# CS61065: Theory And Applications of Blockchain

# Byzantine Agreement Protocols

Department of Computer Science and Engineering

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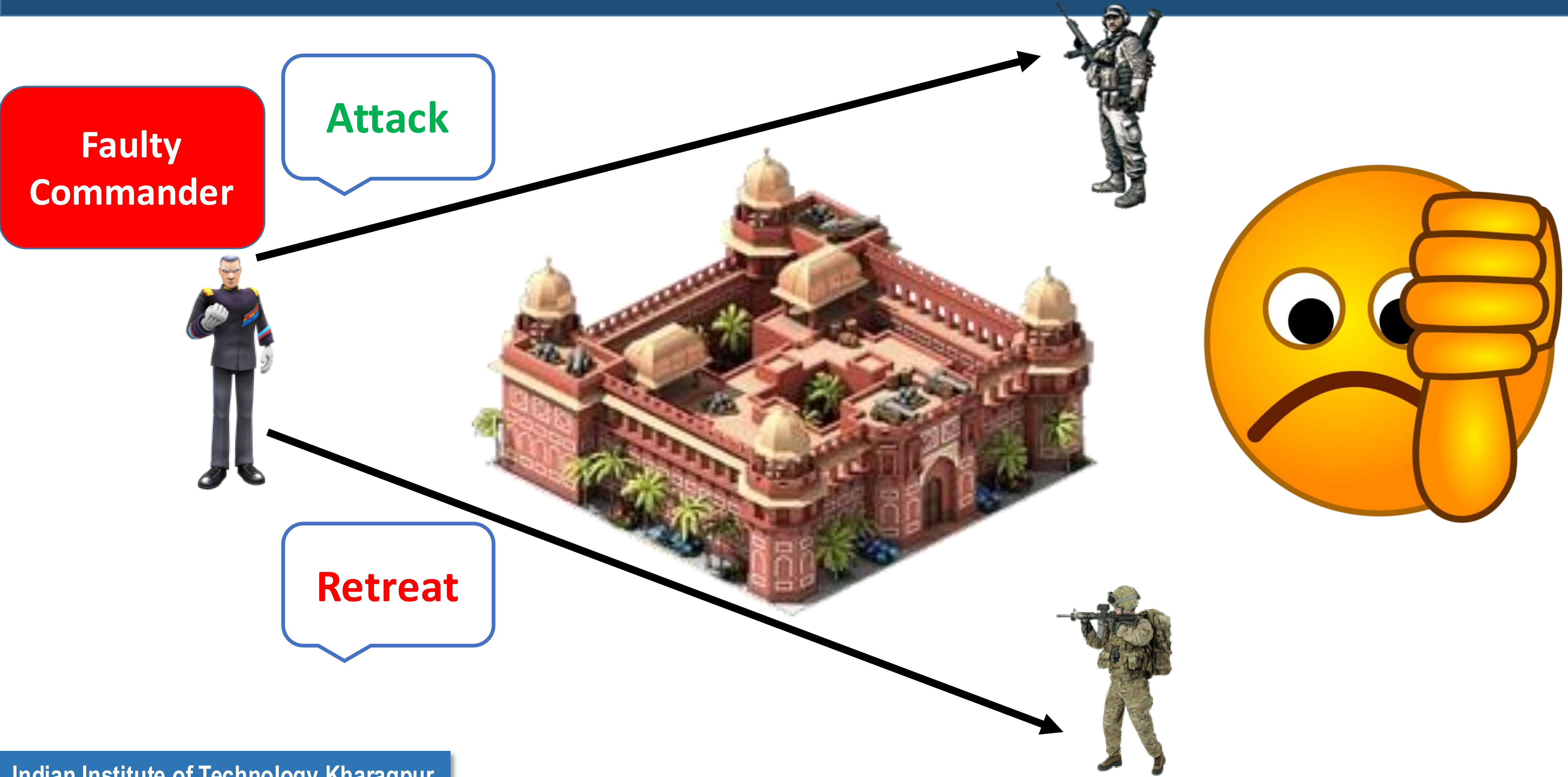

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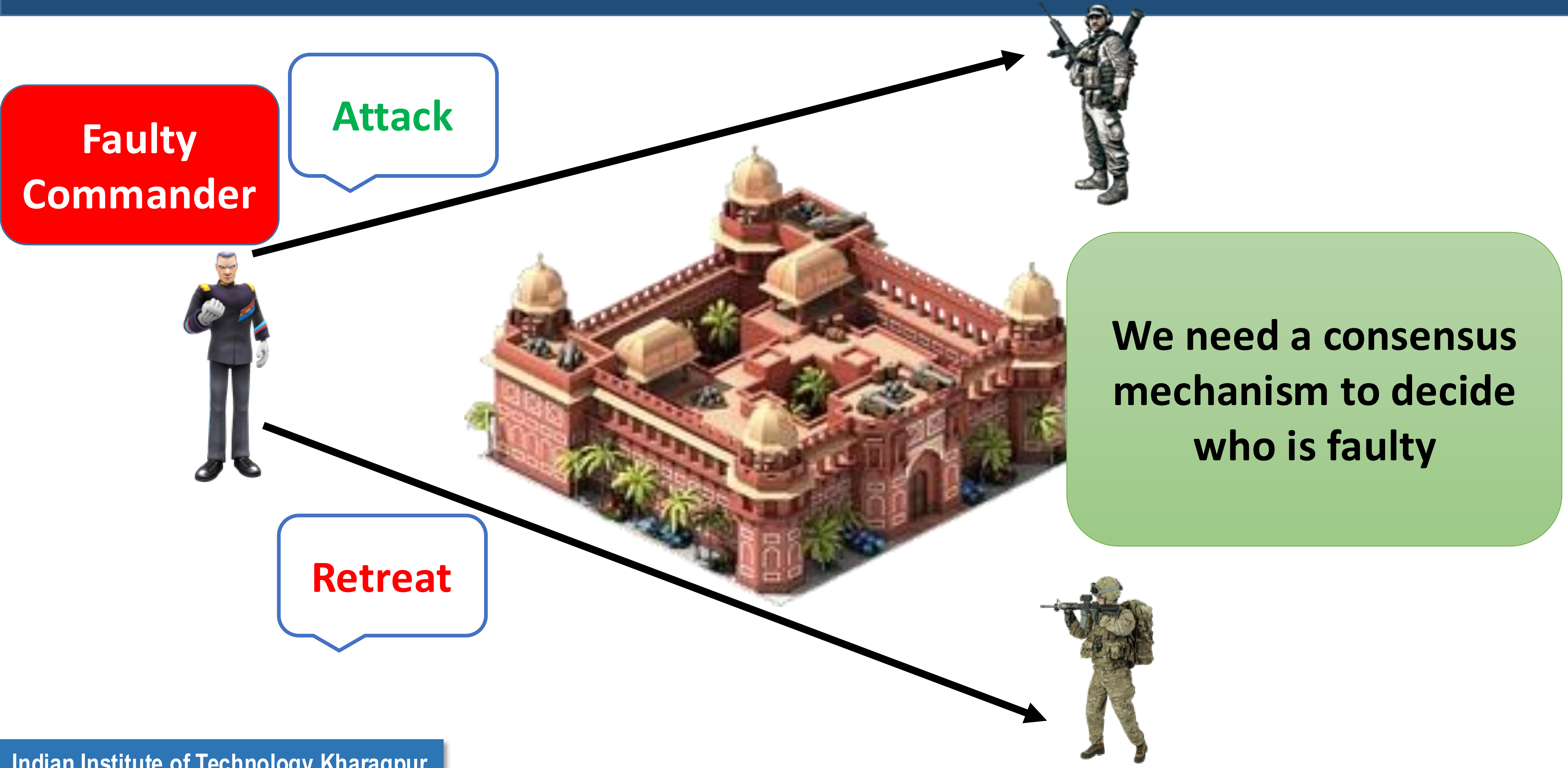

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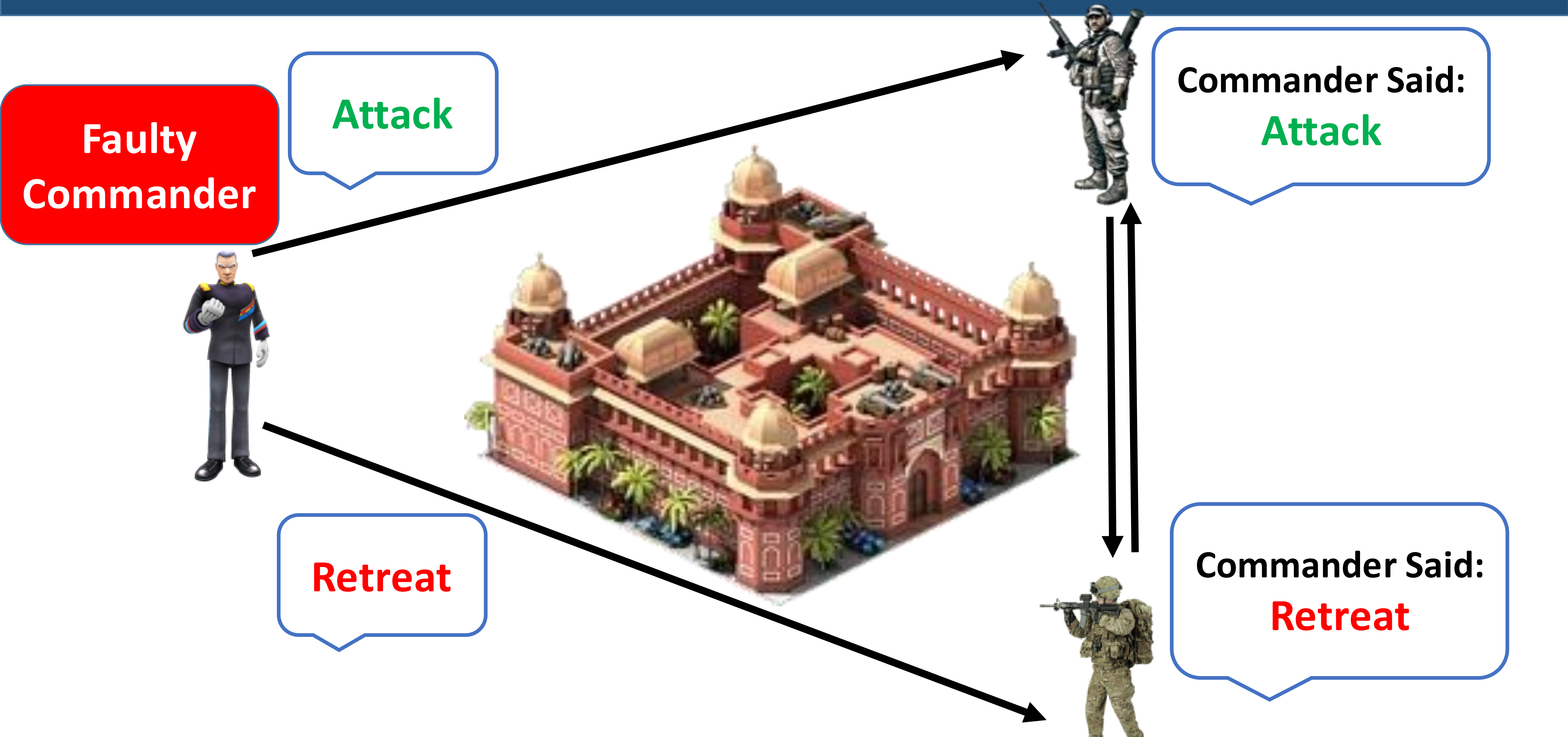

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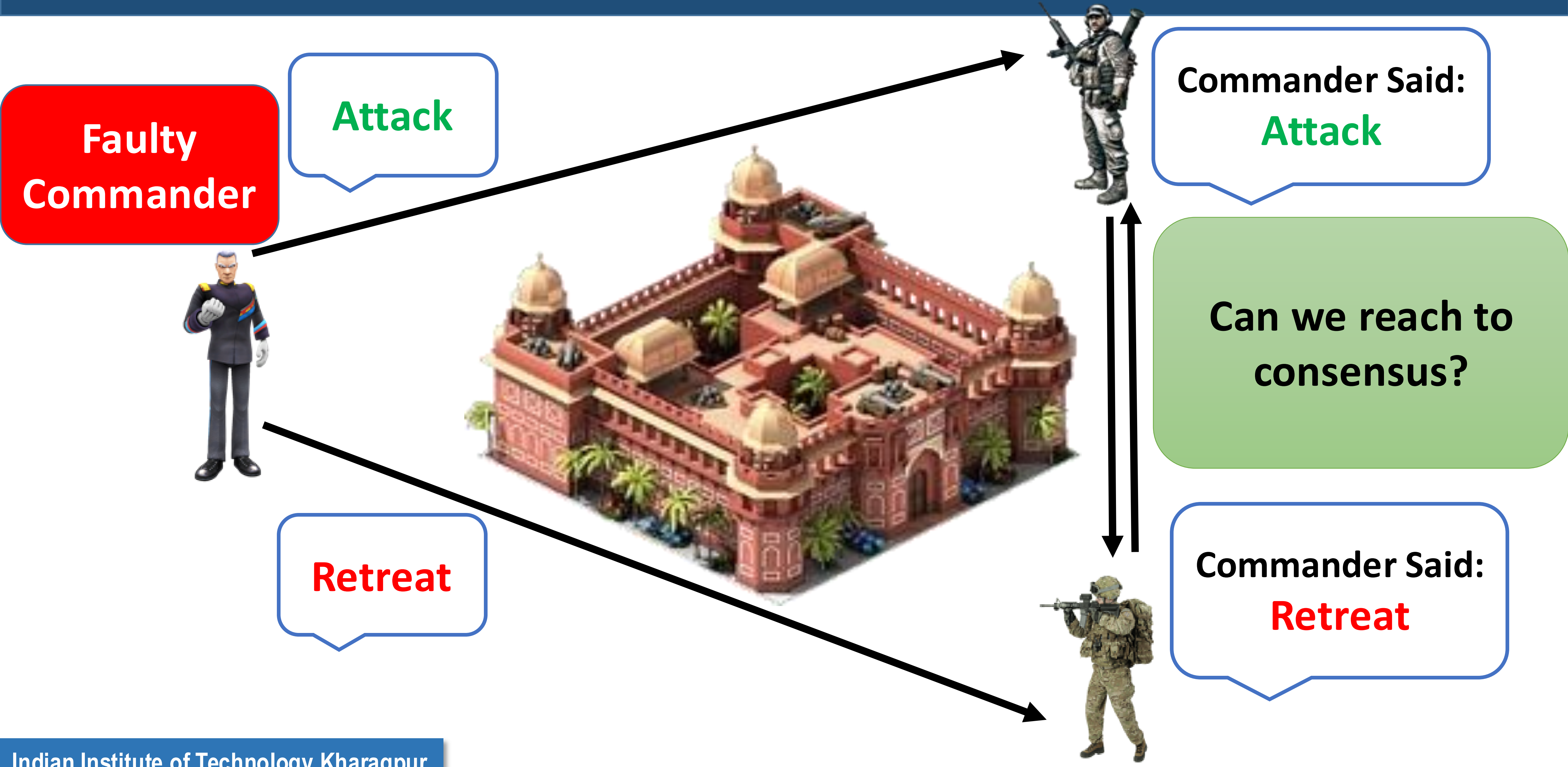

