system – you do not know whether it is a message delay from the primary, or a primary failure

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- **Weak Synchrony:** (1) Both sender and the receiver is correct, (2) Sender keeps retransmitting the messages until it is received, (3) There is an **asymptotic upper bound** on the message transmission delay

View Change

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

View Change

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  - Non-faulty replicas detect the fault
  - Replicas together start view change operation

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

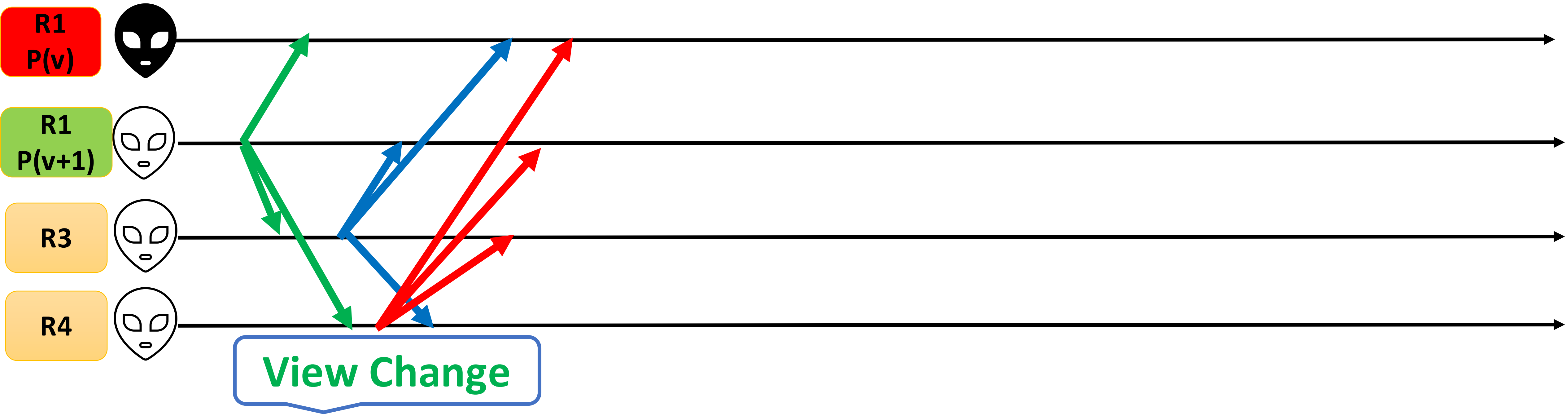
- If the primary fails, backups will not receive any message or will receive faulty messages from the primary

- View changes are triggered by timeouts (weak synchrony assumption)
  - Prevent backups from waiting indefinitely for requests to execute

View Change

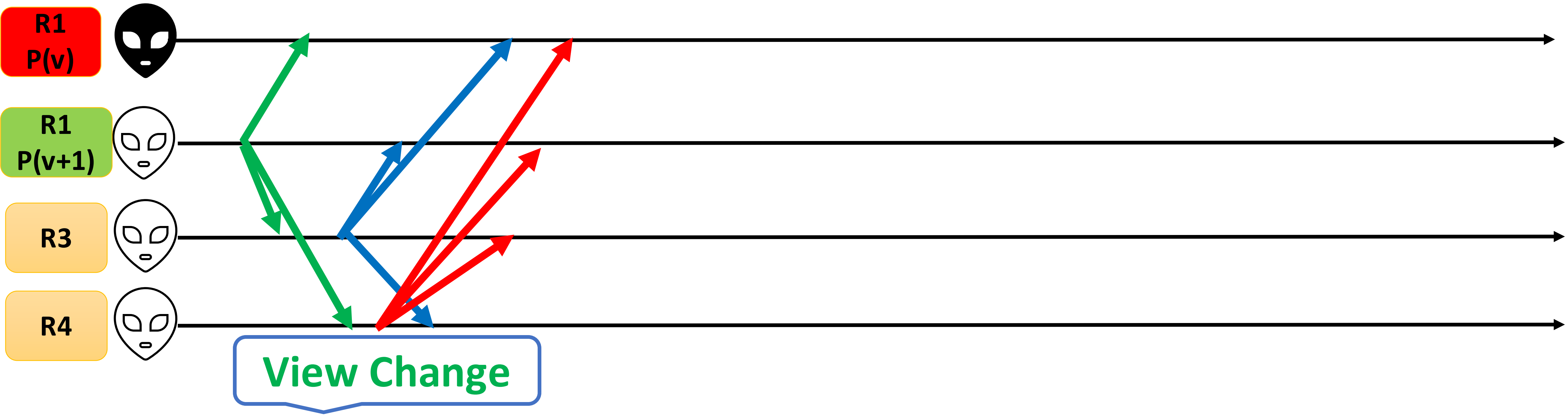
- Backup starts a timer when it receives a request, and the timer is not already running
  - The timer is stopped when the request is executed
  - Restarts when some new request comes
- If the timer expires at view v, backup starts a **View Change** to move to the view $v + 1$

