Reasoning about Byzantine Protocols

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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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Byzantine Generals Problem

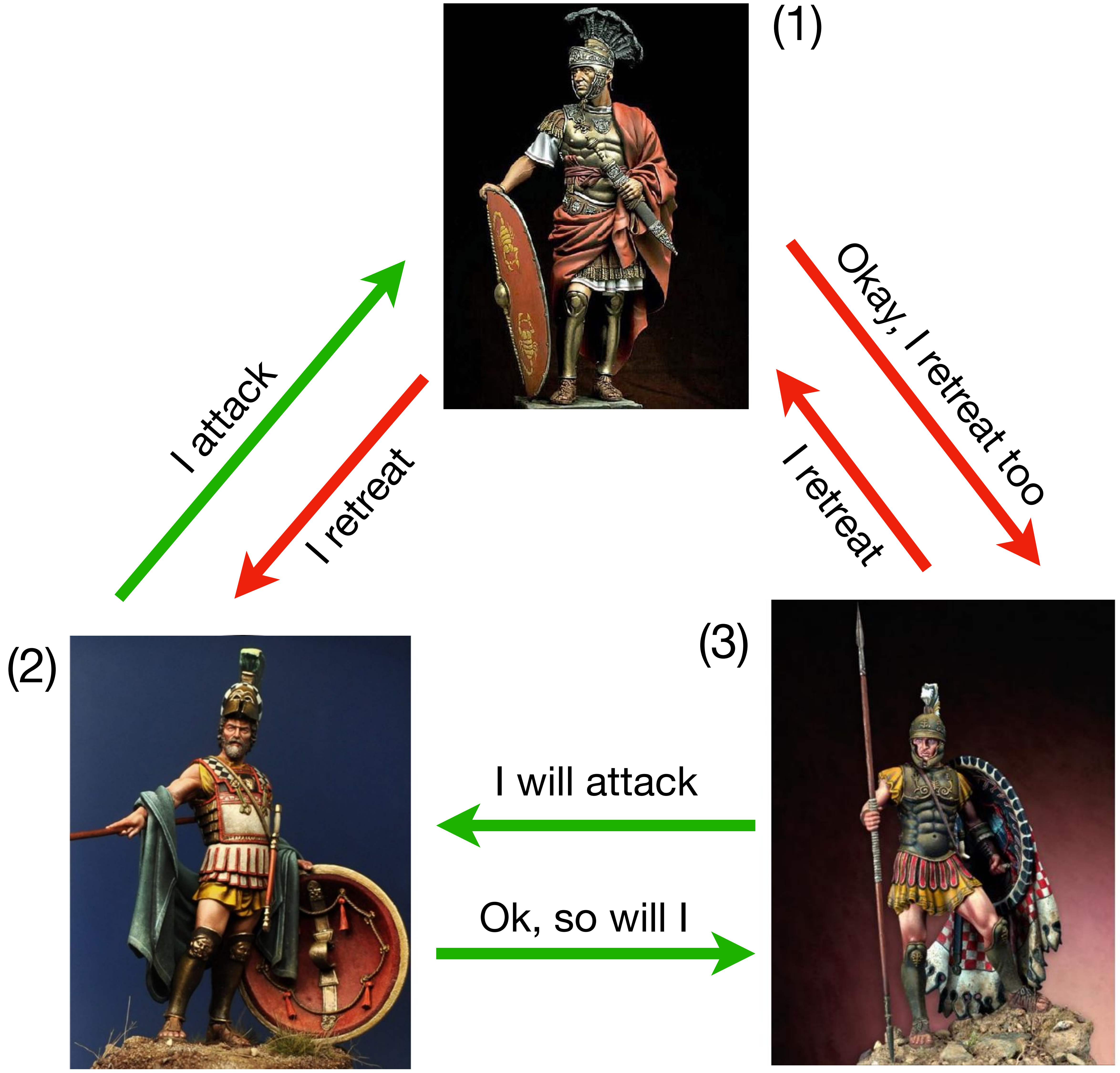
- A Byzantine army decides to attack/retreat
- N generals, f of them are *traitors* (can *collude*)
- Generals camp outside the battle field:
  decide individually based on their field information
- Exchange their plans by unreliable *messengers*
  - Messengers can be *killed*, can be *late*, *etc*.
  - Messengers *cannot **forge*** a general's seal on a message

Byzantine Consensus

- All loyal generals decide upon the *same* plan of action.
- A *small* number of traitors (f << N) *cannot* cause the loyal generals to adopt a bad plan or *disagree* on the course of actions.
- All the usual consensus properties:
  uniformity (amongst the loyal generals), *non-triviality*, and *irrevocability*.

Why is Byzantine Agreement Hard?

- Simple scenario
  - 3 generals, general (3) is a traitor
  - Traitor (3) sends different plans to (1) and (2)
  - If decision is based on majority
    - (1) and (2) decide differently
    - (2) attacks and gets defeated
- More complicated scenarios
  - Messengers get killed, spoofed
  - Traitors confuse others:
    (3) tells (1) that (2) retreats, etc



Byzantine Consensus in Computer Science

- A *general* is a **program component/processor/replica**
  - *Replicas* communicate via ***messages**/**remote procedure calls***
  - *Traitors* are *malfunctioning replicas or adversaries*

- *Byzantine army* is a *deterministic replicate service*
  - All (good) replicas should act similarly and execute the *same logic*
  - The service should cope with failures, keeping its state *consistent* across the replicas

- Seen in *many applications*:
  - replicated file systems, backups, distributed servers
  - shared ledgers between banks, decentralised *blockchain protocols*.

Byzantine Fault Tolerance Problem

- Consider a system of similar distributed replicas (nodes)
  - N replicas in total
  - f of them might be faulty (crashed or compromised)
  - All replicas initially start from the *same state*