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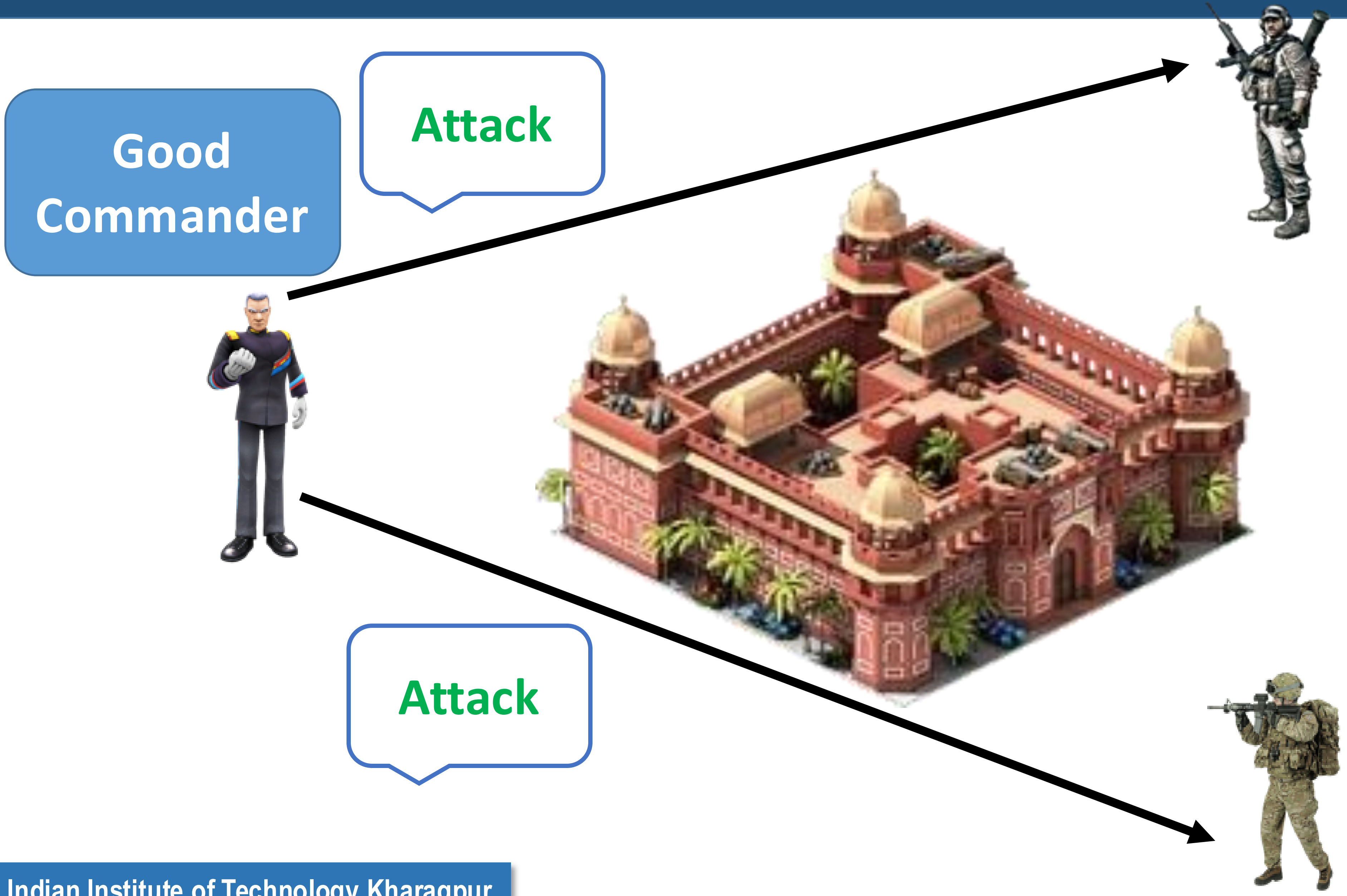

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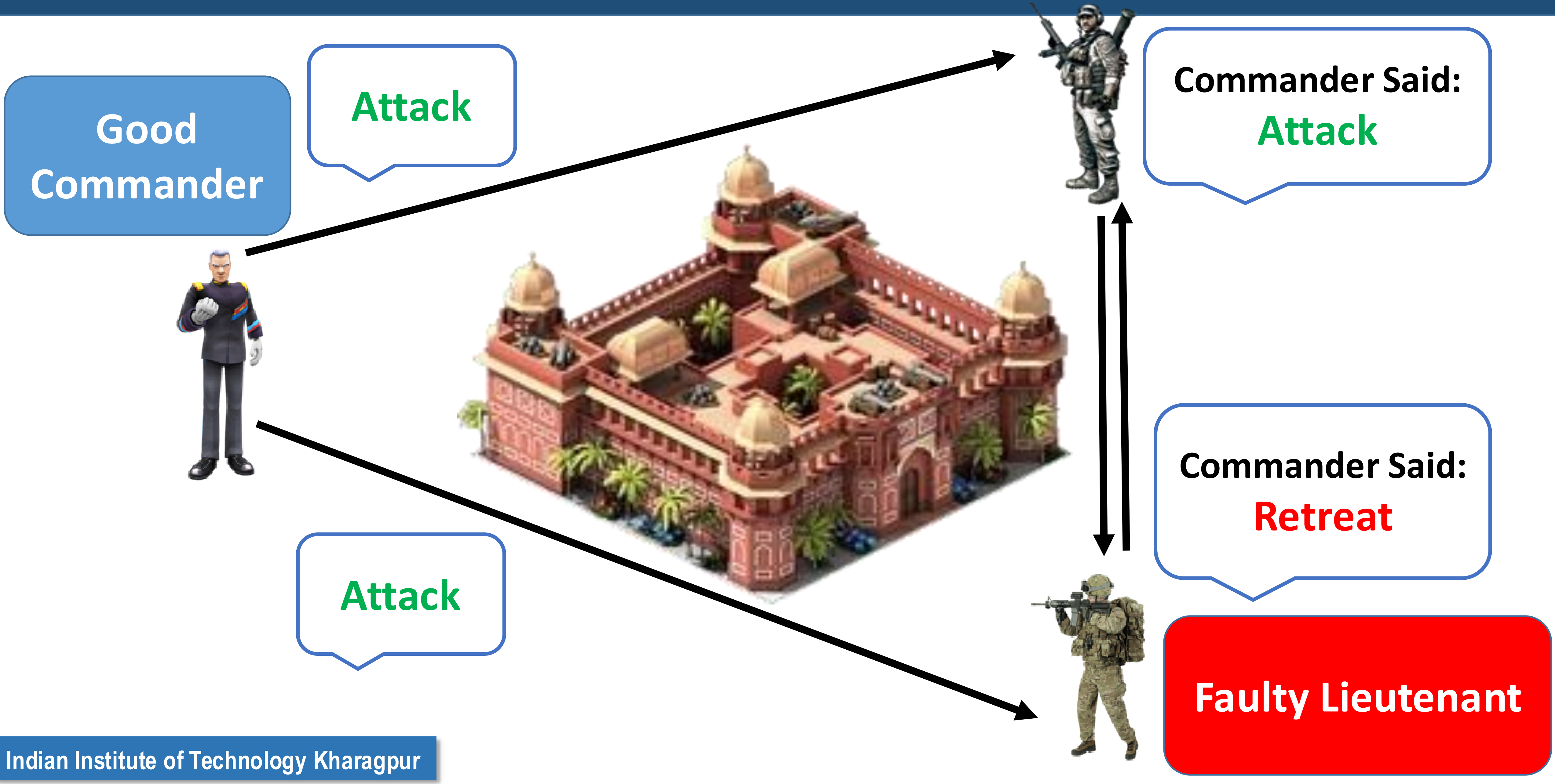

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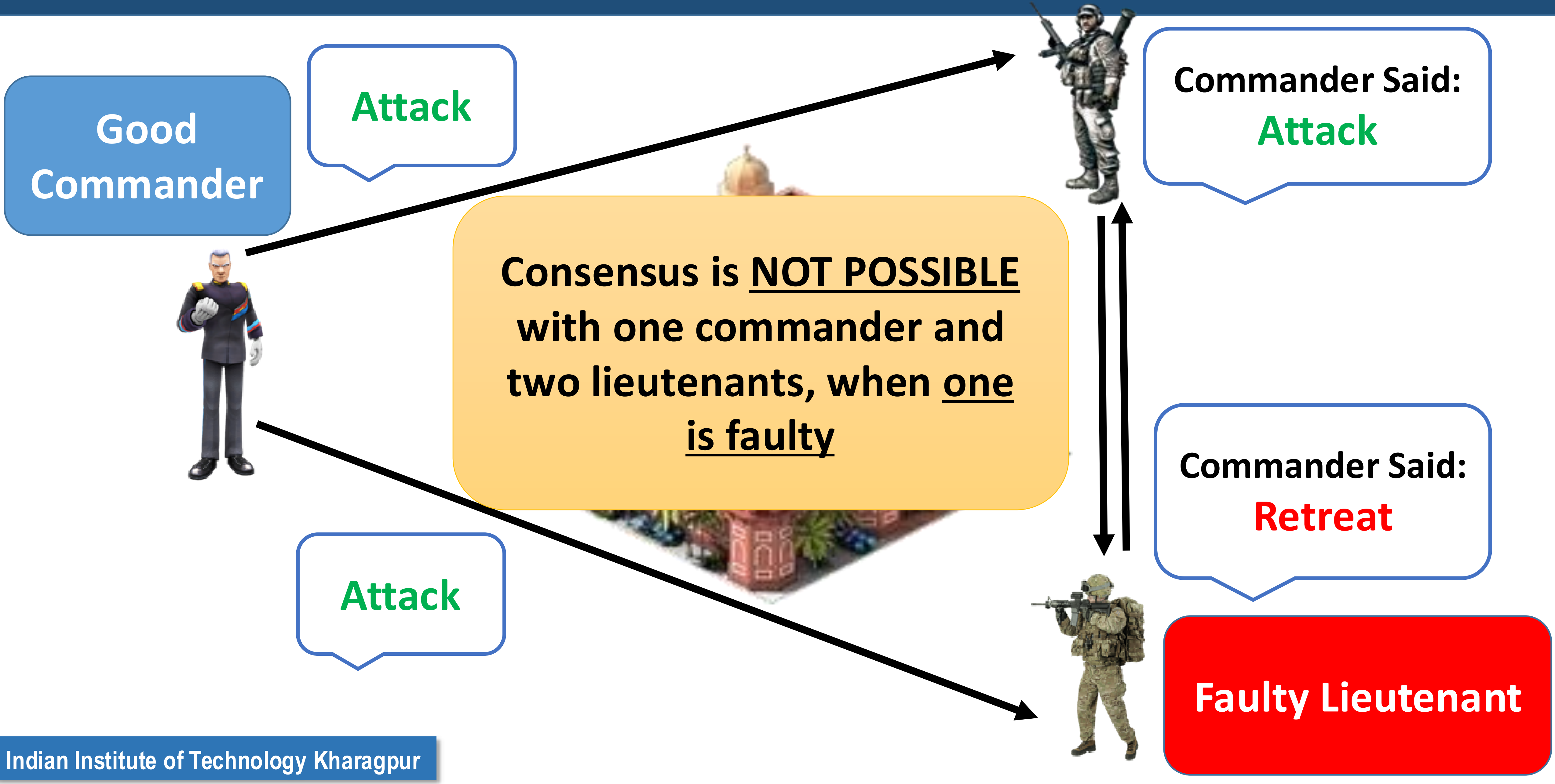

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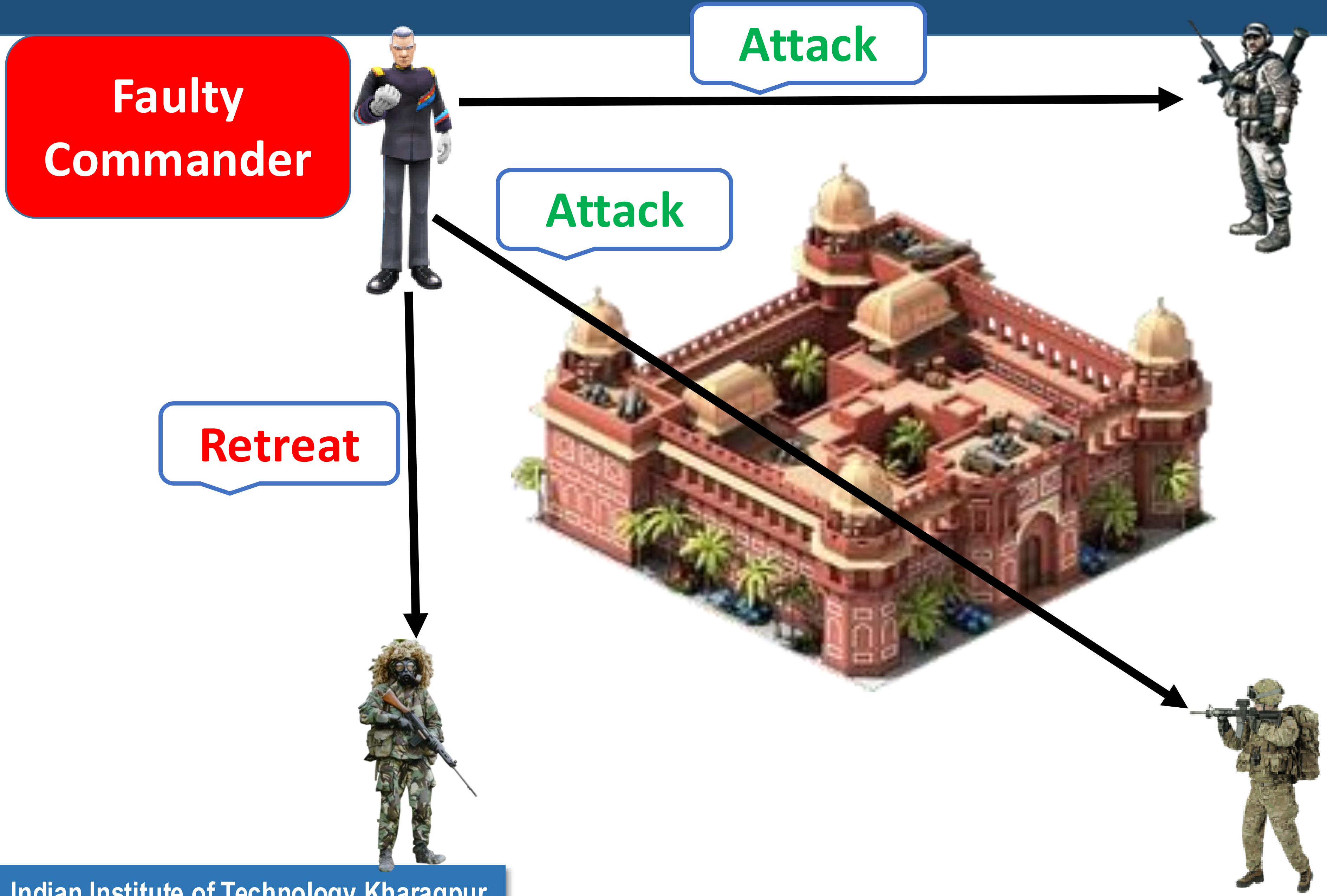

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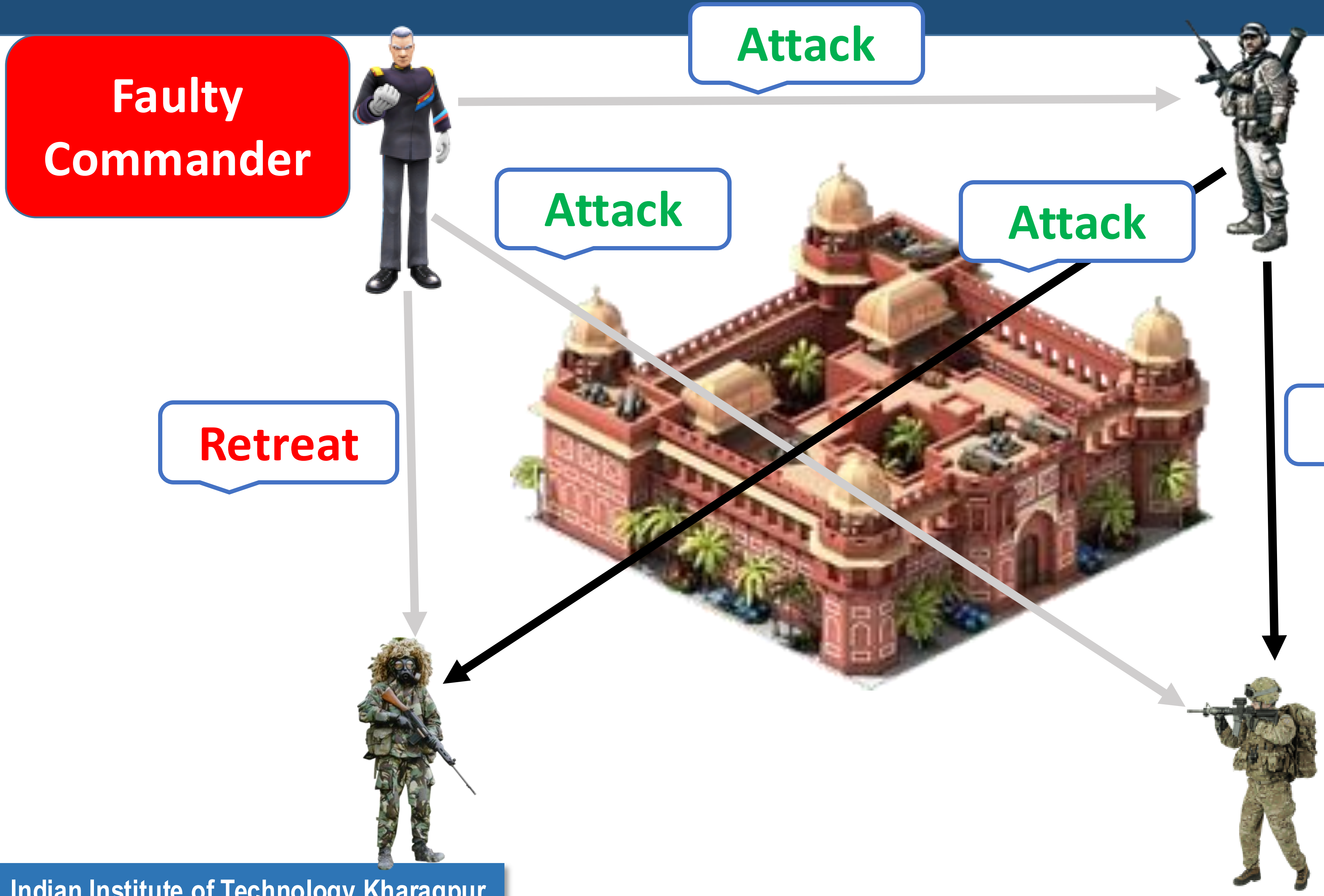