The View Change Protocol



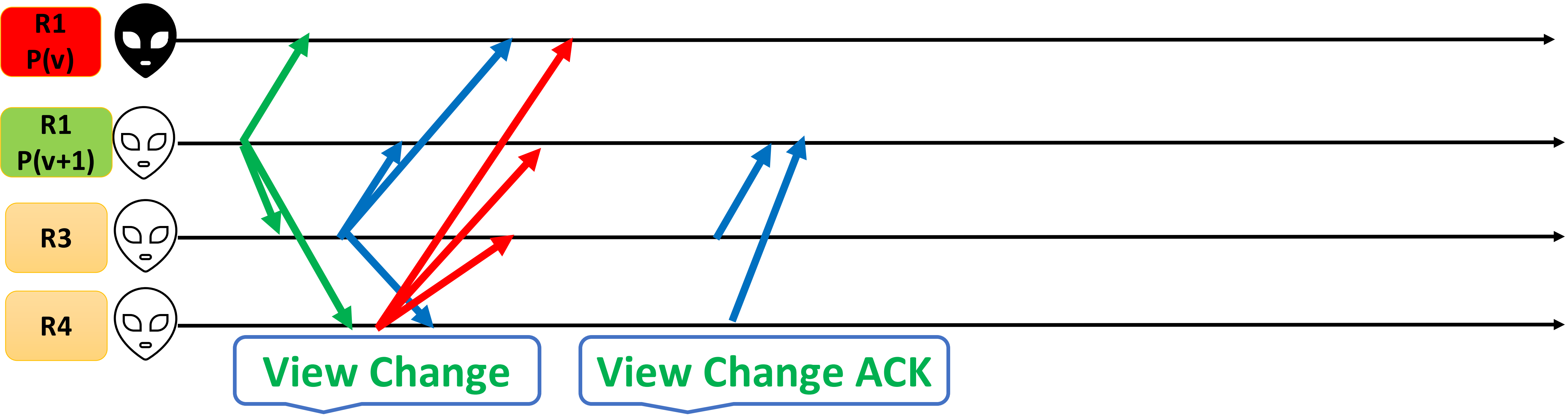
- Multicast the view change message **<VIEW-CHANGE, *v+1, n, C, P, k*>$_{\beta\_k}$**
  - *n* is the sequence number of last stable checkpoint *s* known to *k*
  - *C* is a set of *2f + 1* valid checkpoint messages corresponding to *s*
  - *P* is a set containing a set P_m for each request *m* that prepared at *k* with a sequence number higher than *n*

The View Change Protocol



- The new view is initiated after receiving $2f + 1$ View Change messages
- The primary of a view v is a replica p such that $p = v \bmod |R|$, where R is the set of replicas ($|R| = 3f + 1$, in general)

The View Change Protocol



- Replicas send a View Change ACK – quorum is formed on these messages

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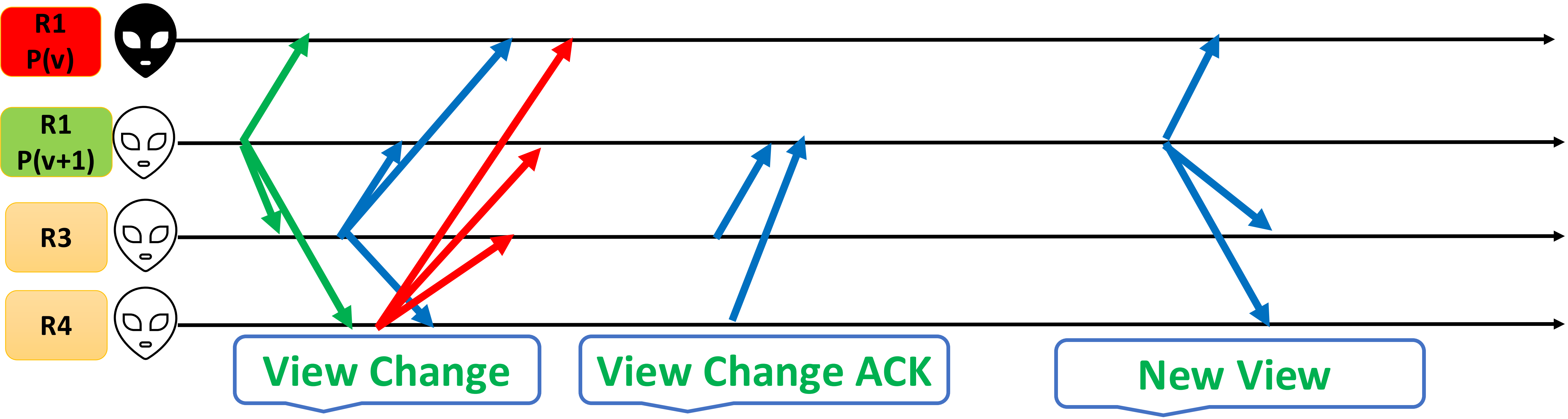