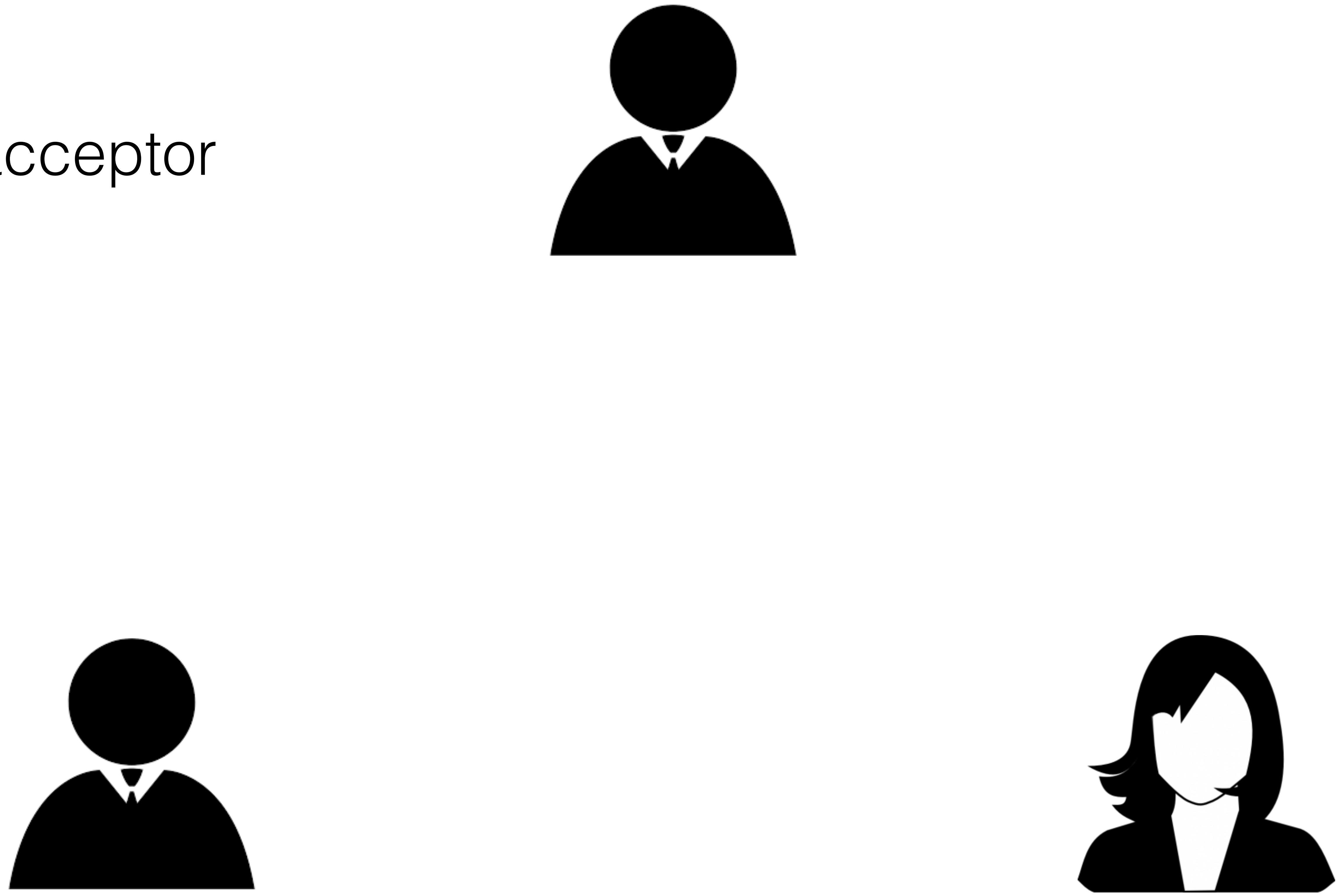
- Given a *request/operation* (e.g., a transaction), the goal is
  - Guarantee that all non-faulty replicas *agree* on the next state
  - Provide system *consistency* even when some replicas may be inconsistent

Previous lecture: Paxos

- Communication model
  - Network is *asynchronous*: messages are *delayed arbitrarily*, but eventually delivered; they *are not deceiving*.
  - Protocol tolerates (benign) crash-failure
- Key design points
  - Works in *two phases* — secure quorum, then commit
  - Require at least $2f + 1$ replicas to tolerate f faulty replicas

Paxos and Byzantine Faults

- N = 3, f = 1
- N/2 + 1 = 2 are good
- everyone is proposers/acceptor



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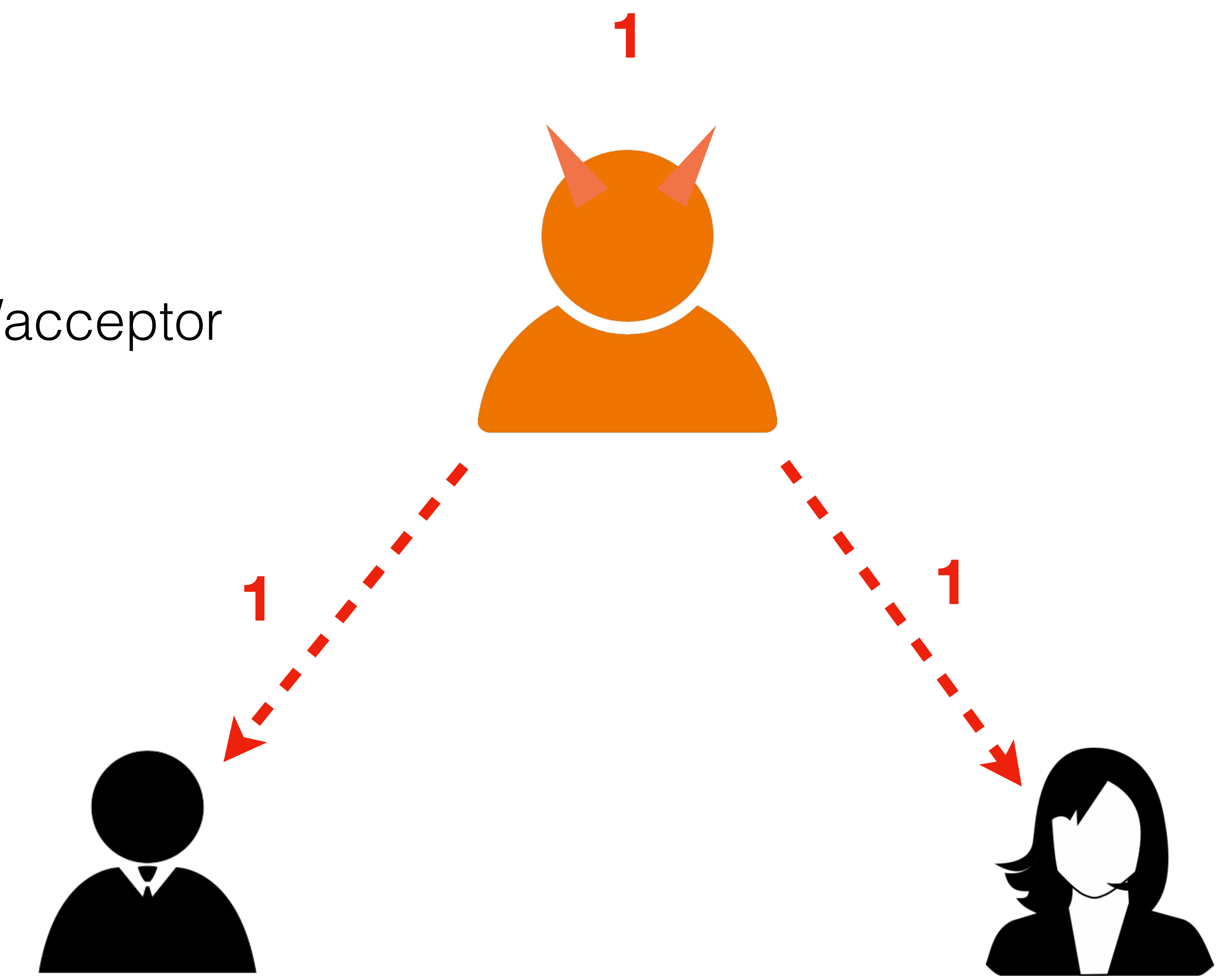