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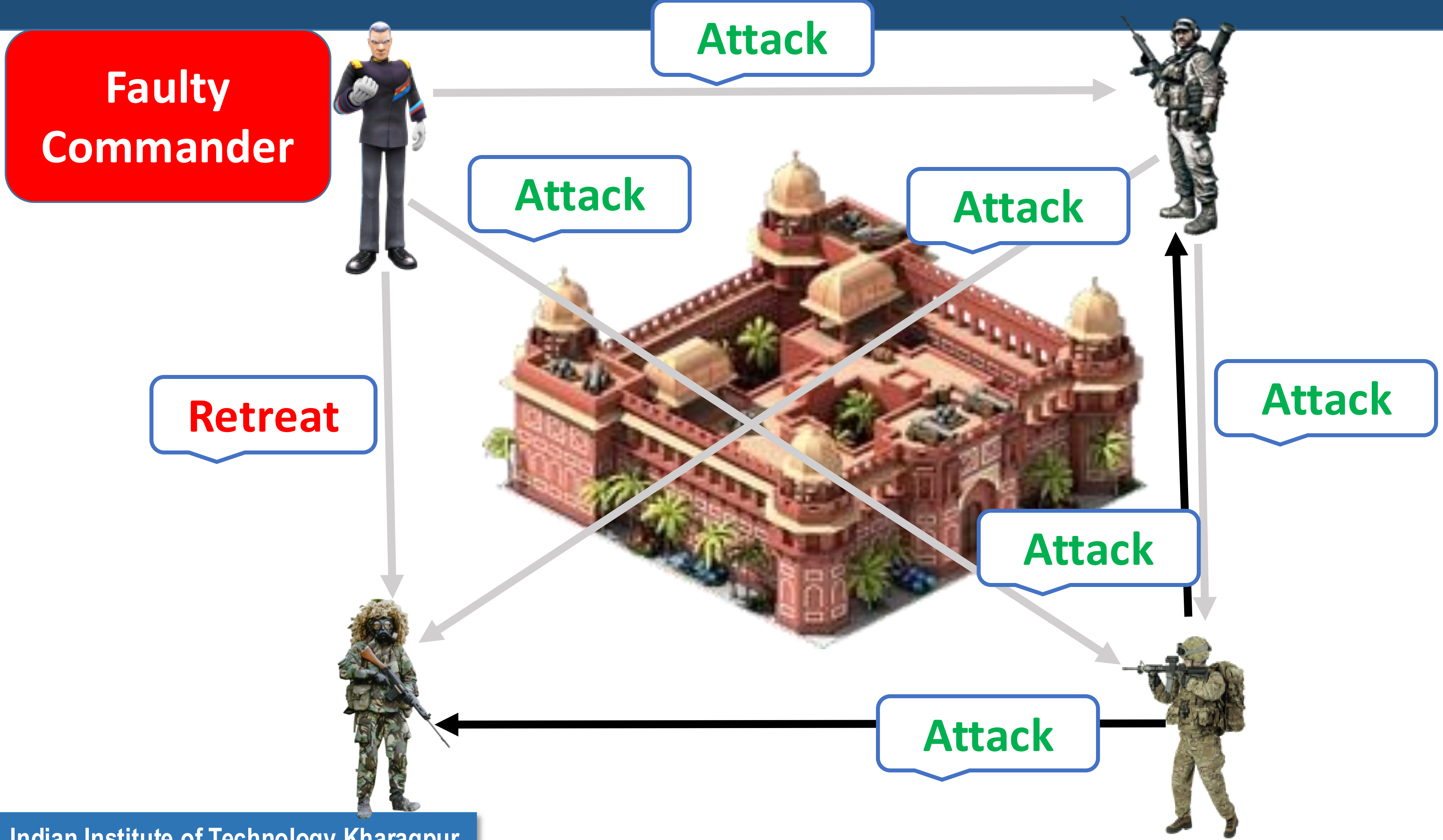

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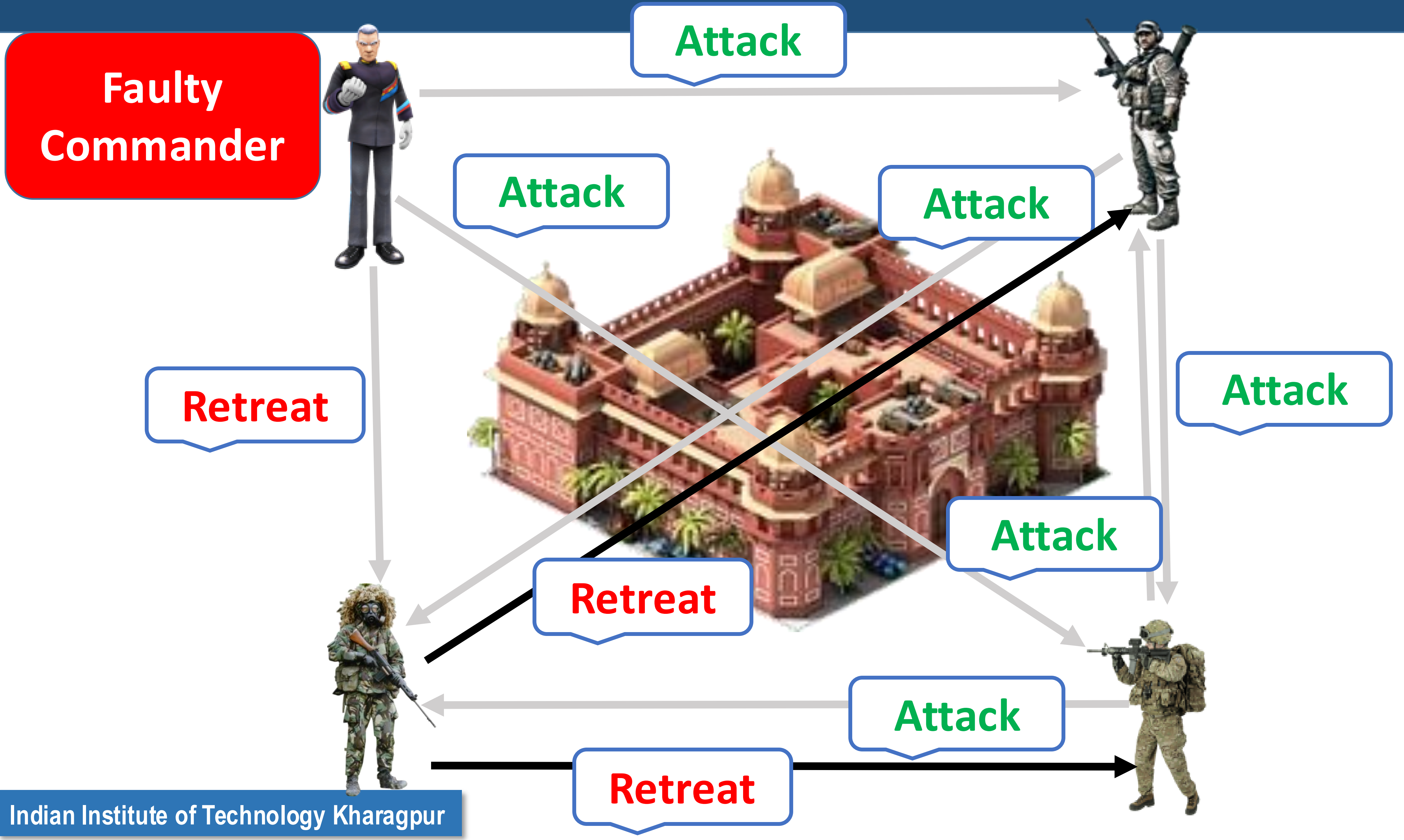

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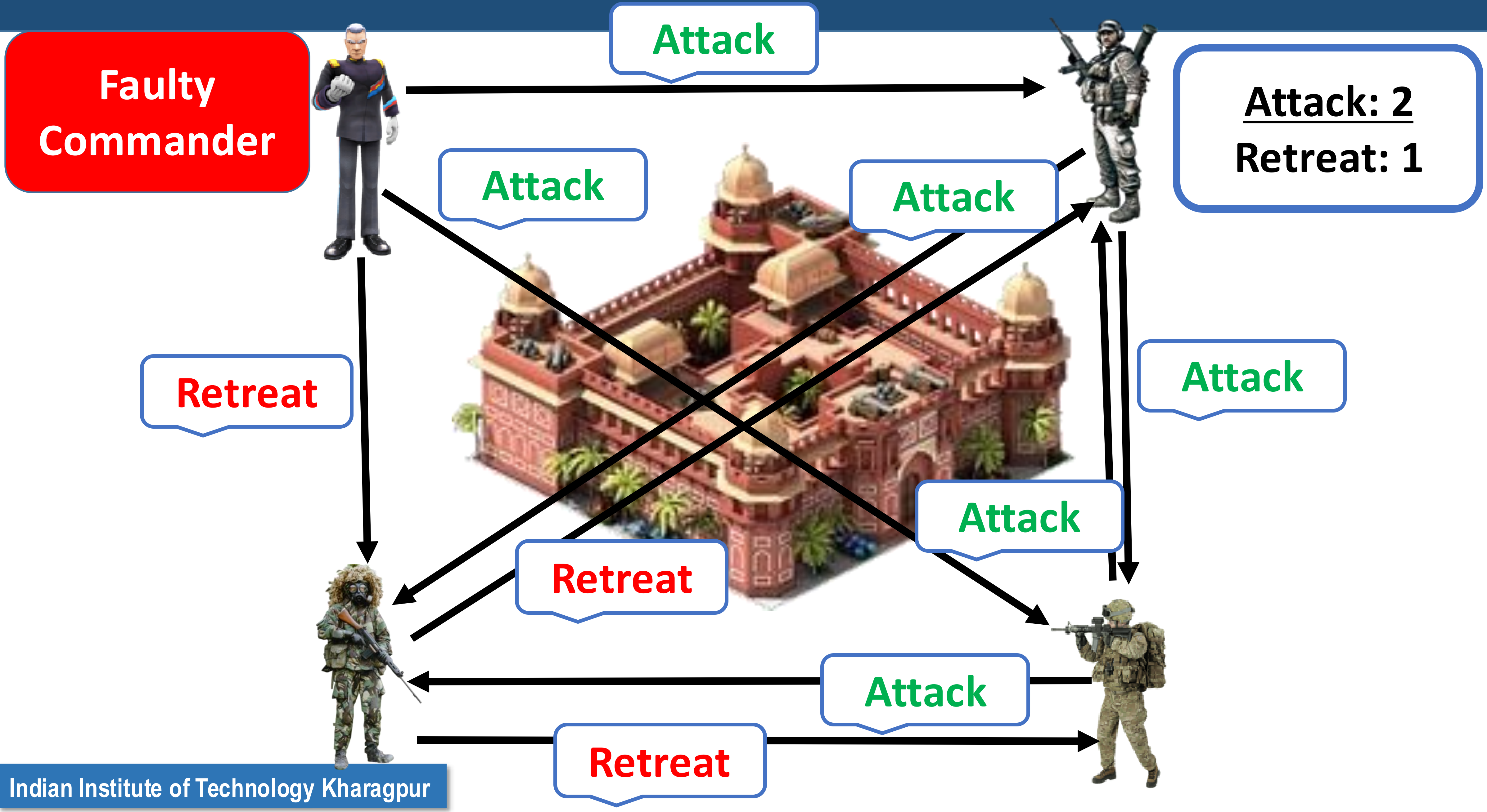

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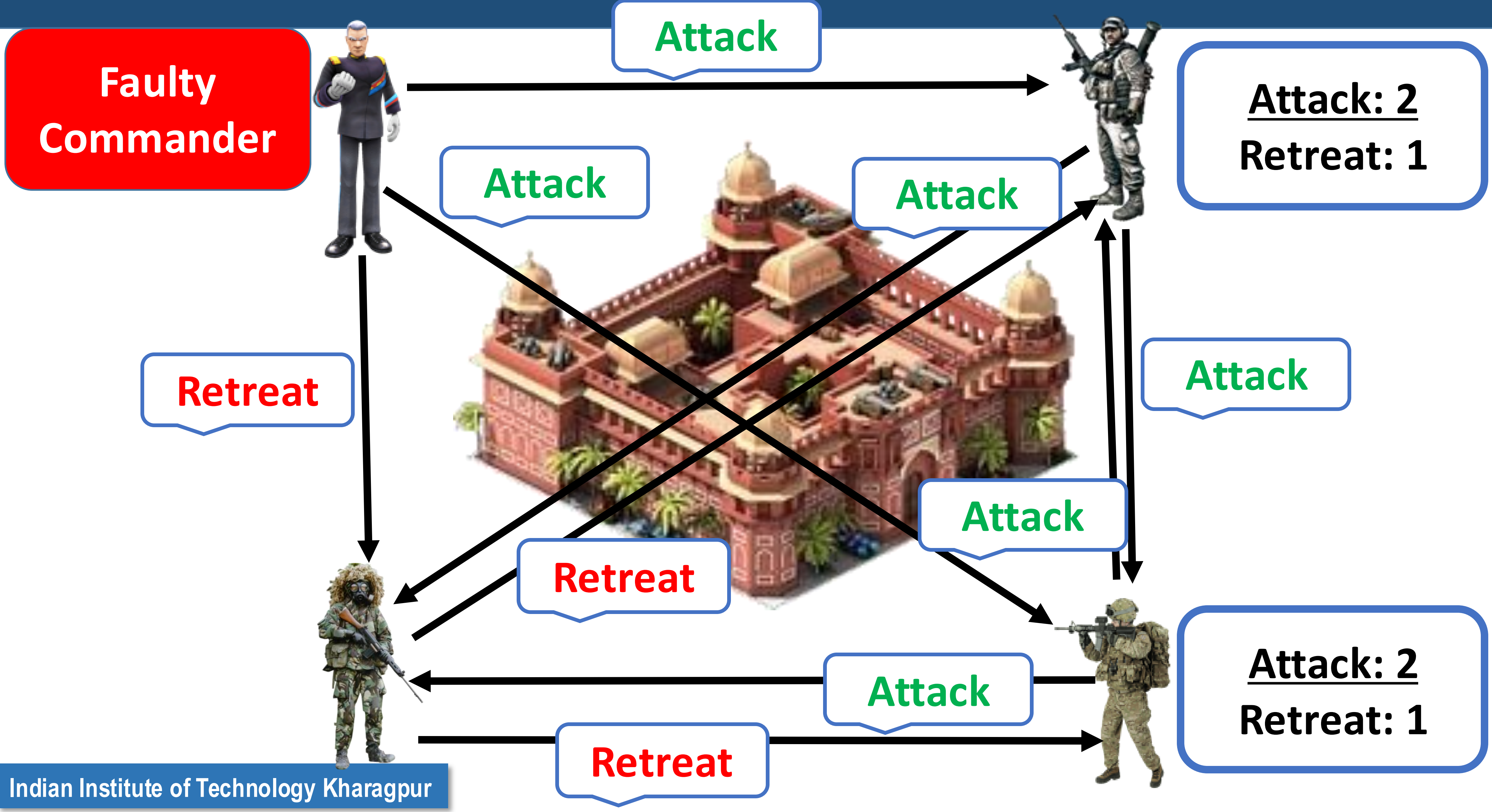