- Replicas send a View Change ACK – quorum is formed on these messages
- New View message to initiate a new view

The View Change Protocol

- The New View message is formatted as <NEW-VIEW, v+1, V, O>$_{\beta\_p}$
  - V is the set containing the valid view change messages received by the new primary plus the view change message that it sent (**or would have been sent**)
  - O is the set of pre-prepare messages

The View Change Protocol

- How do the new primary computes O?
  - The primary determines the sequence number *min-s* of the latest stable checkpoint in V and the highest sequence number *max-s* in a prepare message in V.
  - The primary creates a new pre-prepare message for view *v+1* for each sequence number between *min-s* and *max-s*.
  - Two cases are handled
    - There is at least one set in the *P* component of some view-change message in V with sequence number n: creates a new message $\langle$PRE-PREPARE, v+1, n, d$\rangle_{\beta_p}$, d is the request digest in the pre-prepare message for sequence number n with the highest view number in V.
    - There is no such set: creates a new message $\langle$PRE-PREPARE, v+1, n, $d^{null}\rangle_{\beta\_p}$, d^{null} is the digest of a special null request; a null request goes through the protocol like other requests, but its execution is a no-op.

The View Change Protocol

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- Next the primary appends the messages into its own log.
  - If *min-s* is greater than the sequence number of its latest stable checkpoint, the primary also inserts the proof of stability for the checkpoint with sequence number *min-s* in its log
  - It then enters the view v+1 and starts accepting messages for the view v+1

- Backups accept the view change message for view v+1 if it is signed properly, if the view-change messages it contains are valid for view 1, and if the set O is correct (checked through a similar computation as of the primary).

Garbage Collection

- When do a replica can discard the messages it received from others?
  - For the safety condition to hold, messages must be kept in a replica's log until it knows that
    - The requests they concern have been executed by at least *f+1* non-faulty replicas
    - It can prove this to others in view changes.
  - If some replica misses messages that were discarded by all other non-faulty replicas, it will need to be brought up to date by transferring all or a portion of the service state.
    - Therefore, replicas also need some proof that the state is correct.

Garbage Collection

- Generating the proofs after every operation is expensive -> PBFT replicas generate these proofs at every i^{th} sequence number (say i=100)
  - Are called the checkpoints: Checkpoints with a proof are called **stable checkpoints**

- A replica maintains several service states
  - Last stable checkpoint
  - Zero of more checkpoints which are not stable
  - The current state

- Copy on Write to maintain the states – space efficient

How Does a Replica Generate the Proof of a Checkpoint

- When a replica *i* produces a checkpoint, it multicasts a message <CHECKPOINT, *n, d, i*>$_{\beta\_i}$ to other replicas
  - *n* is the sequence number of the last request whose execution is reflected in the state and *d* is the digest of the state
- Each replica collects checkpoint messages in its log until it has *2f+1* of them for the sequence number *n* with the same digest *d* signed by different replicas (including possibly its own such message).
  - These messages are the proof of correctness for the checkpoint
- Once a checkpoint with sequence number *n* becomes stable, a replica deletes all old checkpoints for sequence number less than *n*

Another Logical Proof for $n = 3f + 1$

- You have at most f number of Byzantine faulty nodes in the system
  - The protocol must work after communicating with n-f number of replicas

- Say, you do not receive the responses from f number of replicas
  - These f replicas can be the ones which are faulty (as Byzantine faulty replicas can stop responding)
  - It might also be possible that the responses are delayed from these replicas as the communication channel is asynchronous; but these are actually the non-faulty replicas
    - So, the n-f responses that are received might have the responses from f faulty nodes

- For the second case, we need to ensure that the responses still have enough number of replicas from the non-faulty set
  - So, $n - 2f > f \Rightarrow n > 3f$

Must Read

- Gabriel Bracha and Sam Toueg. 1985. Asynchronous consensus and broadcast protocols. J. ACM 32, 4 (Oct. 1985), 824–840. https://doi.org/10.1145/4221.214134
- Lamport, Leslie, Robert Shostak, and Marshall Pease. "The Byzantine generals problem." Concurrency: the works of Leslie Lamport. 2019. 203-226.
- Castro, Miguel, and Barbara Liskov. "Practical byzantine fault tolerance and proactive recovery." ACM Transactions on Computer Systems (TOCS) 20.4 (2002): 398-461.

Happy Learning