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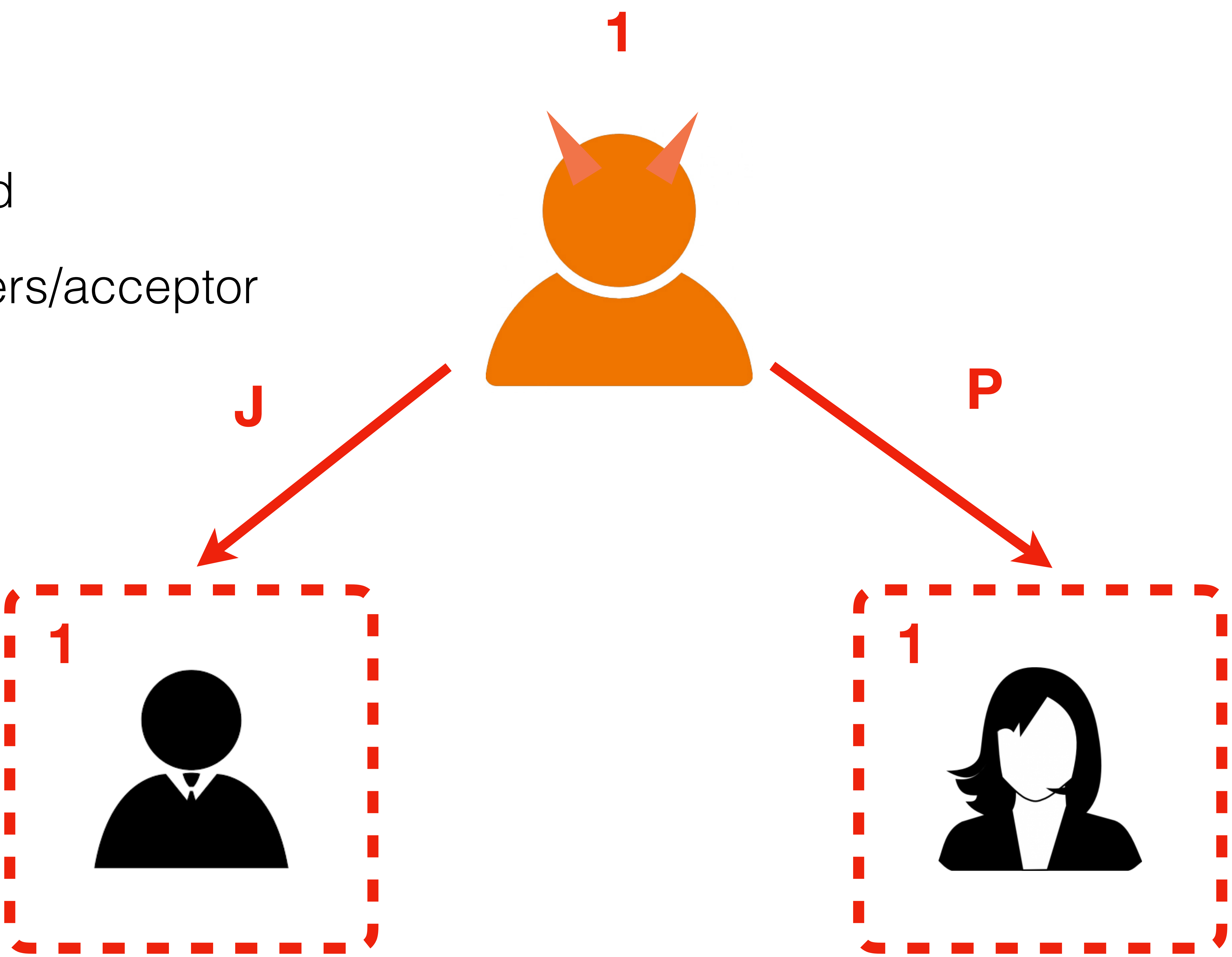

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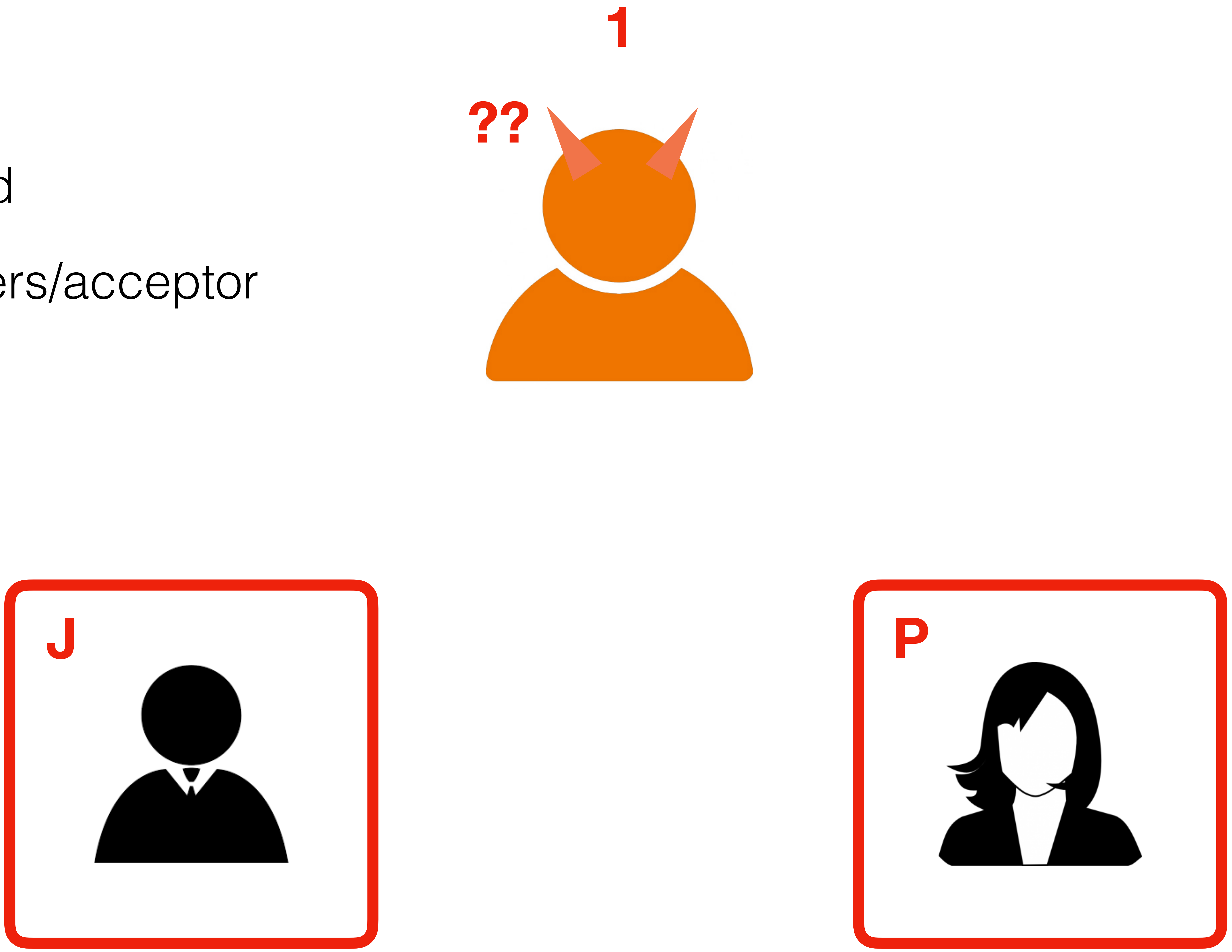
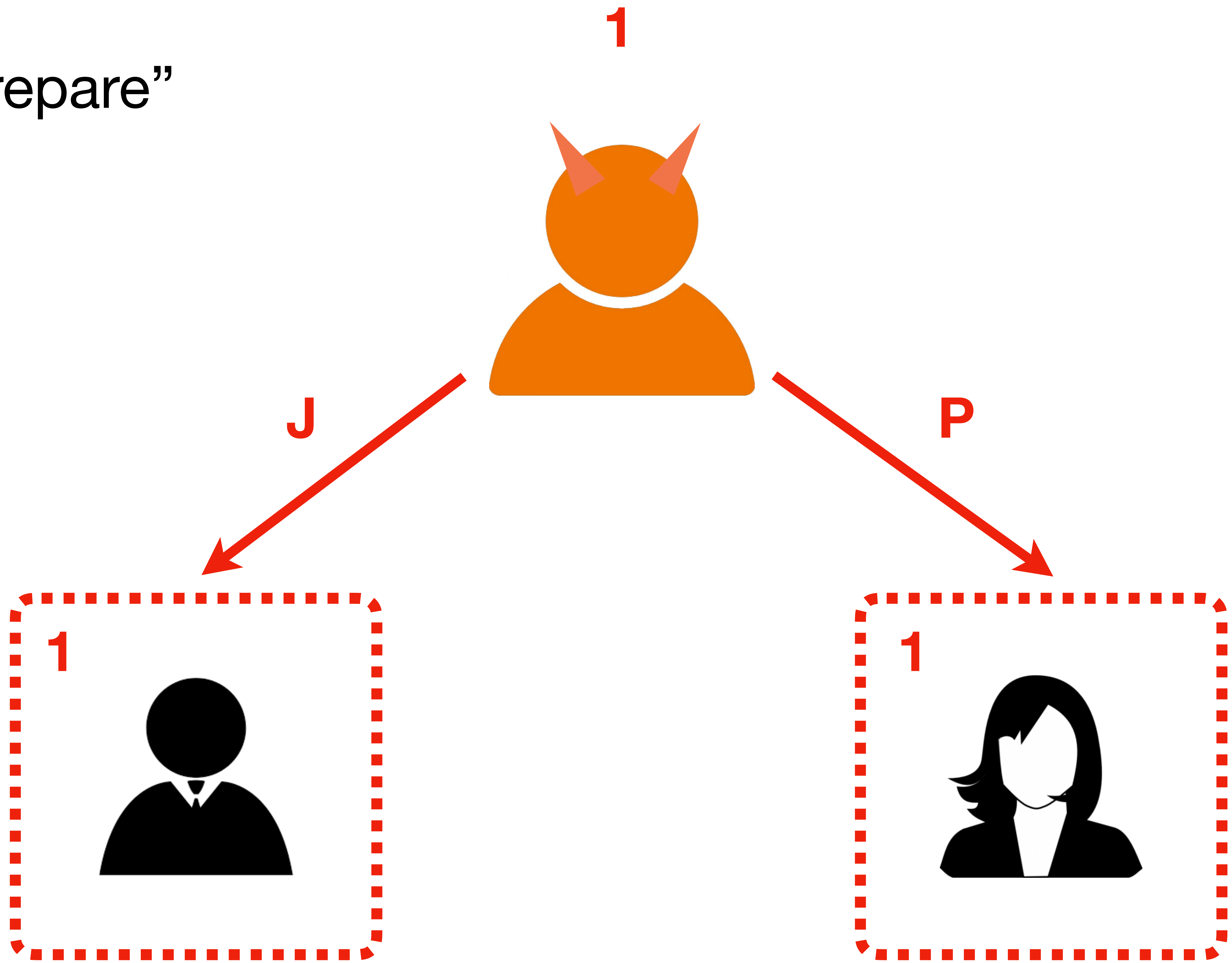