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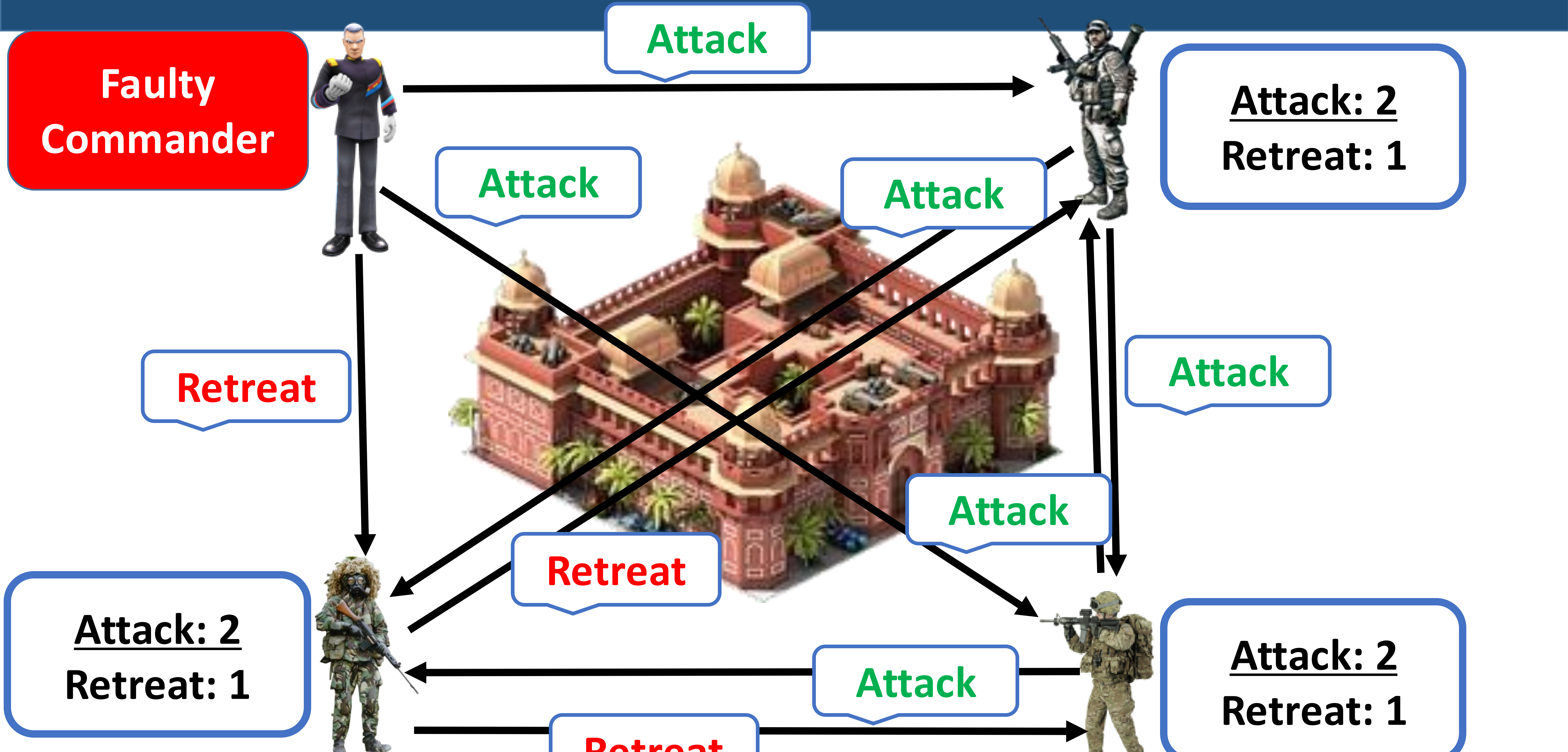

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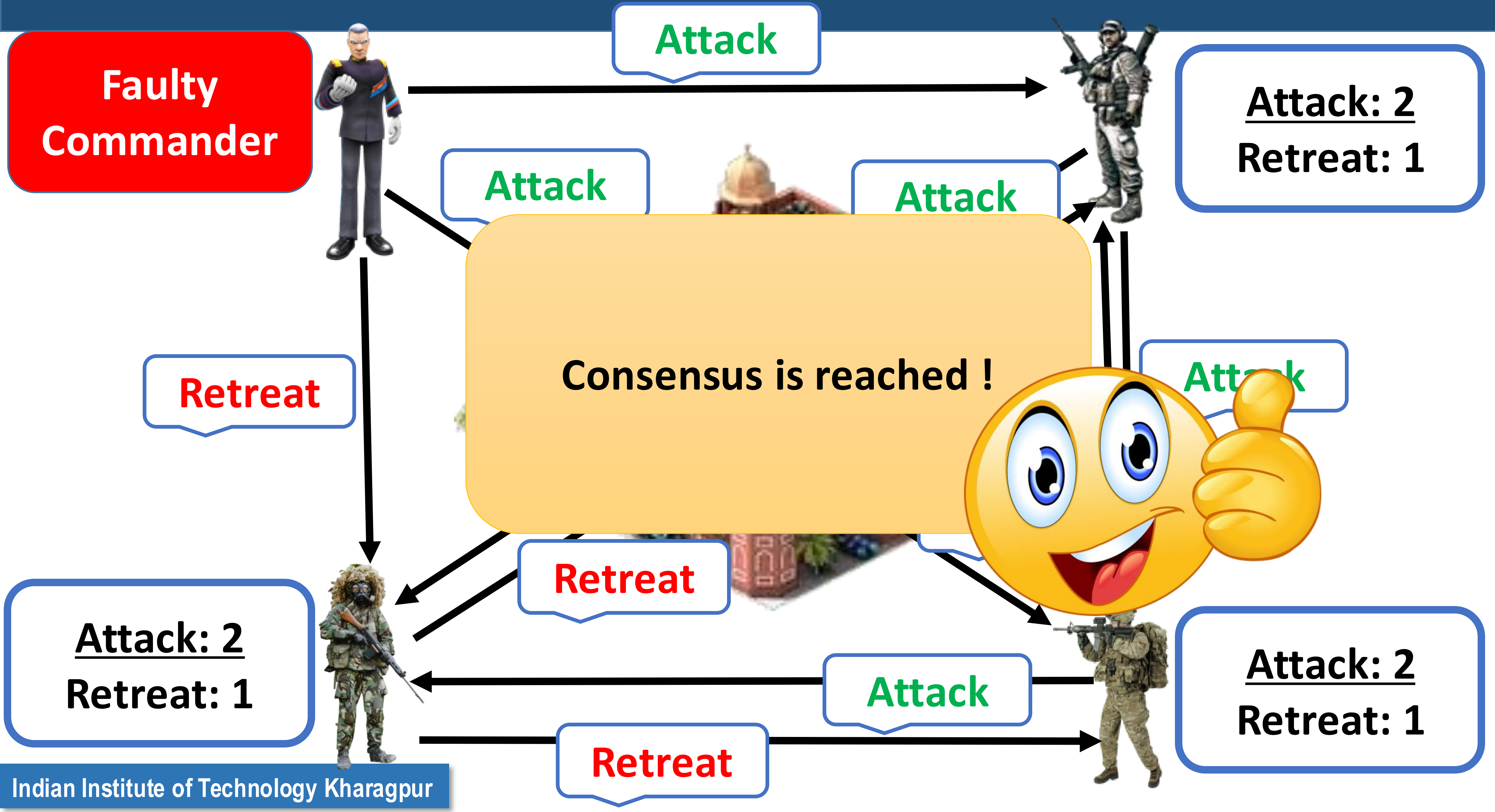

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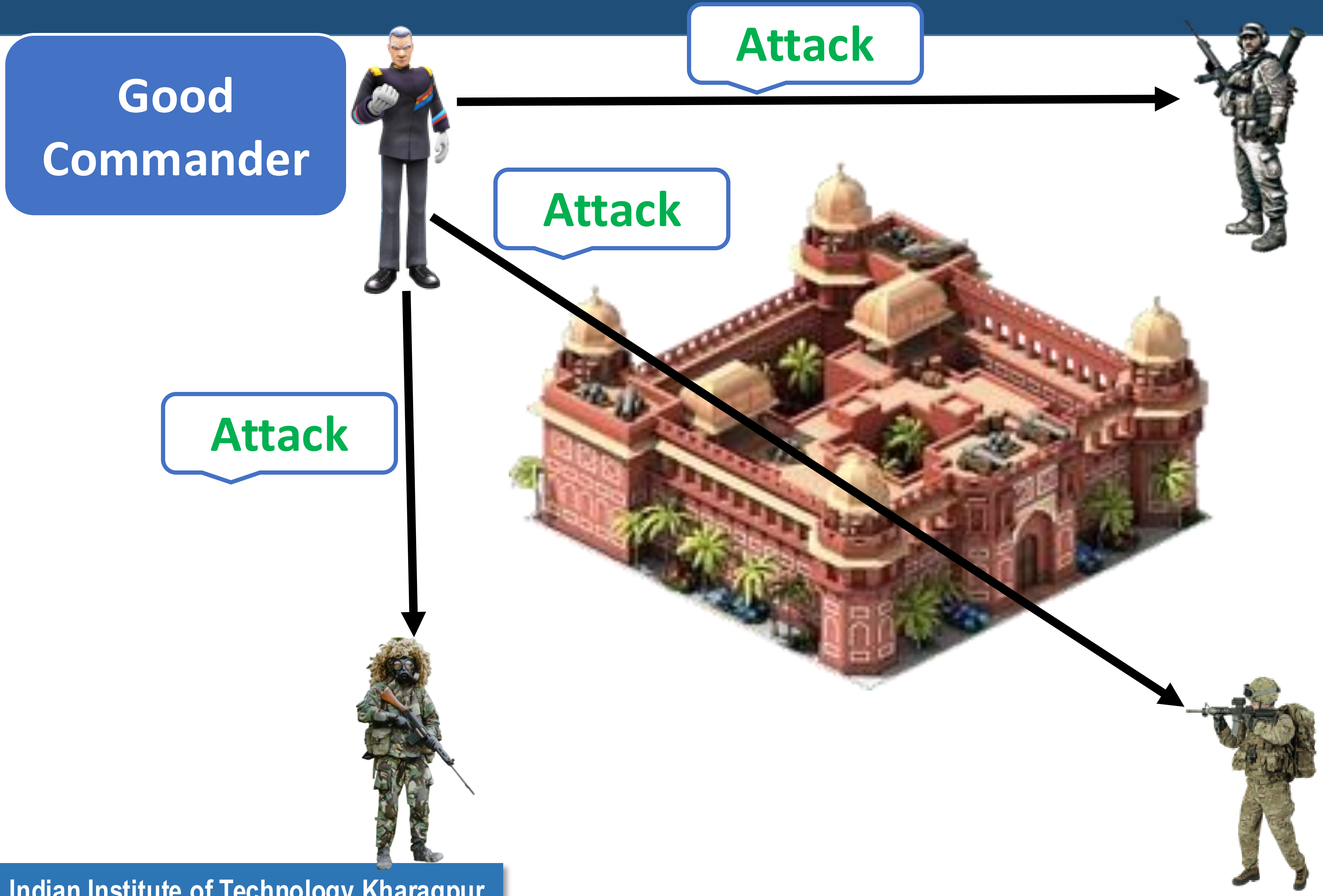

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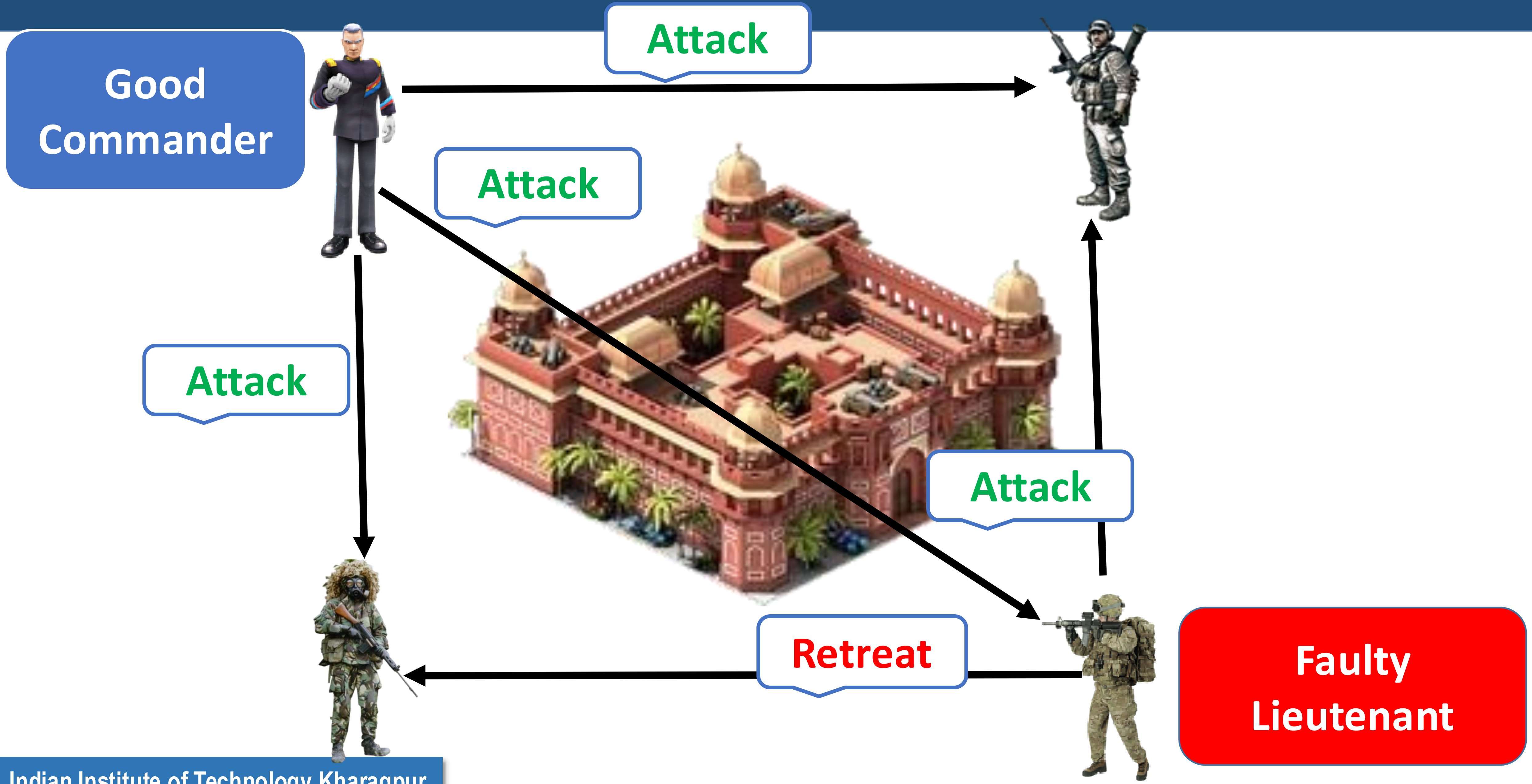

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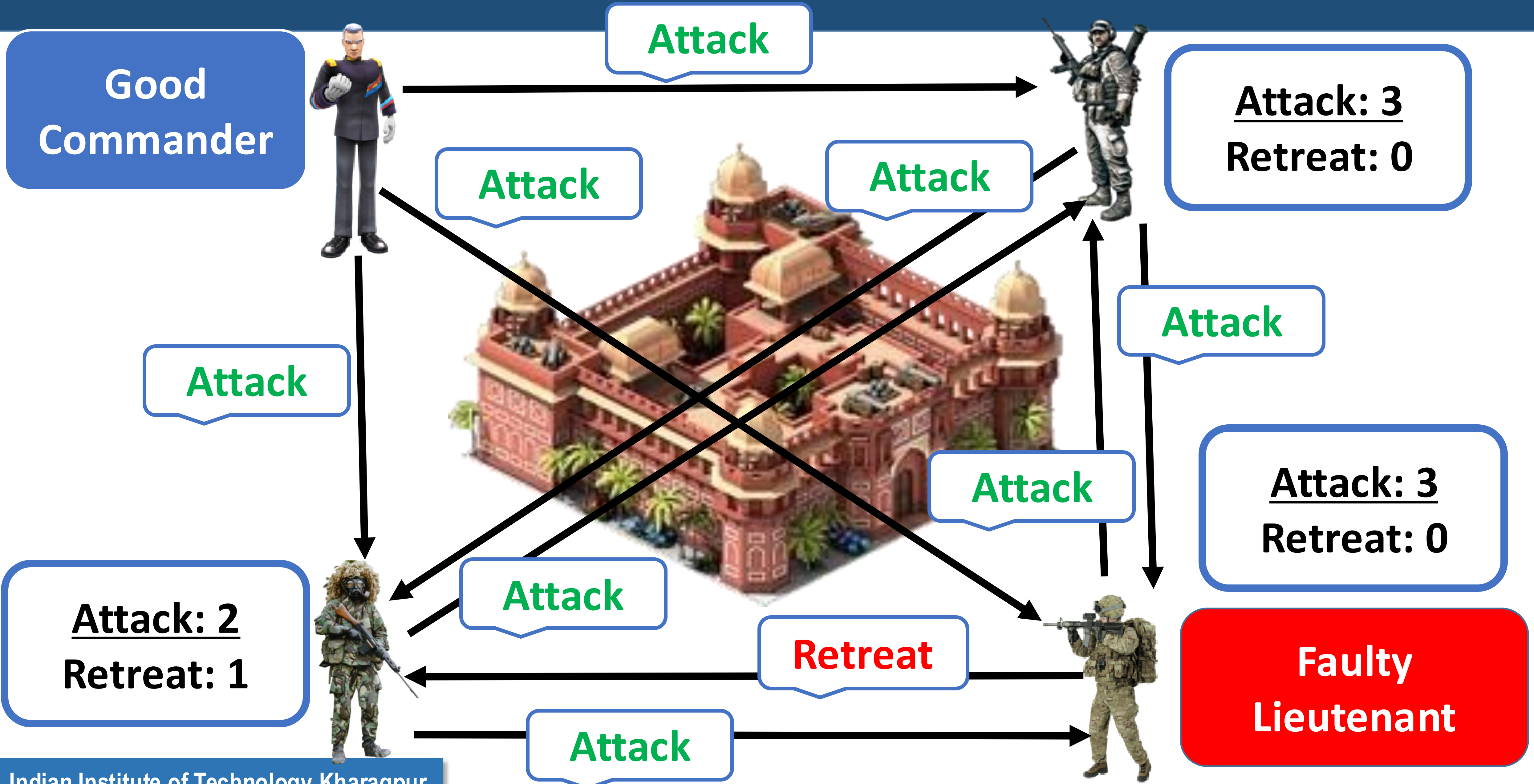