What went wrong?

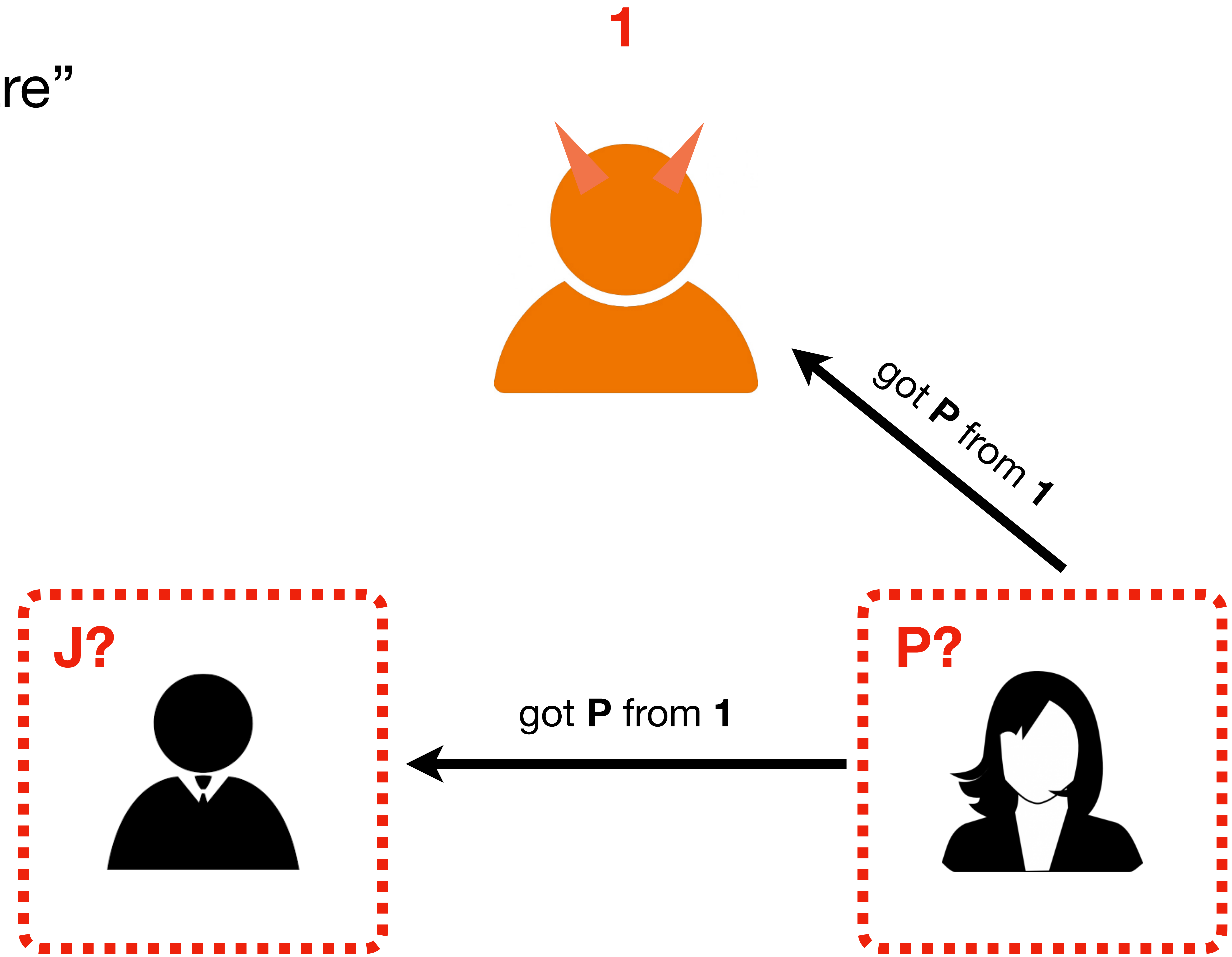
- Problem 1:
  Acceptors did not communicate with each other to check the consistency of the values proposed to everyone.

- Let us try to fix it with an additional Phase 2 (Prepare), executed *before* everyone commits in Phase 3 (Commit).

Phase 1: "Pre-prepare"



Phase 2: “Prepare”



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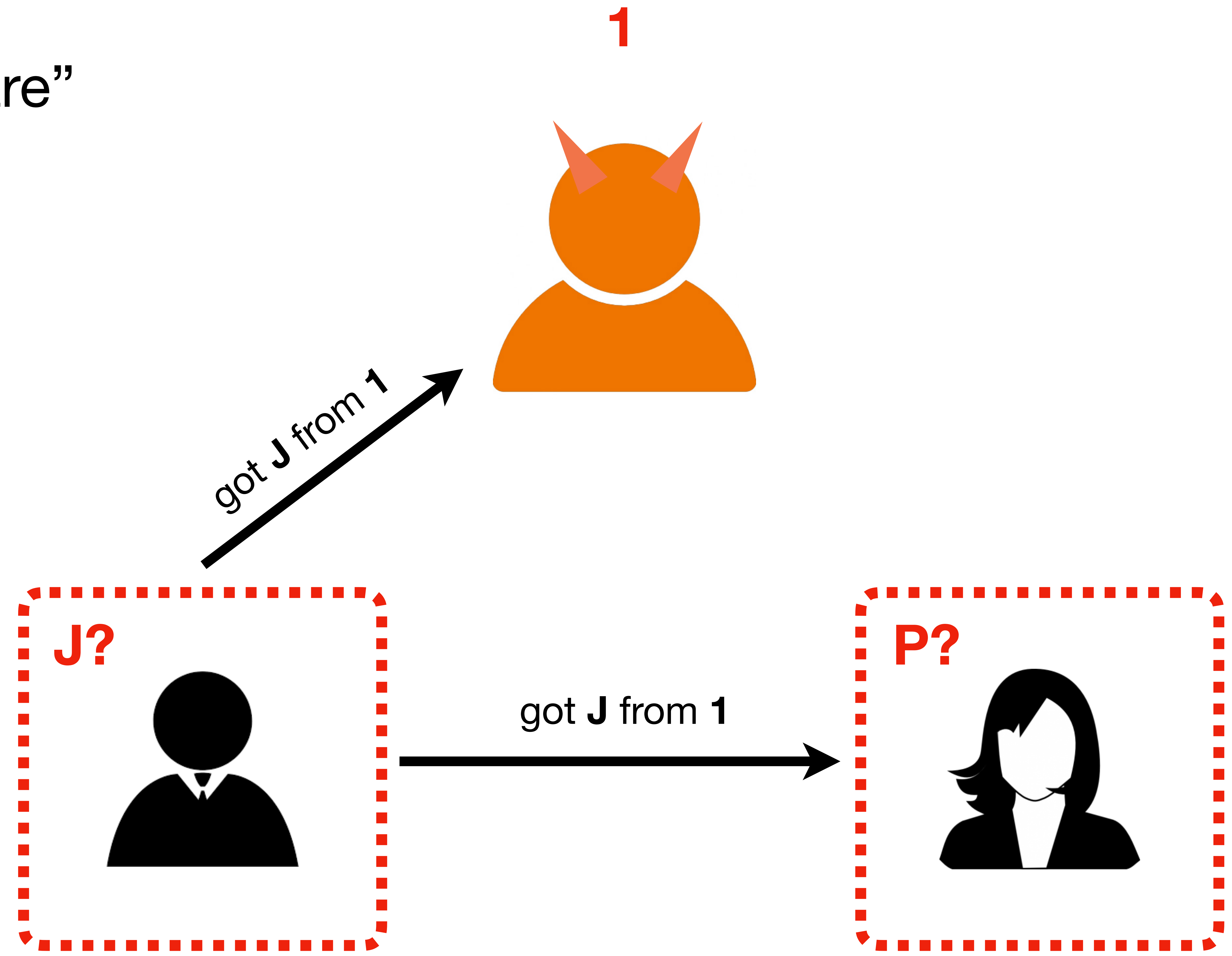

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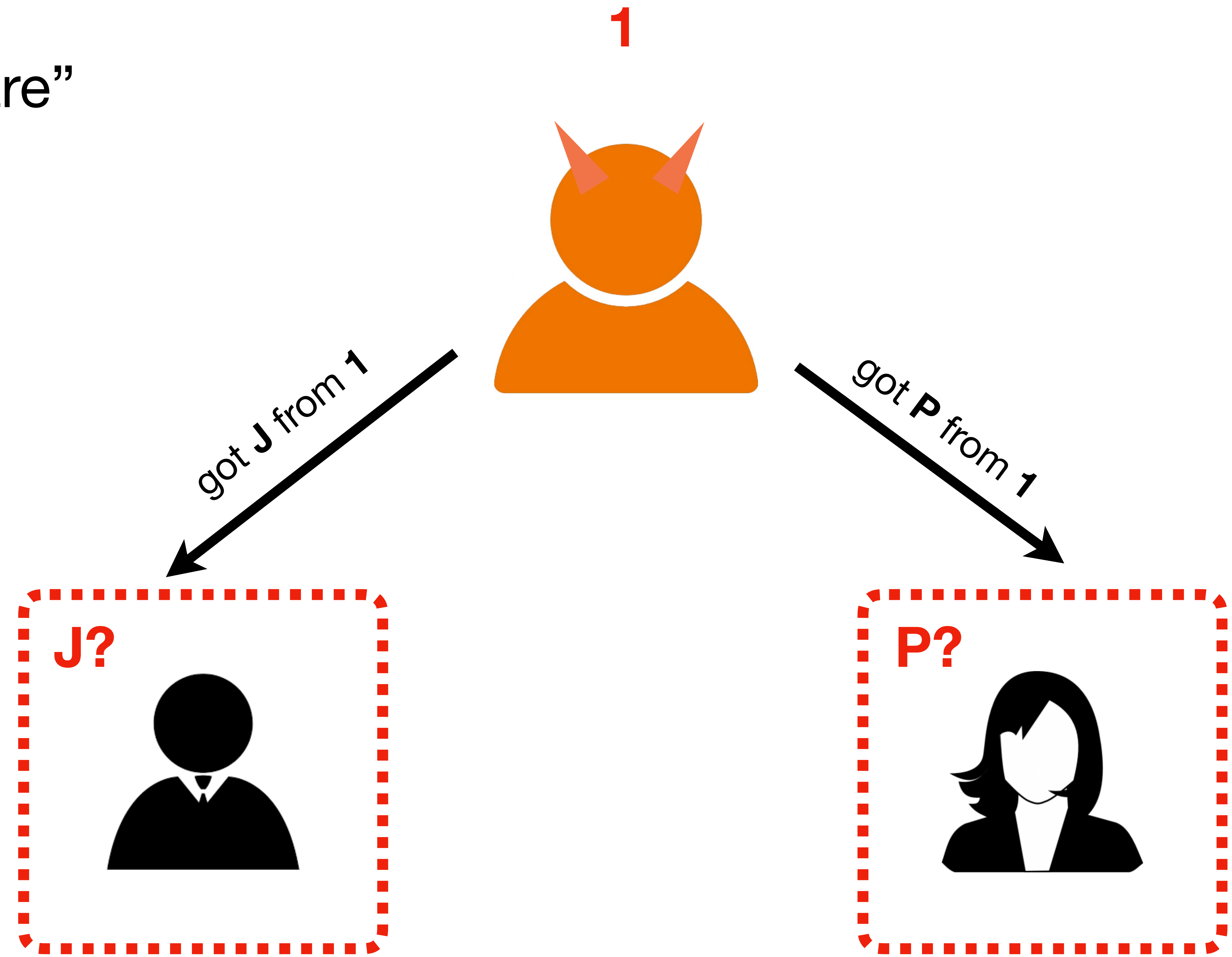