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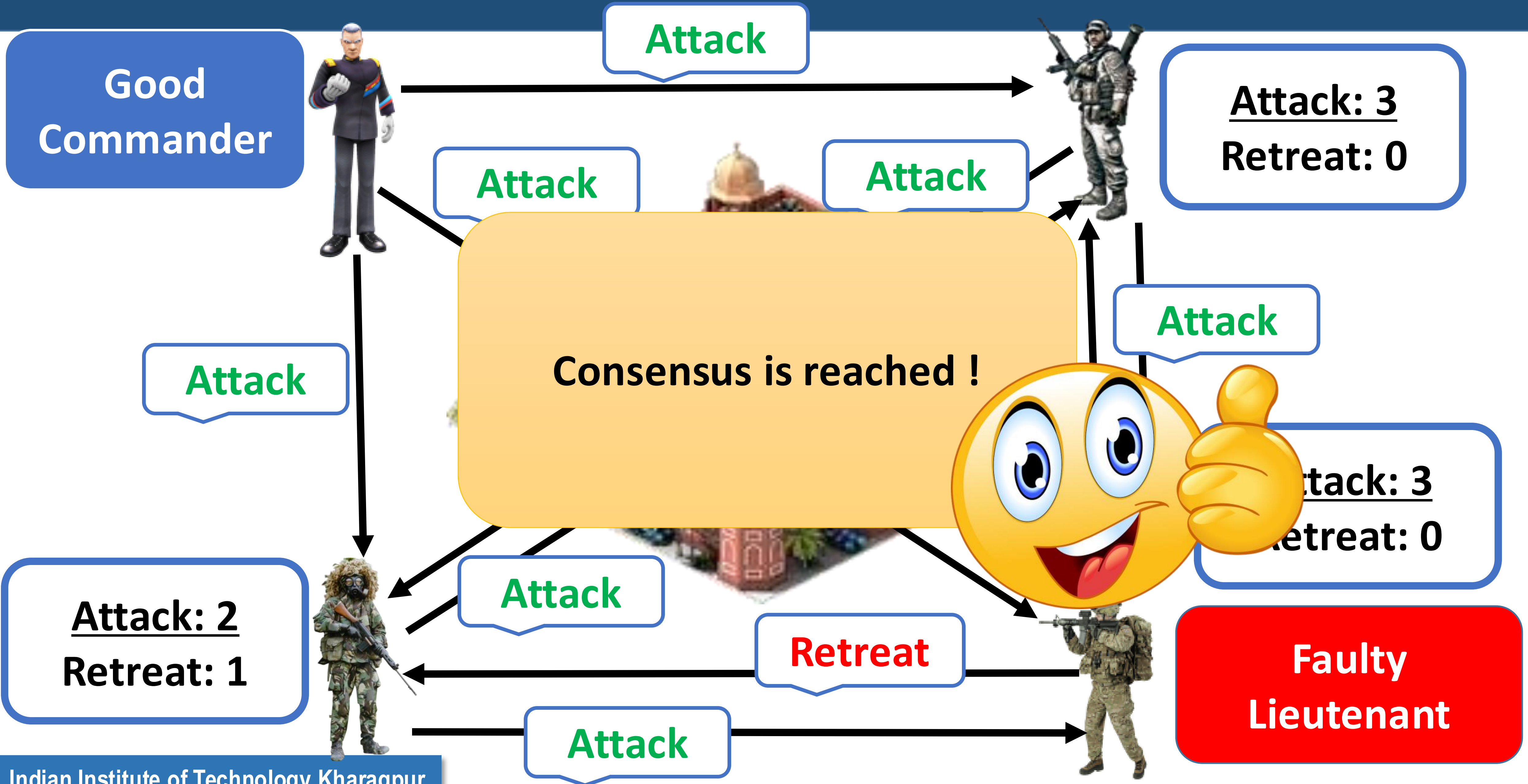

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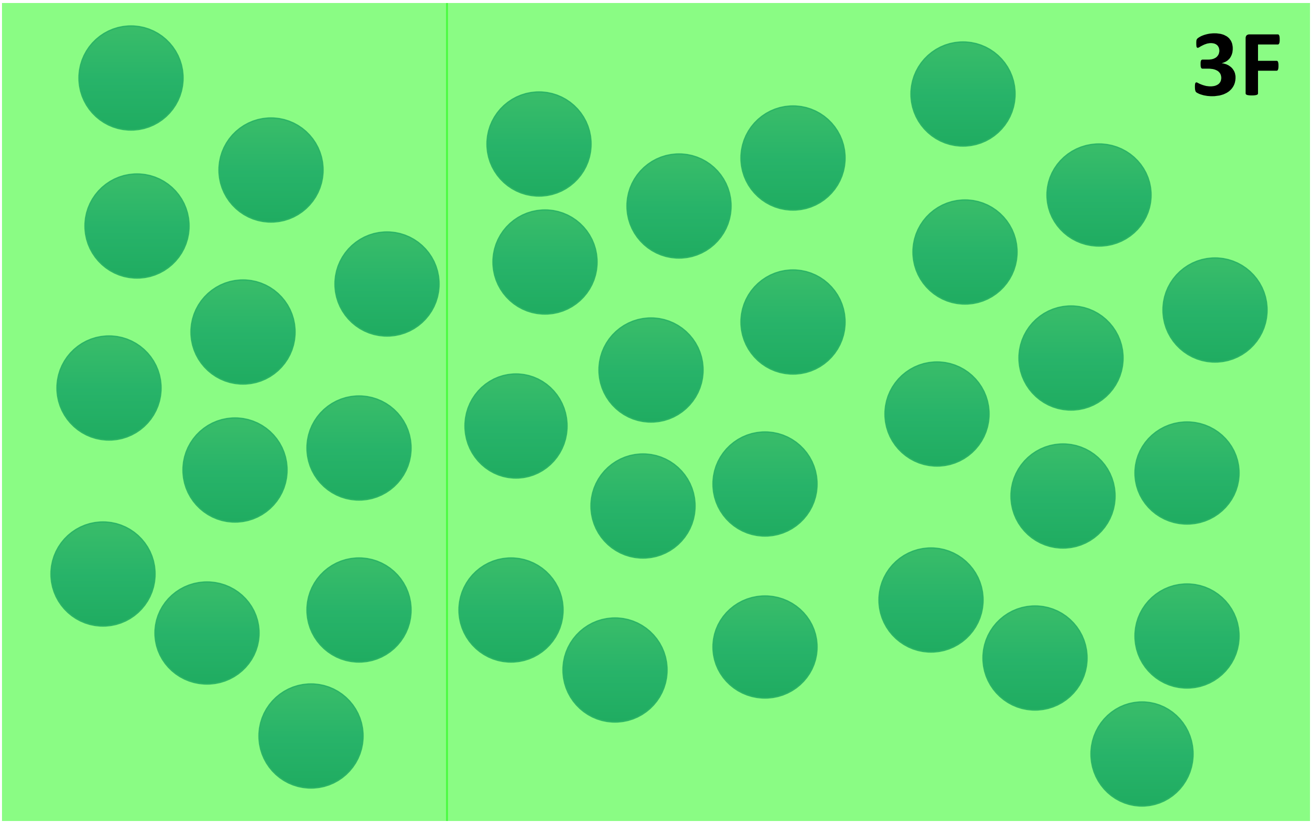

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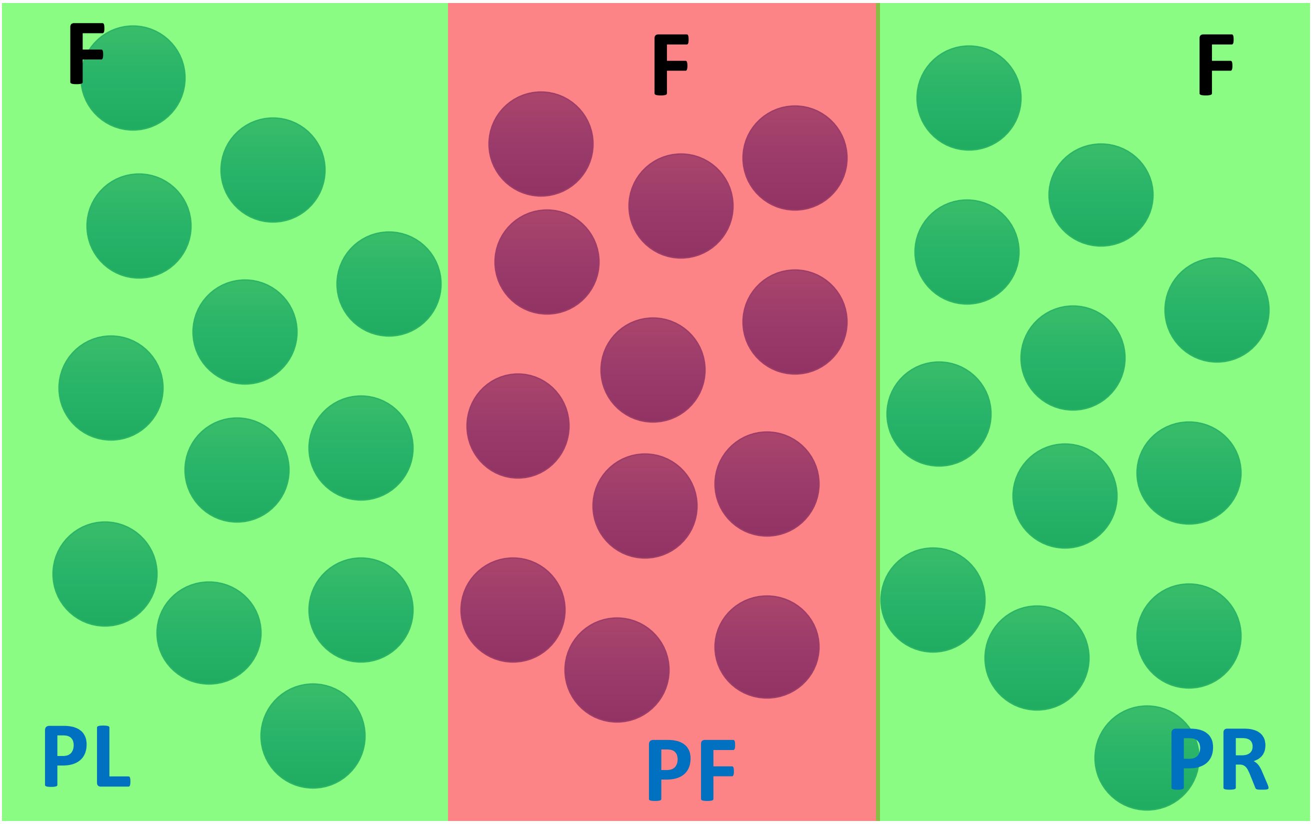

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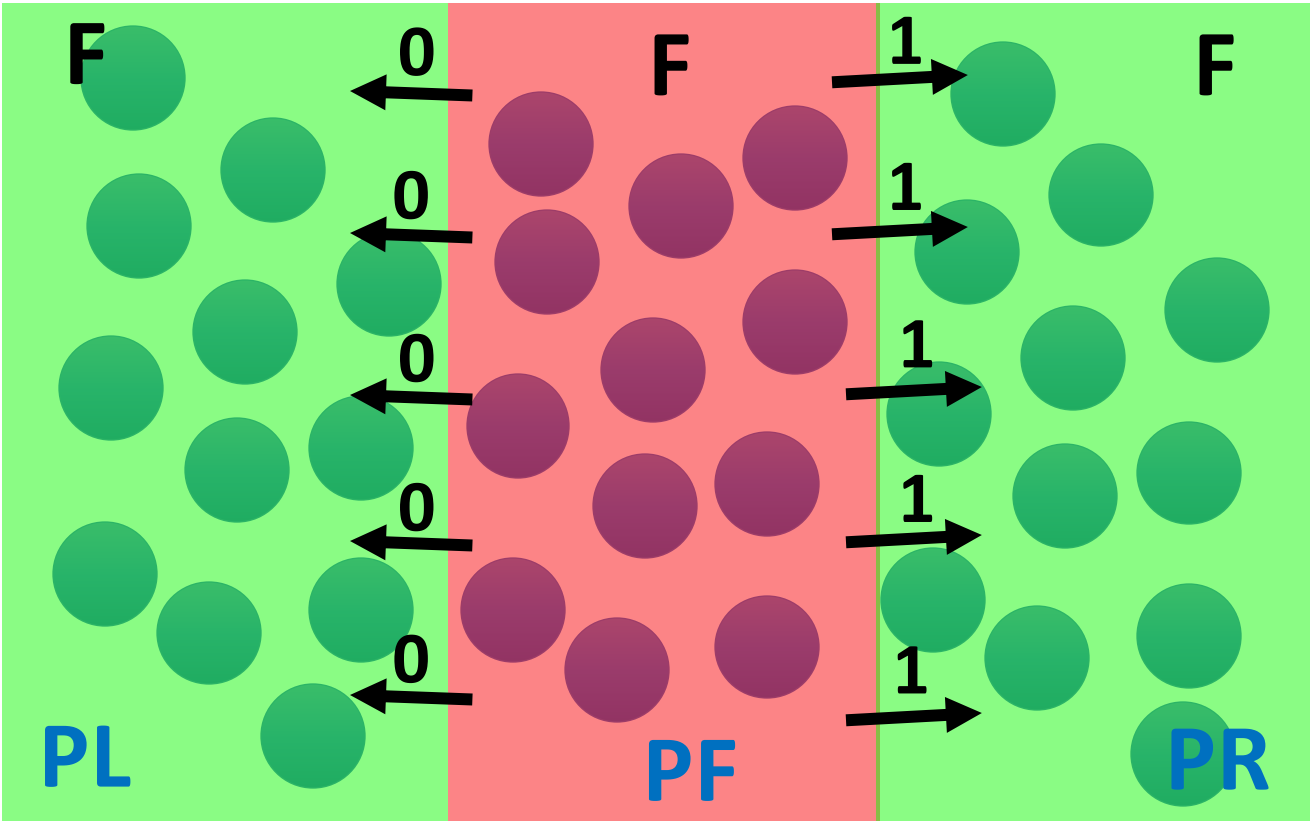