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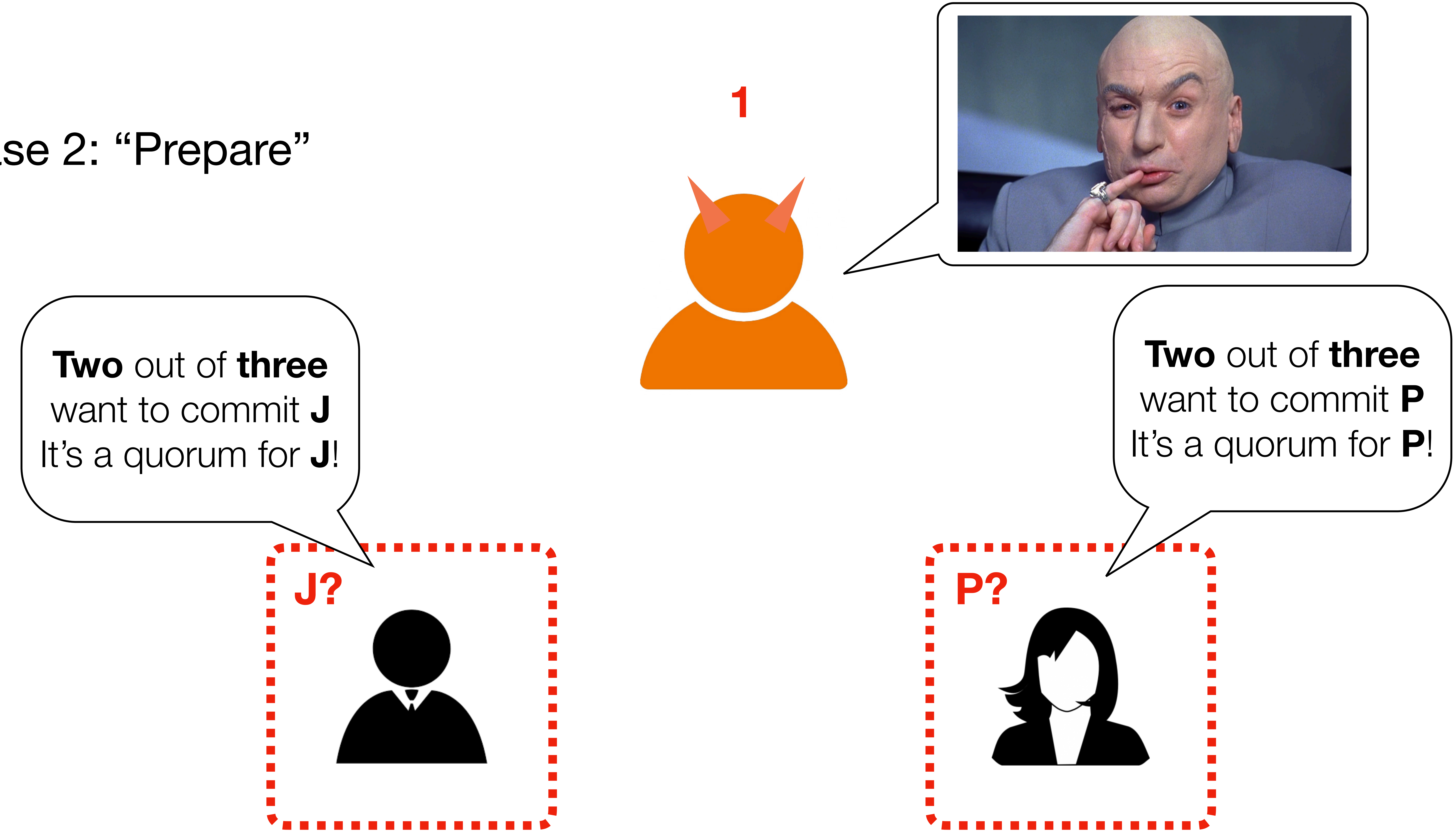
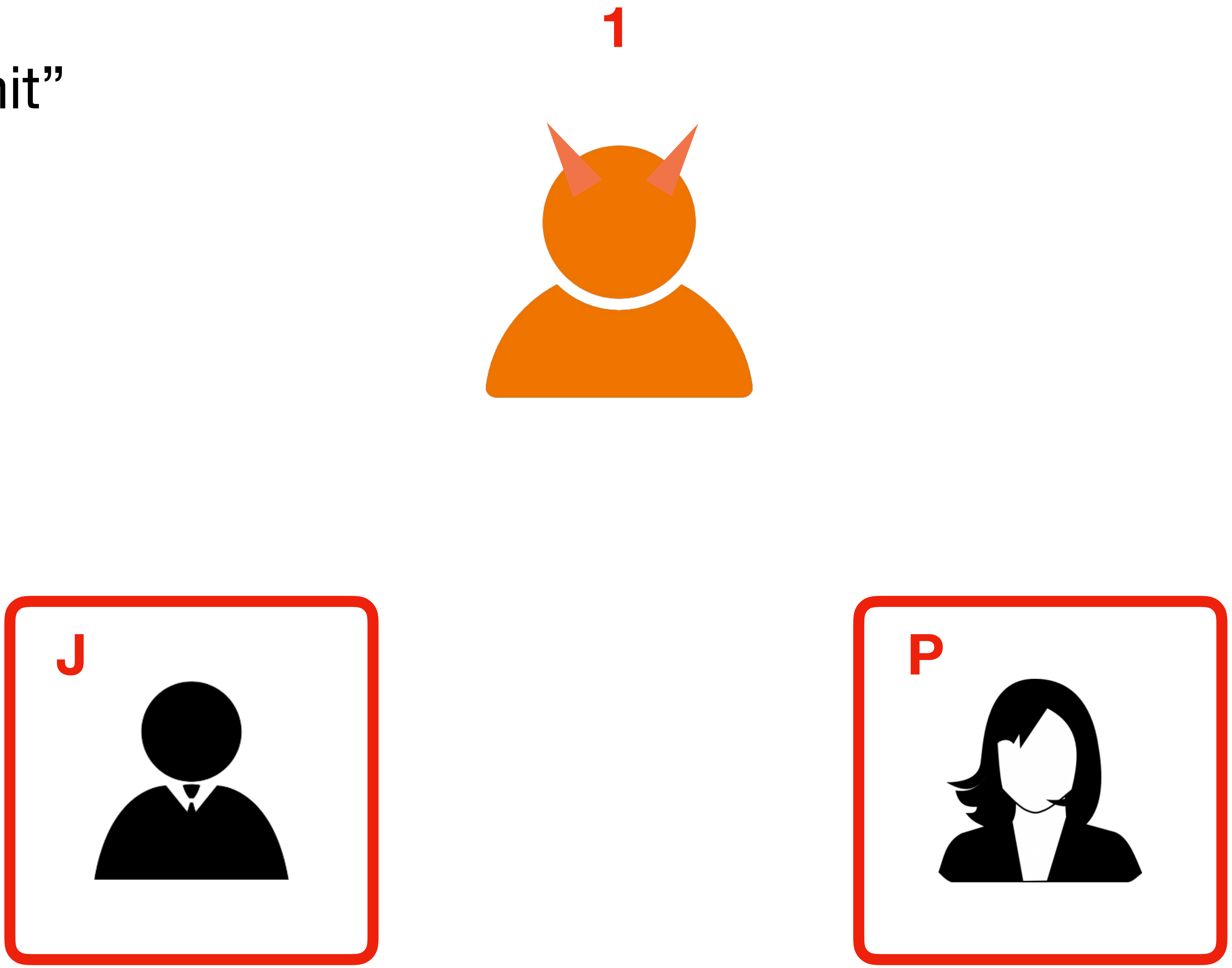


Phase 3: “Commit”



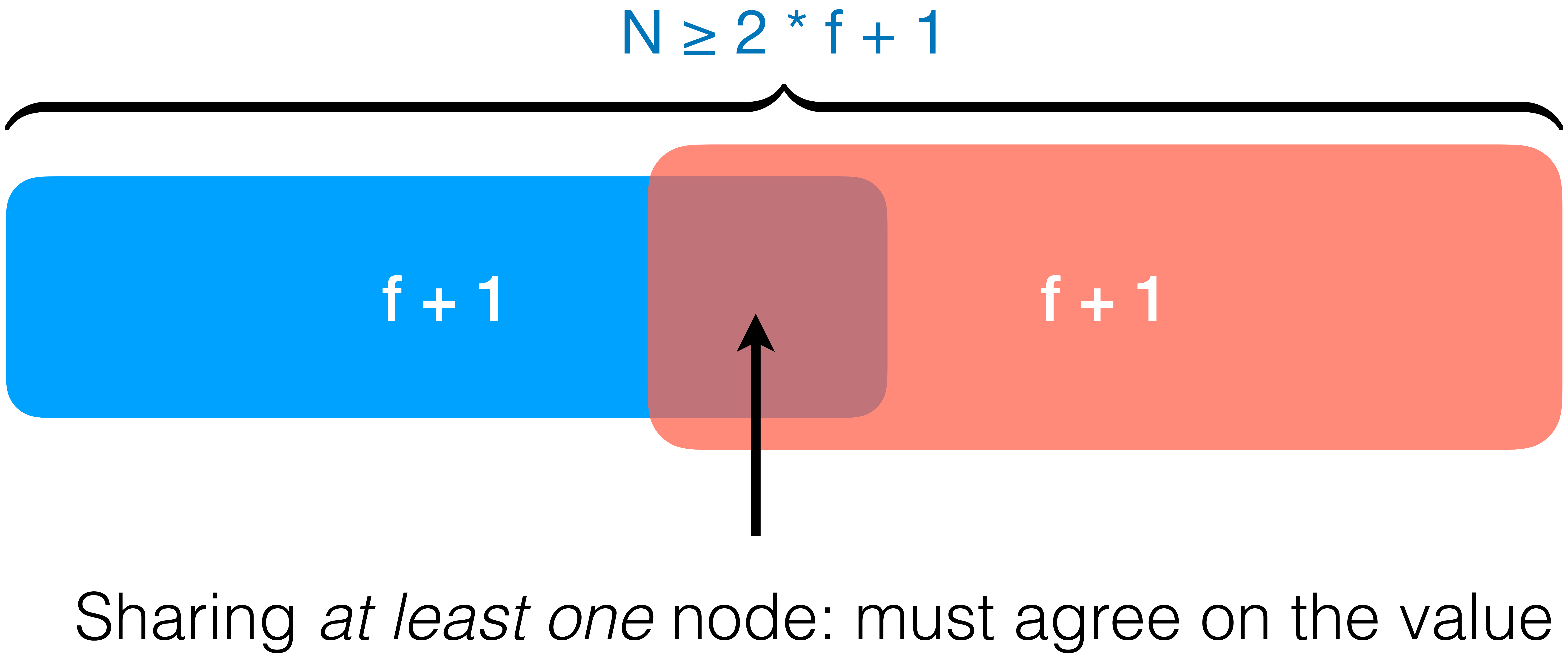
What went wrong now?

- Problem 2:
  Even though the acceptors communicated, the *quorum size* was *too small* to avoid “contamination” by an adversary.

- We can fix it by *increasing* the quorum size relative to the *total number of nodes*.

Choosing the Quorum Size

- *Paxos:* any two quorums must have non-empty intersection



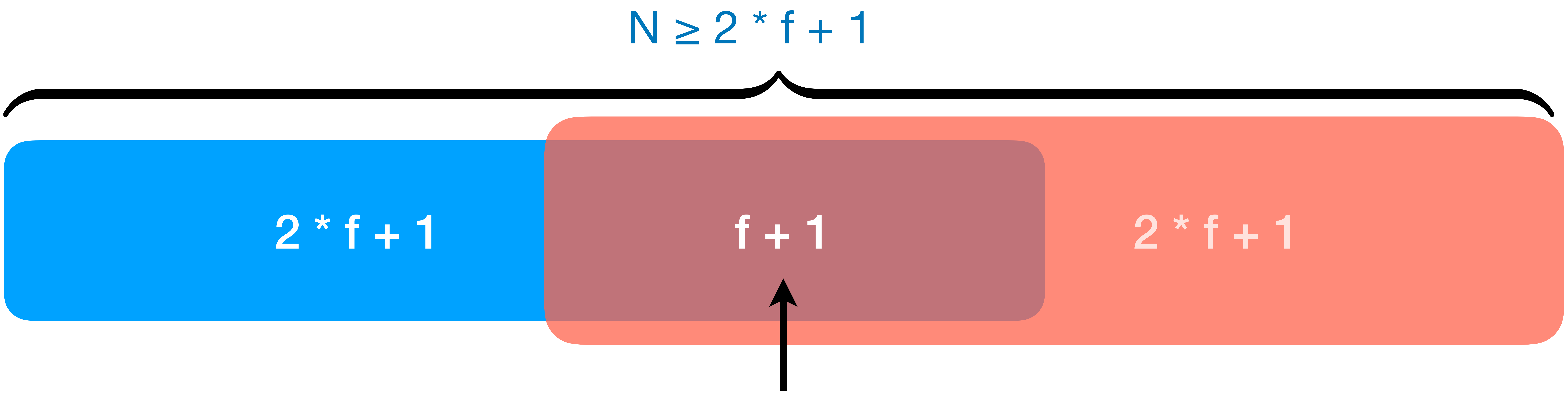
Choosing the Quorum Size

An adversarial node *in the intersection* can “lie” about the value:

to honest parties it might look like *there is not split, but in fact, there is*!

Choosing the Quorum Size

- *Byzantine consensus:* let's make a quorum to be ≥ $2/3 * N + 1$
any two quorums must have **at least one non-faulty node** in their intersection.



Up to f adversarial nodes *will not manage* to deceive the others.

Two Key Ideas of Byzantine Fault Tolerance

- **3-Phase protocol**: *Pre-prepare, Prepare, Commit*
  - Cross-validating each other's intentions amongst replicas
- **Larger quorum size**: 2/3*N + 1 (instead of N/2 + 1)
  - Allows for up to 1/3 * N adversarial nodes
  - Honest nodes still reach an agreement

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:
  - *Asynchronous* 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 proposer/leader
  - A primary can be re-elected if suspected to be compromised
  - **Backups** — other, non-primary replicas