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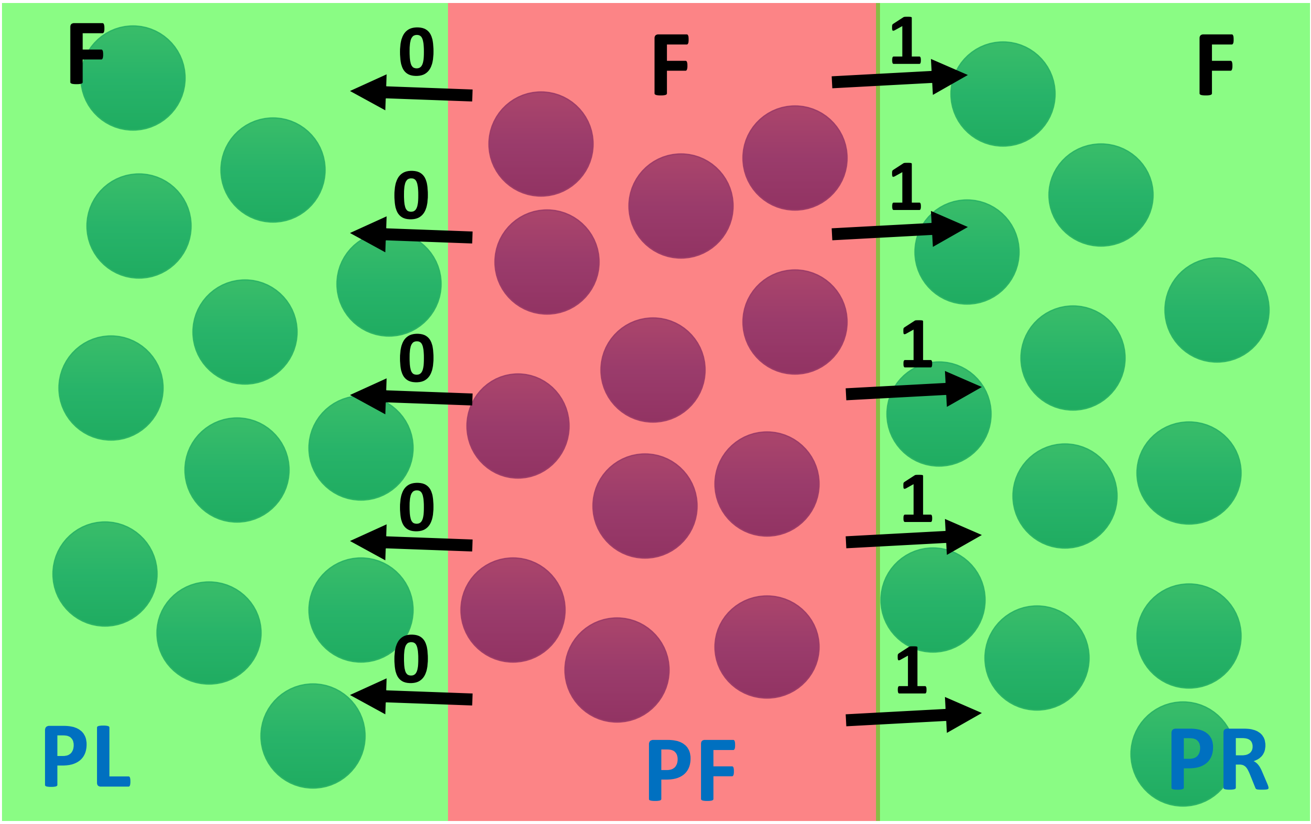


**Either PL or PR must break the tie**

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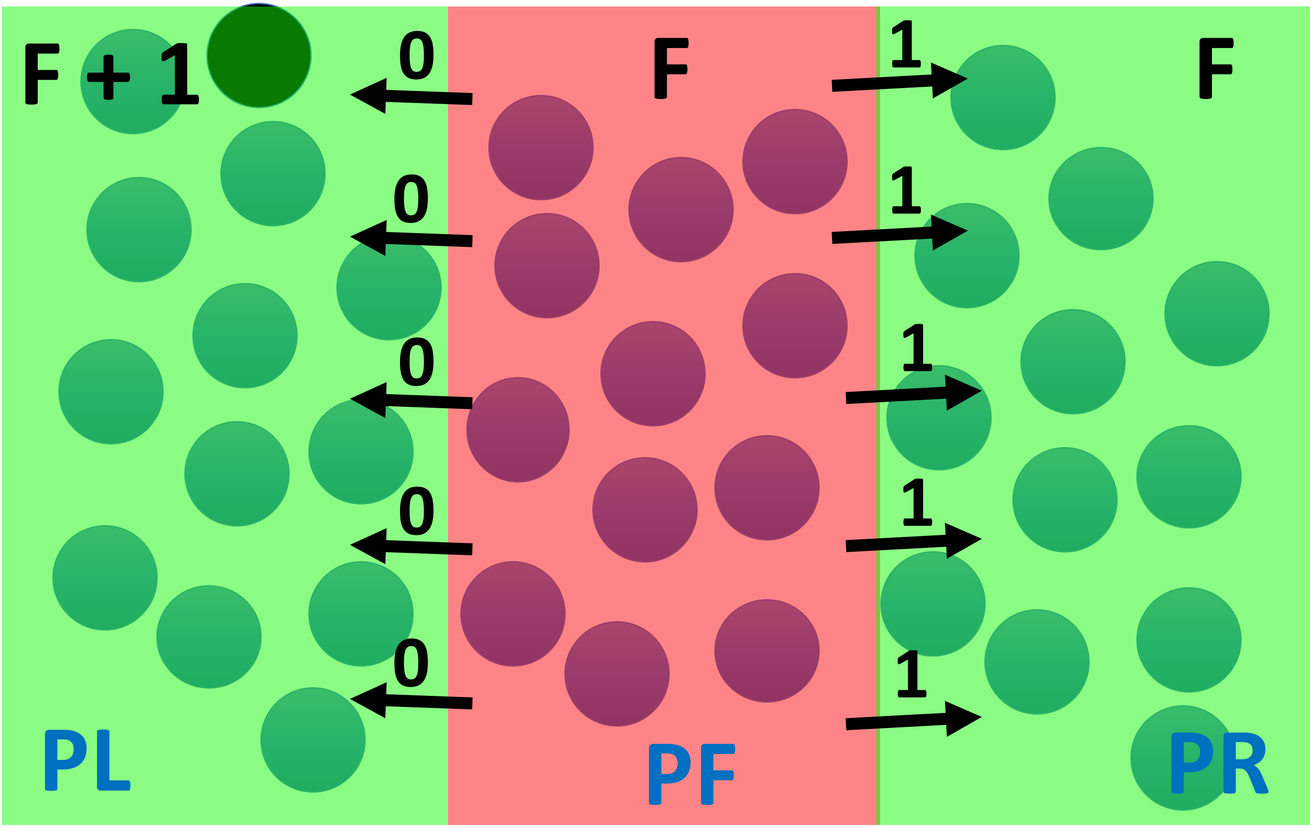


**Put one additional node to PL / PR**

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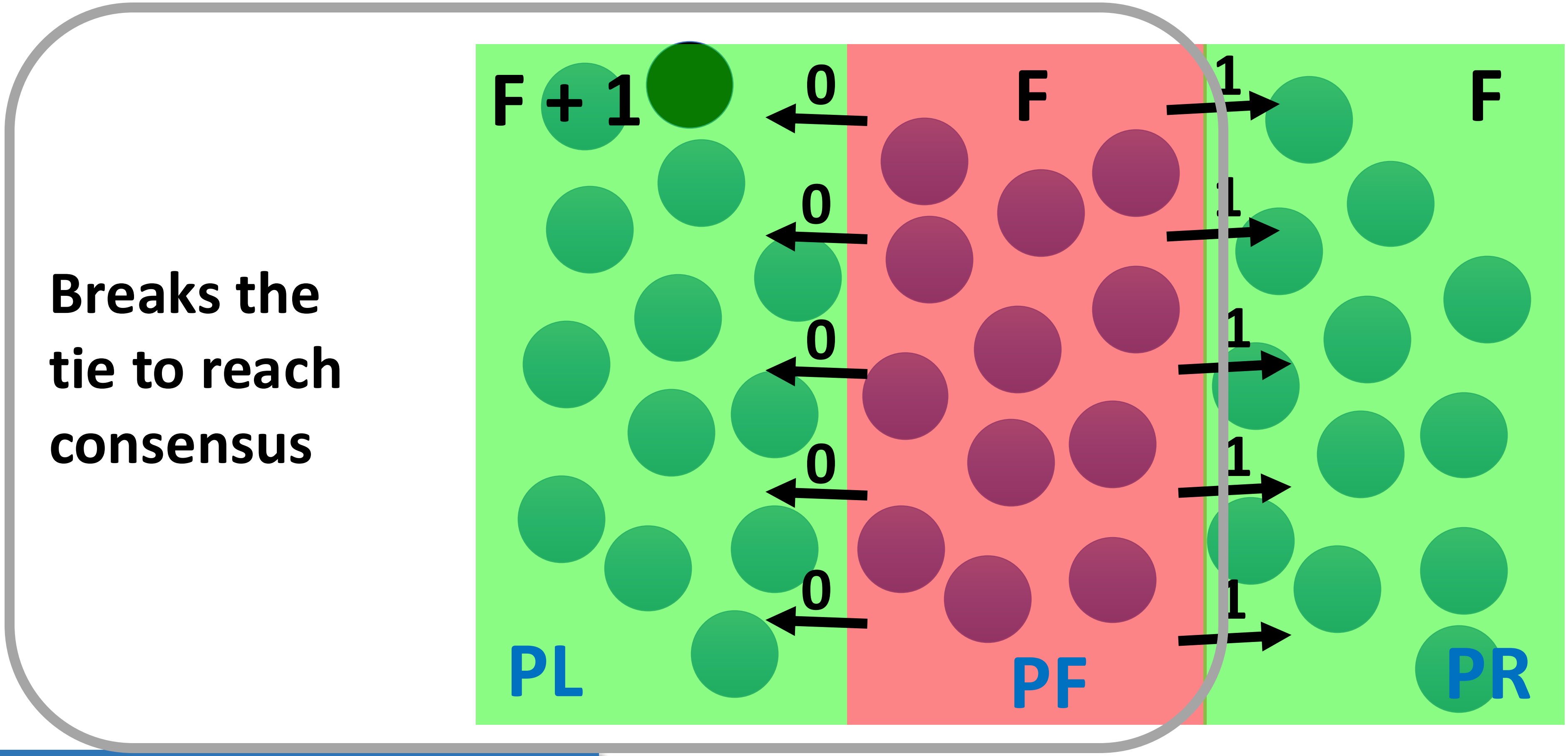


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# BFT Consensus

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

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**Unrealistic assumptions for real networks**

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# BFT Consensus

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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.

# 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

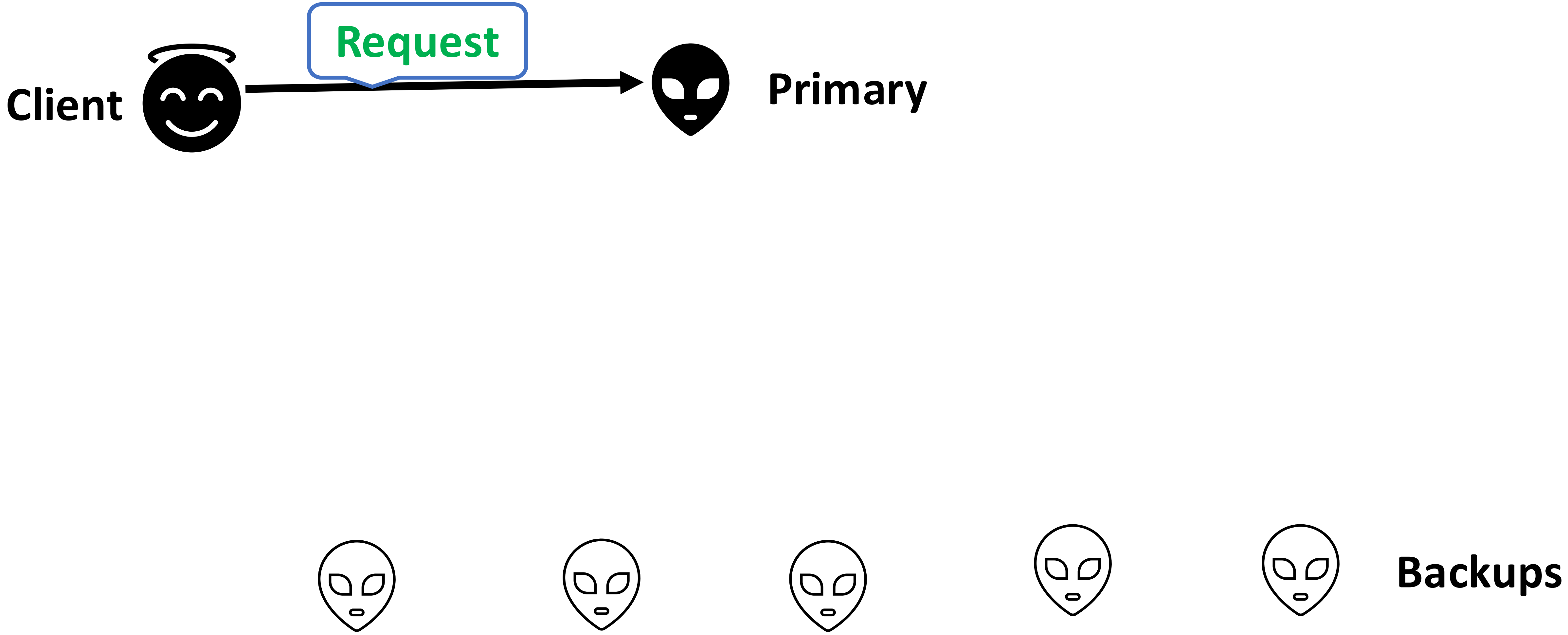
- Incorporated in a large number of distributed applications including blockchain
  - Tendermint
  - Hyperledger Fabric

- 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 **primary** (works like a leader), and others are considered **backups**
  - 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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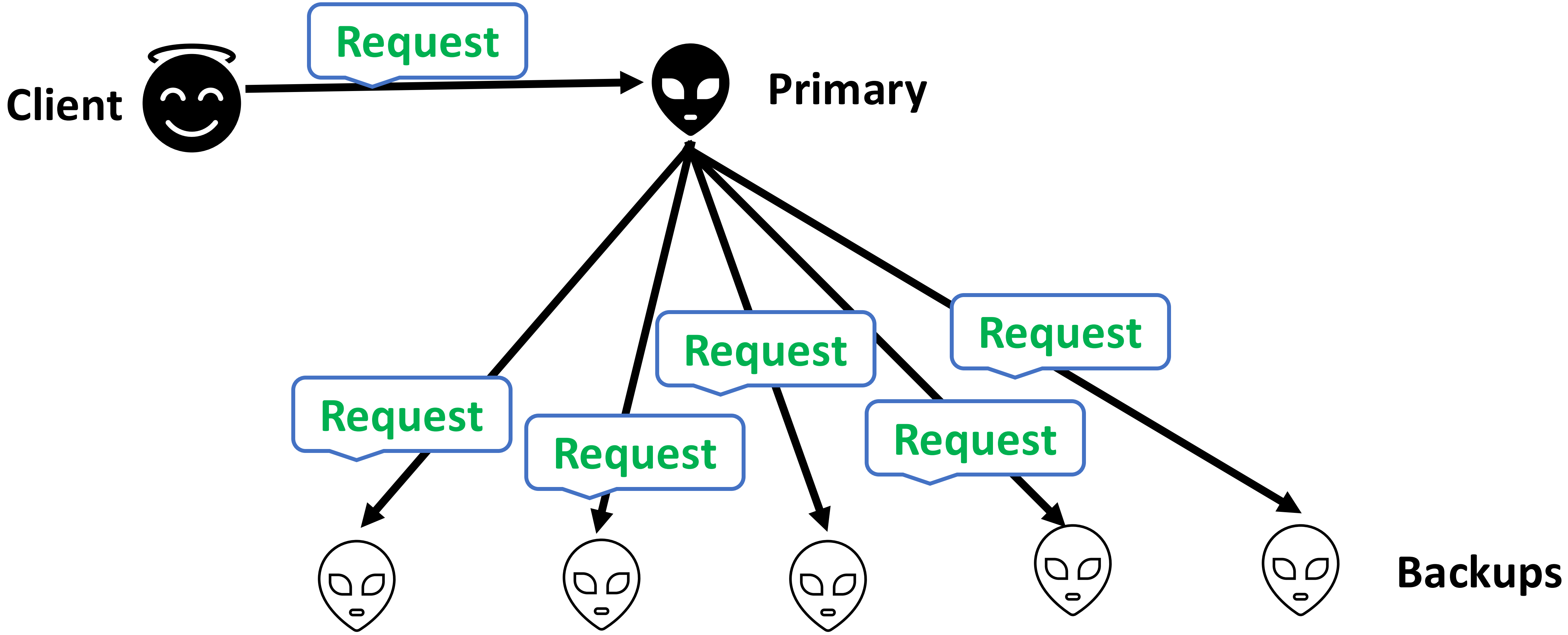

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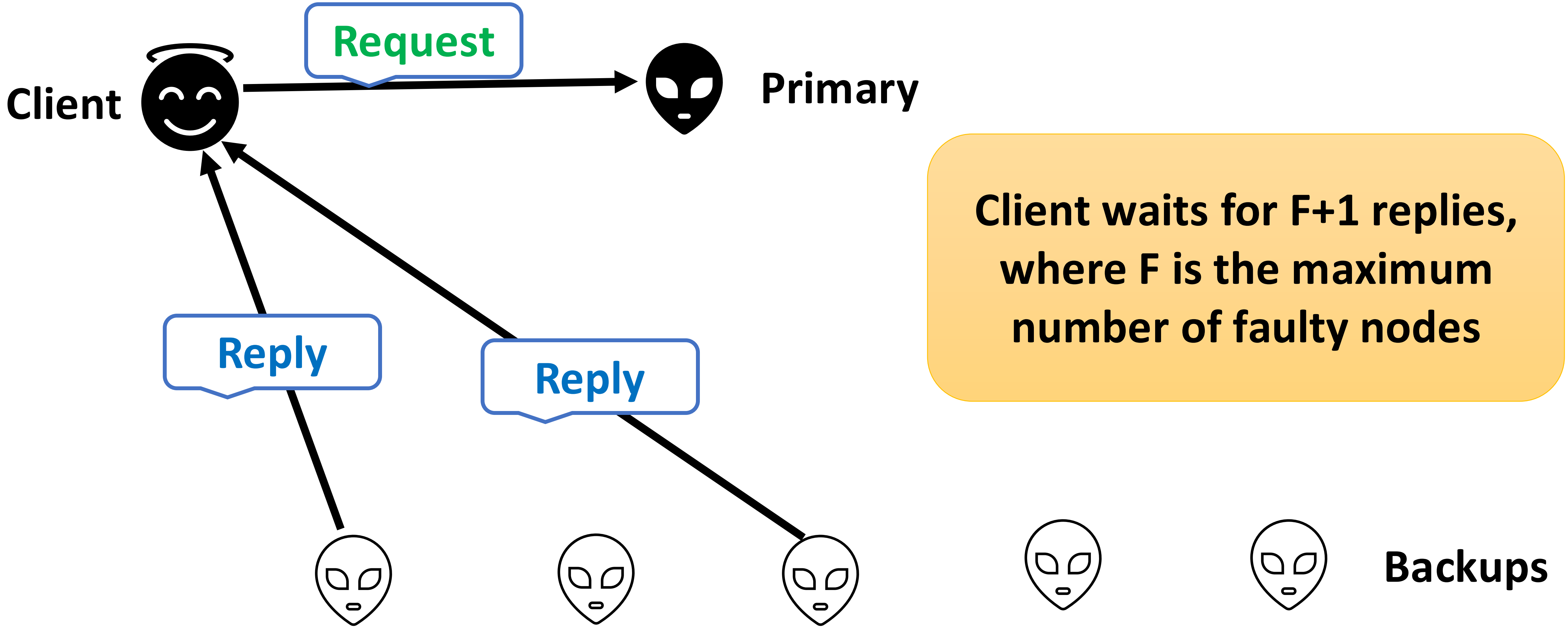
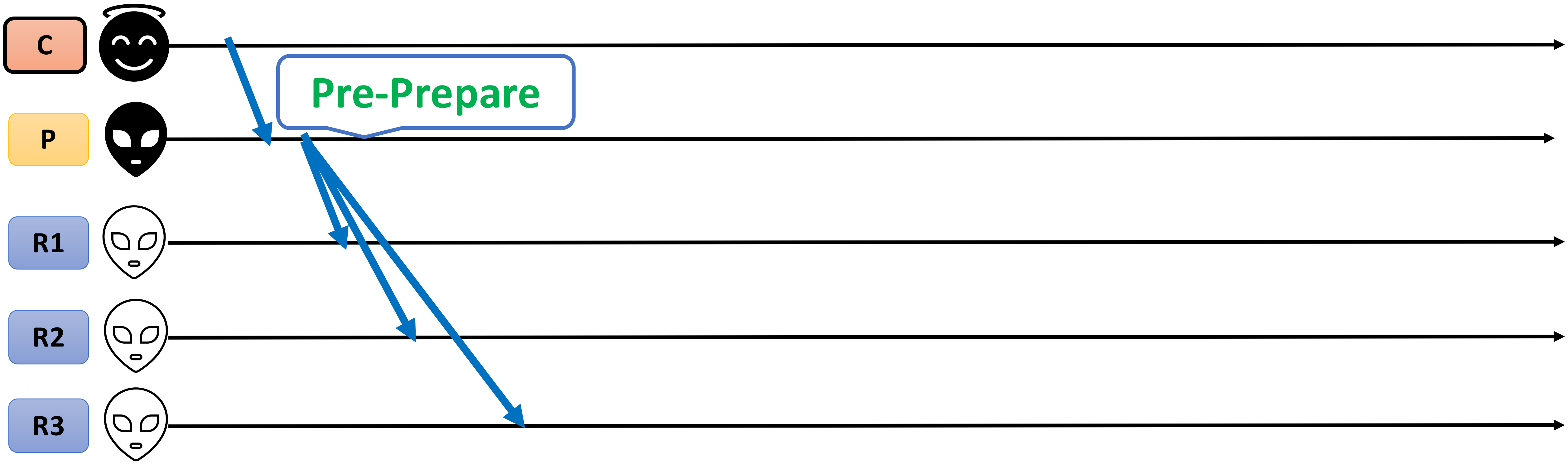



Client waits for F+1 replies, where F is the maximum number of faulty nodes

# PBFT – The Algorithm

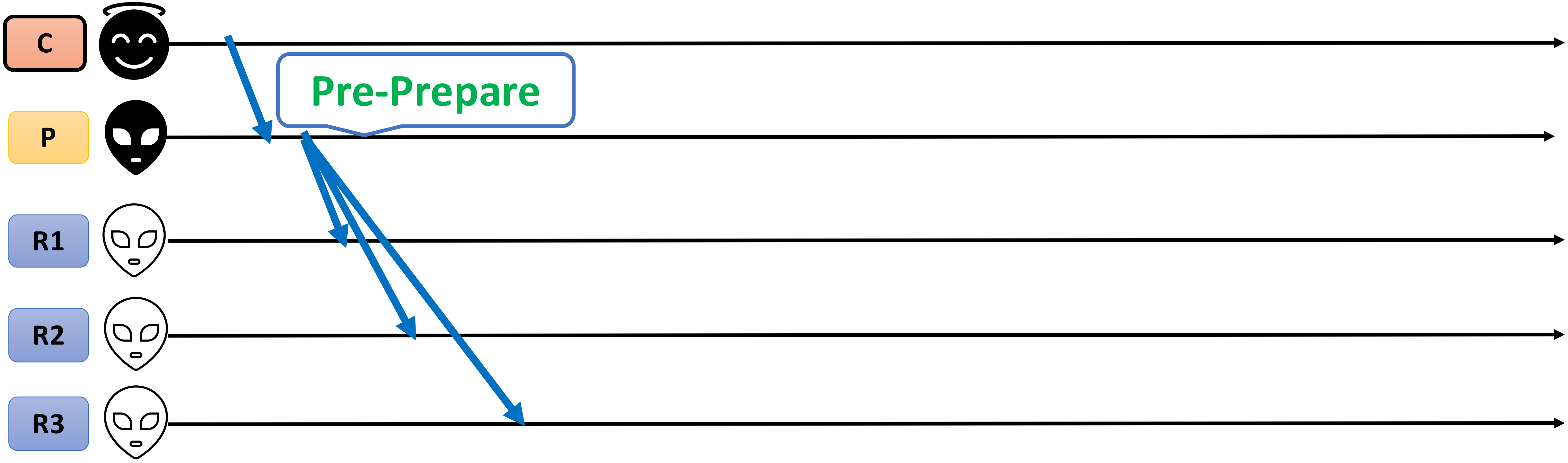

- The protocol starts by the client sending a Request message to the primary
- The primary collects all the Request messages from different clients and order them based on certain pre-defined logic

# 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



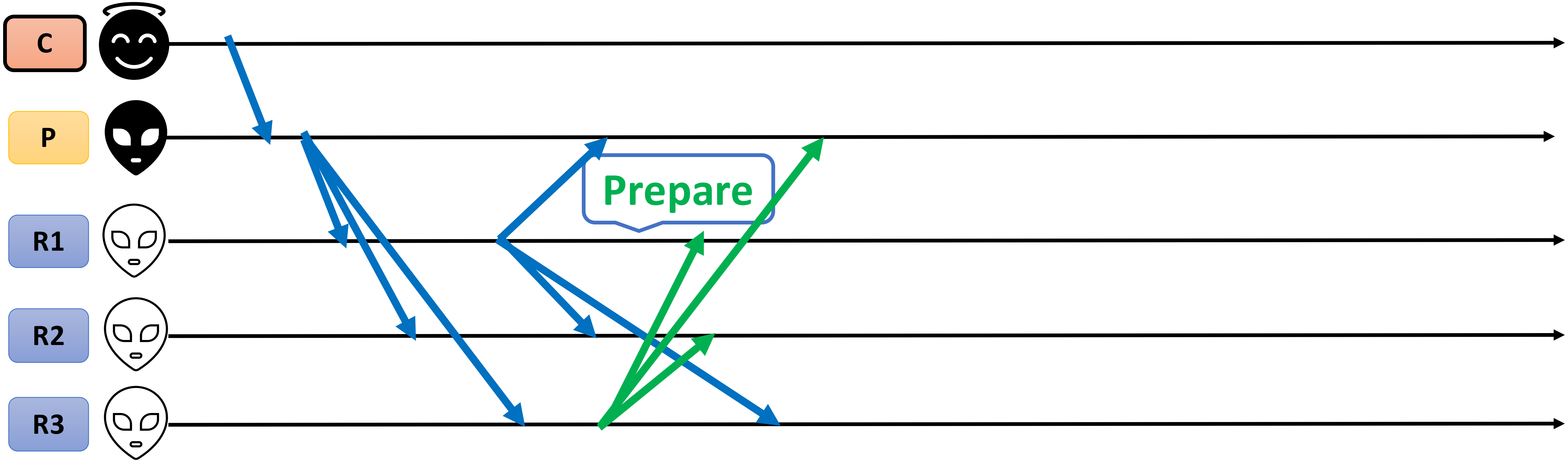

- Pre-prepare works as a proof that the Request was assigned a sequence number *n* for the view *v*

# PBFT – The Algorithm

A backup accepts the Pre-prepare message, if

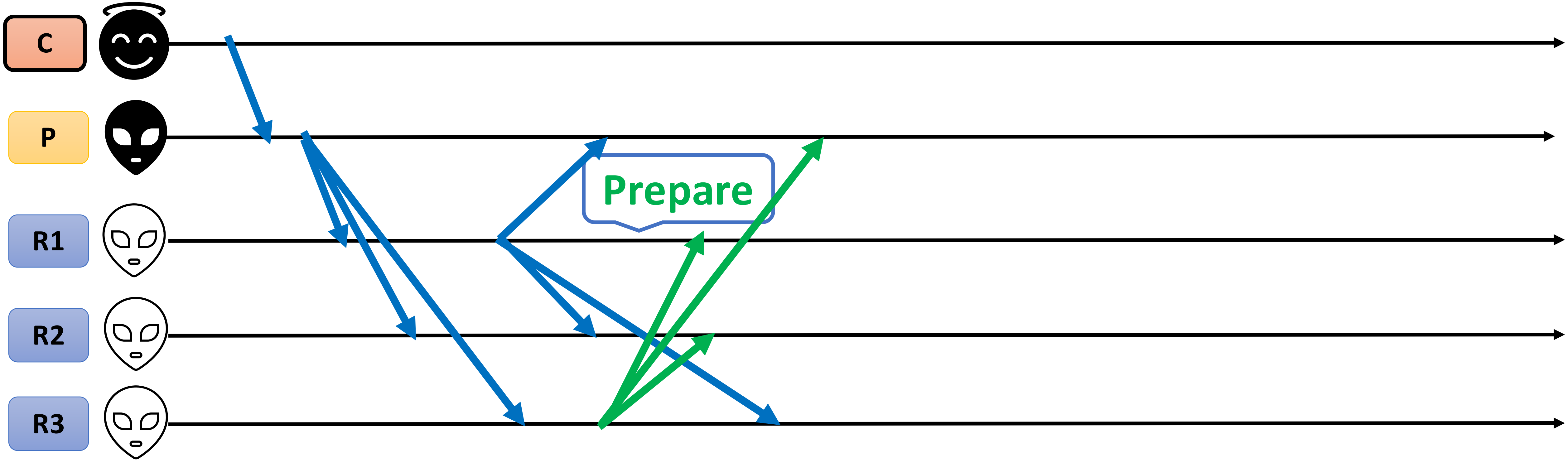
- The signature is correct and *d* is the digest of the message *m*
- The backup is in view *v*
- It has not received a different Pre-Prepare message with sequence *n* and view *v* with a different message digest
- The sequence number is within a threshold (the message is not too old – prevents a reply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

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- 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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  - **Intersection:** Any two quorums have at least one correct replica in common
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- PBFT uses Byzantine Dissemination Quorum with $2f + 1$ replicas

# Quorum in PBFT

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

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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

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

- **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

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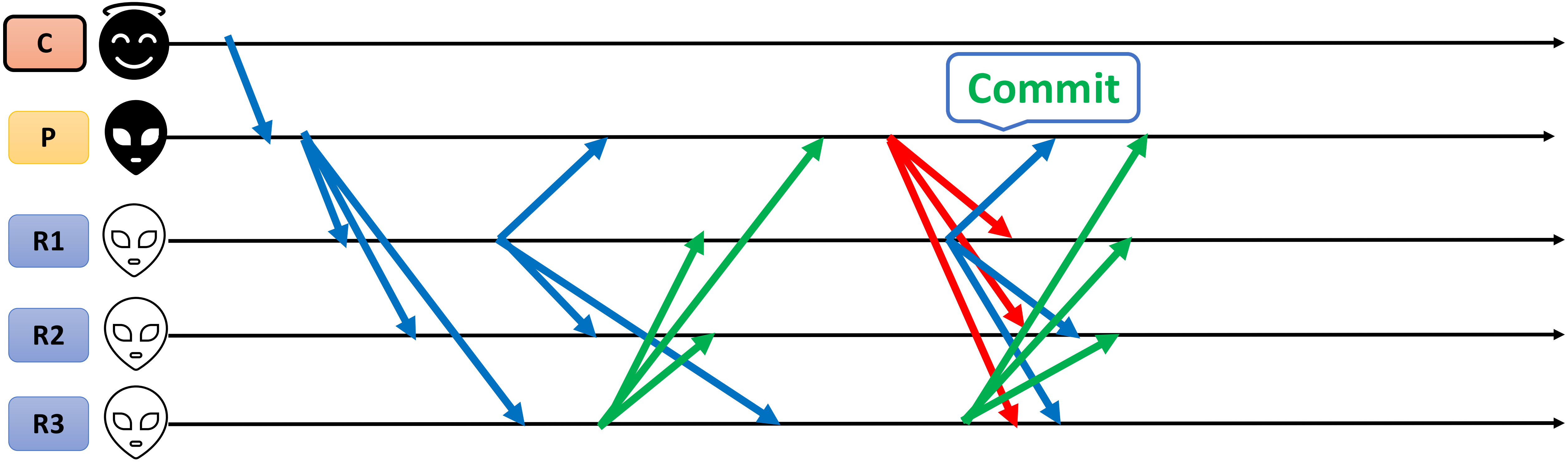
**Remember, you are on an asynchronous channel – messages get delayed and can be received out of order**

**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

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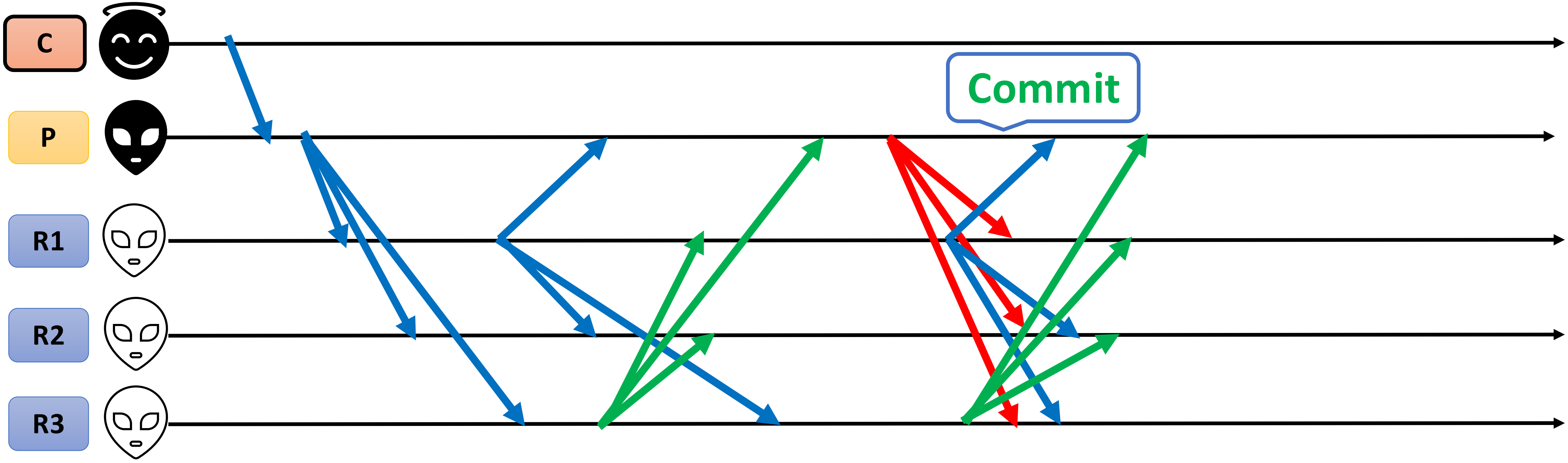


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- The protocol is committed for a replica when
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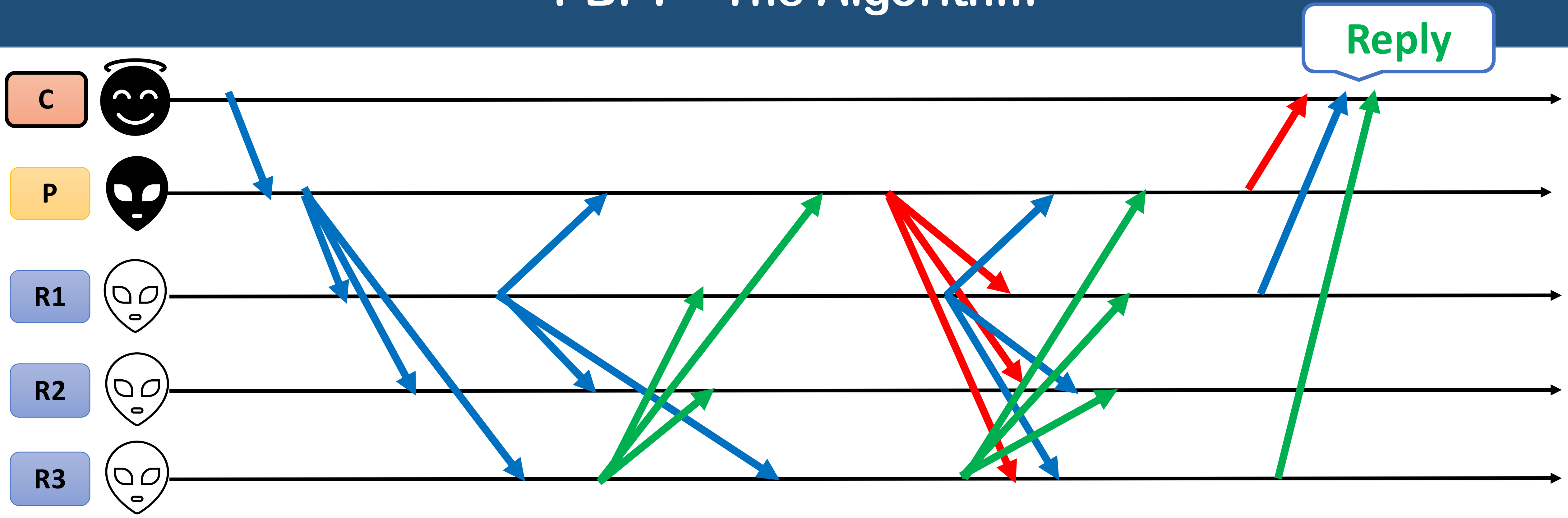


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# Liveness and Weak Synchrony

- 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
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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
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  - 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

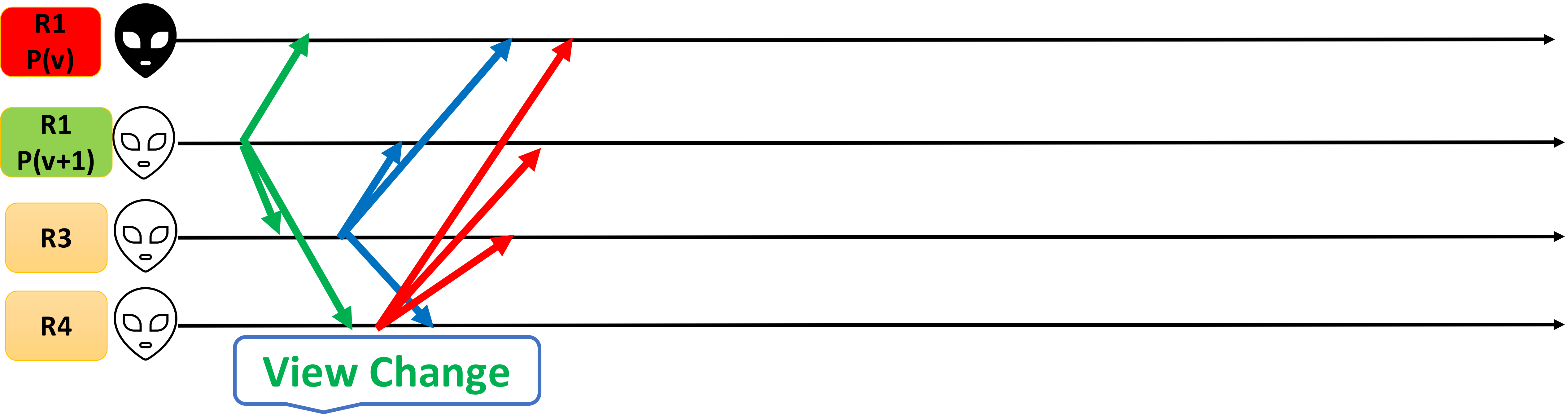
- View changes are triggered by timeouts (weak synchrony assumption)
  - Prevent backups from waiting indefinitely for requests to execute

# 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*

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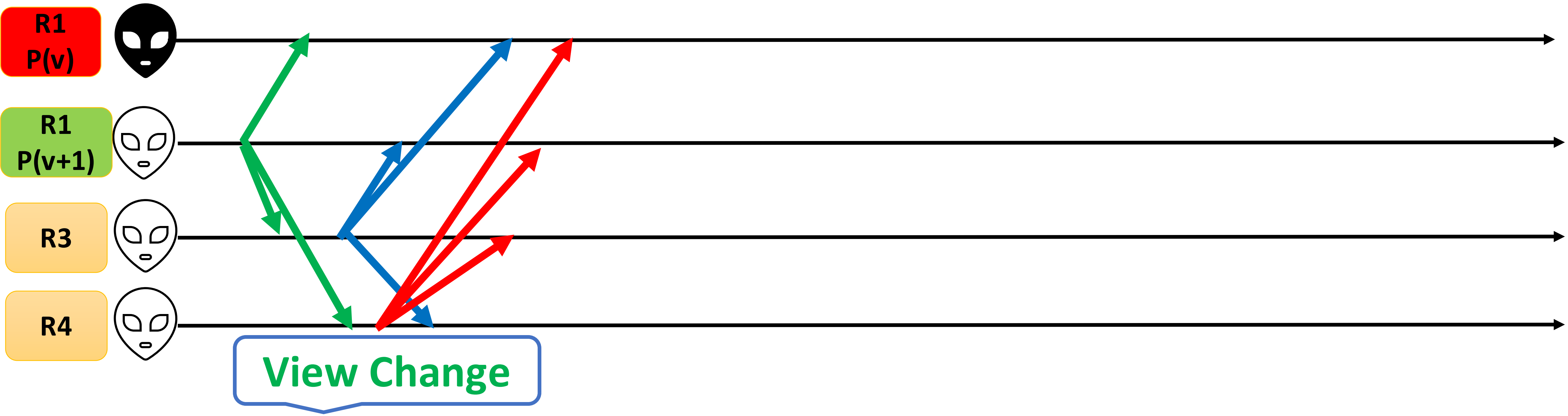


- The new view is initiated after receiving *2f + 1* View Change messages
- Next primary selection
  - Round Robin (Hyperledger Sawtooth)
  - Leader election (Hyperledger Fabric)

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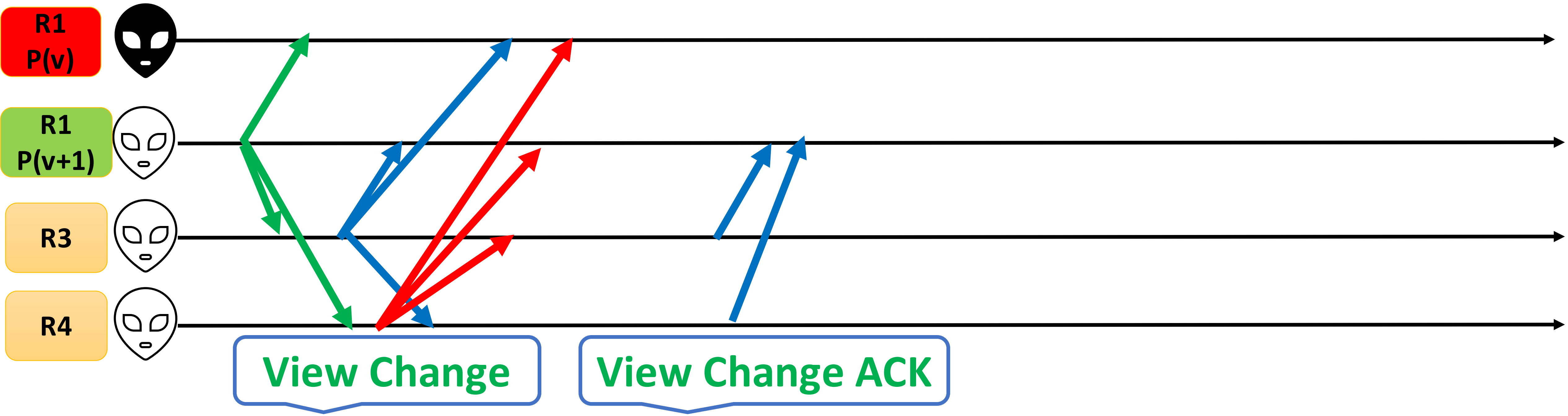
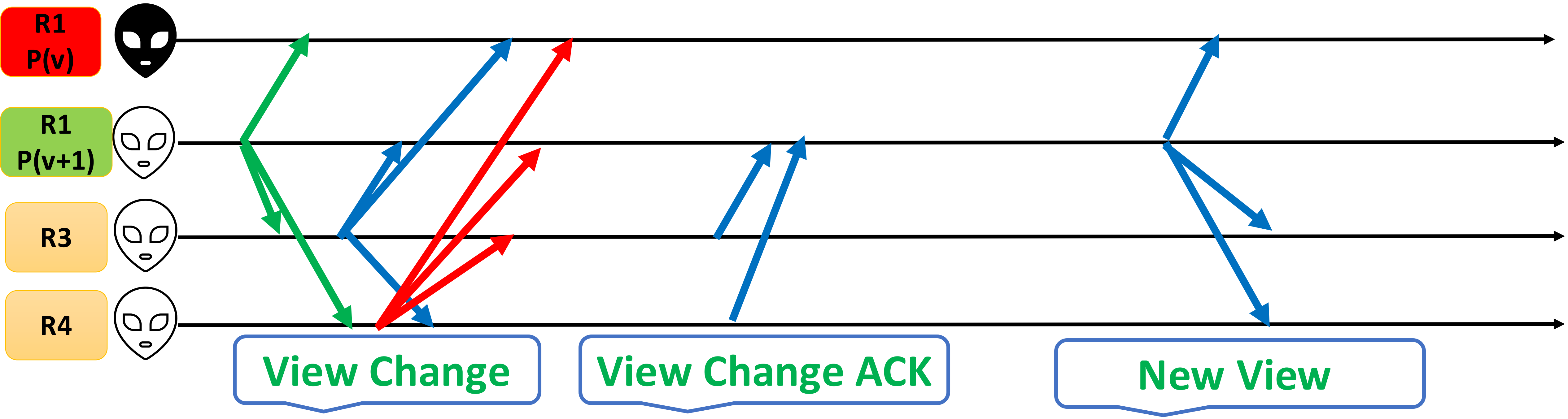



- Replicas send a View Change ACK – quorum is formed on these messages

# The View Change Protocol




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

# PBFT and Its Use in Blockchain

- PBFT ensures safety under strong synchrony and liveness under weak synchrony
  - A practical approach considering the current Internet

- Several blockchain platforms like Zilliqa, Hyperledger, Quorum, Steller, and Tendermint use PBFT (or its variants) to achieve consensus under Byzantine faults or presence of malicious nodes
  - For example, in Tendermint Core (Cosmos hub), a validator is selected as block proposer in each round, and then a three-phase commit protocol (pre-vote, pre-commit, commit) like PBFT is used to reach consensus on the block
  - Hyperledger Indy uses a variant of PBFT, called RBFT (Redundant Byzantine Fault Tolerance) -- uses redundant leaders (a set of backup leaders)
  - Quorum uses Istanbul Byzantine Fault Tolerance (IBFT) consensus algorithm, which is based on PBFT.

# Redundant Byzantine Fault Tolerance (RBFT)

- Used in Hyperledger Indy
  - Provides a blockchain-based solution for decentralized identity management; we shall discuss the details later on

- An optimized version of PBFT (Practical Byzantine Fault Tolerance)
  - Designed to improve fault tolerance, availability, and performance

- RBFT enhances PBFT by introducing redundant leaders and a more proactive monitoring mechanism
  - Allows the system to maintain performance even in the presence of Byzantine faults or slow leaders

# Redundant Byzantine Fault Tolerance (RBFT)

- In PBFT, a single primary (leader) is responsible for proposing transactions or blocks
  - If the leader fails or behaves maliciously, the system must initiate a view change to elect a new leader (**Cause delays**)

- RBFT introduces **multiple redundant leaders**
  - **One Primary Leader**: Responsible for proposing transactions and leading the consensus process
  - **Multiple Backup Leaders:** monitor the performance of the primary leader, take over if the primary leader fails or behaves maliciously

# Consensus Process in RBFT

- **Transaction Proposal**
  - The primary leader proposes a block of transactions to the other nodes (replicas) in the network (similar to PBFT’s *Pre-Prepare* phase)
  - Backup leaders receive and monitor this proposal
    - If the primary leader is behaving correctly, they will simply validate and forward the proposal.

- **Pre-vote Phase:**
  - After receiving the proposed block, all replicas (validators) in the network send a Pre-Vote message to the other replicas, indicating that they have received and validated the proposal.
  - The backup leaders continue to monitor the primary's performance

# Consensus Process in RBFT

- **Pre-commit Phase:**
  - Replicas exchange Pre-Commit messages with each other to finalize the agreement on the proposed block.
    - Similar to the Commit phase in PBFT
  - If the replicas receive enough (*$2f+1$*) Pre-Commit messages from honest nodes, they move forward to commit the block to their local ledgers

- **Commit Phase:**
  - Once enough Pre-Commit messages are gathered, the replicas finalize the block and commit it to the blockchain.
  - Backup leaders ensure that this process is executed smoothly by monitoring the timing and behavior of the primary leader.

# RBFT: Monitoring and Detection of Faulty Leaders

- **Proactive Monitoring**
  - Backup leaders continuously evaluate the primary leader’s performance and compare it with expected behavior (e.g., response times and message consistency)
- **Detection of Faults**
  - If the backup leaders detect abnormal behavior (such as a slow or Byzantine primary), they initiate view change faster than traditional PBFT's reactive approach.

# RBFT: Redundant Leader Takeover

- The view change is initiated when $f + 1$ nodes (including the backup leaders) detect that the primary leader has failed or is malicious
  - Broadcast a view change message (along with the latest stable checkpoint), similar to PBFT
- Do not require a full view-change like PBFT
  - Can switch leadership to one of the backup leaders (backup leaders already have the information about the previous view)
  - Reduces downtime and ensures that the system can continue processing transactions with minimal interruption
  - The leader selection is usually based on a predetermined rotation or round-robin mechanism
  - The new leader determines the most up-to-date stable checkpoint (the most recent valid state agreed upon by the majority of the network)

# Benefits of RBFT over PBFT

- **Improved Fault Tolerance**
  - Redundant leaders ensure that the system can quickly recover from faults without major interruptions.
- **Fast Leader Transition**
  - Backup leaders are always ready to step in, so the system does not have to wait for a new leader to be elected from scratch.
- **Minimized Downtime**
  - By having a set of backup leaders, the view change process is faster and less disruptive than in PBFT, where a faulty leader can cause significant delays.

thank you!