- *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*

Overview of the Core PBFT Algorithm

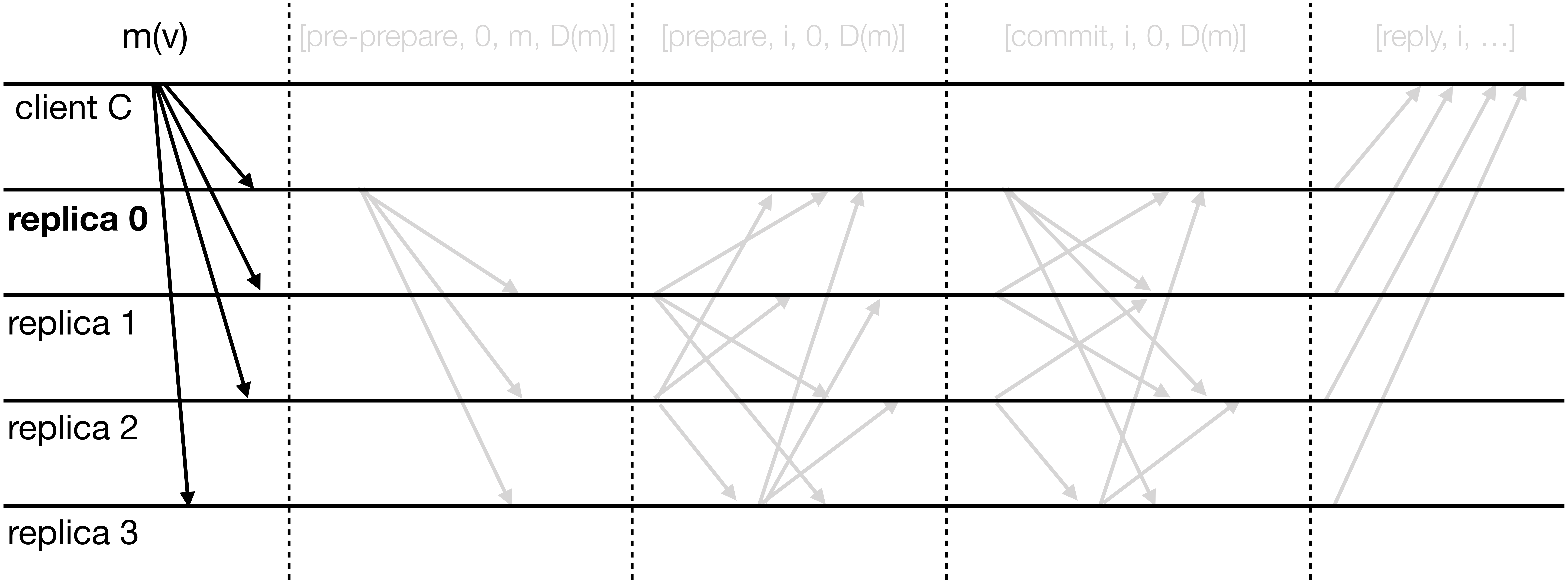
Request → **Pre-Prepare → Prepare → Commit** → Reply

Executed by Client

Executed by Replicas

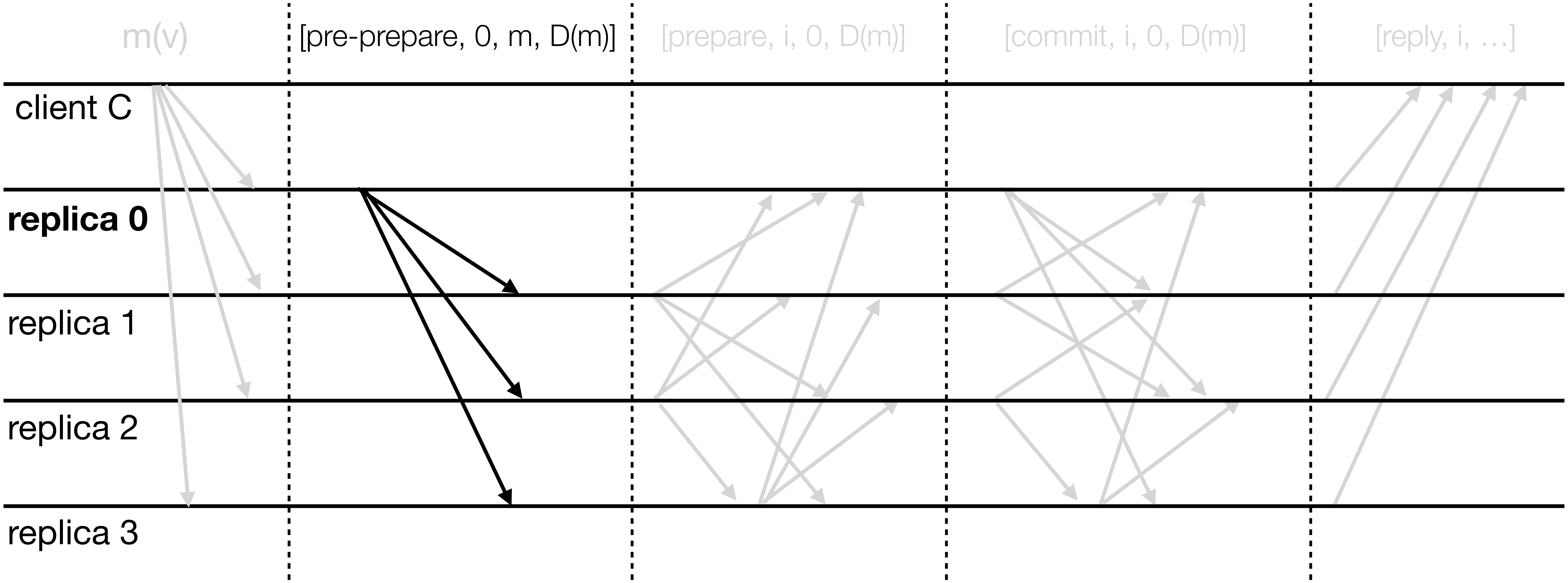
Request

Client C sends a message to *all* replicas



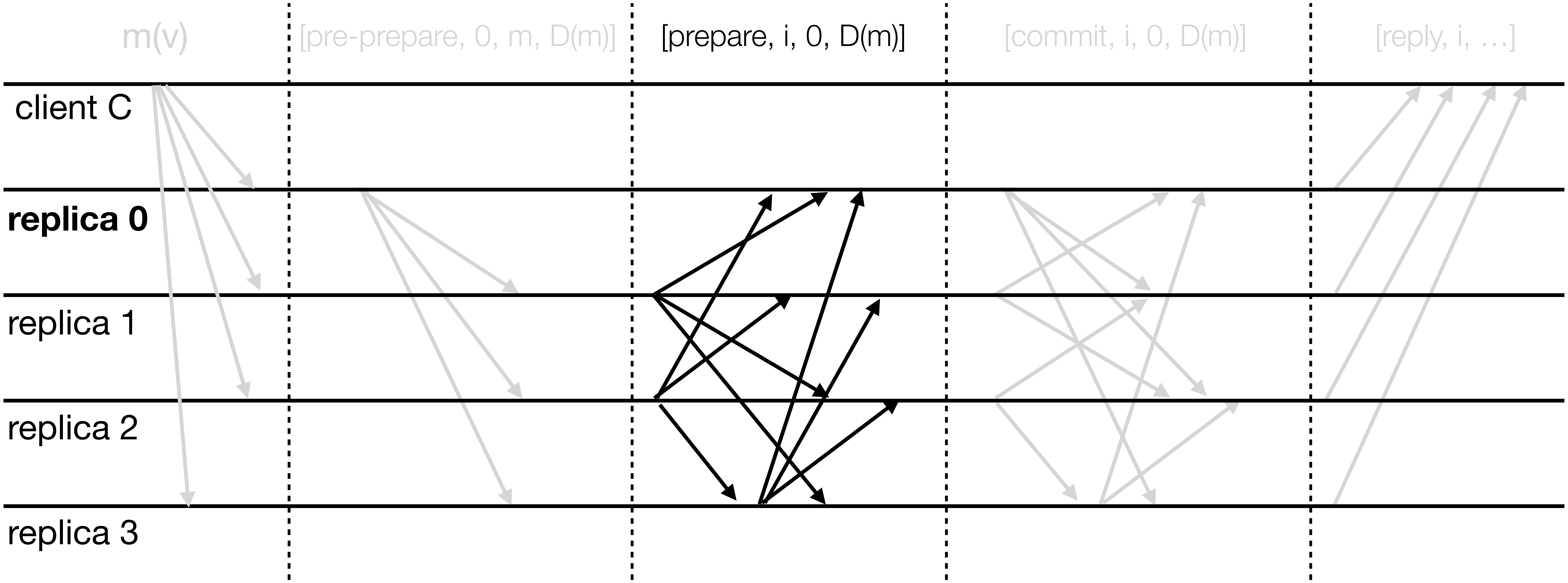
Pre-prepare

- 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



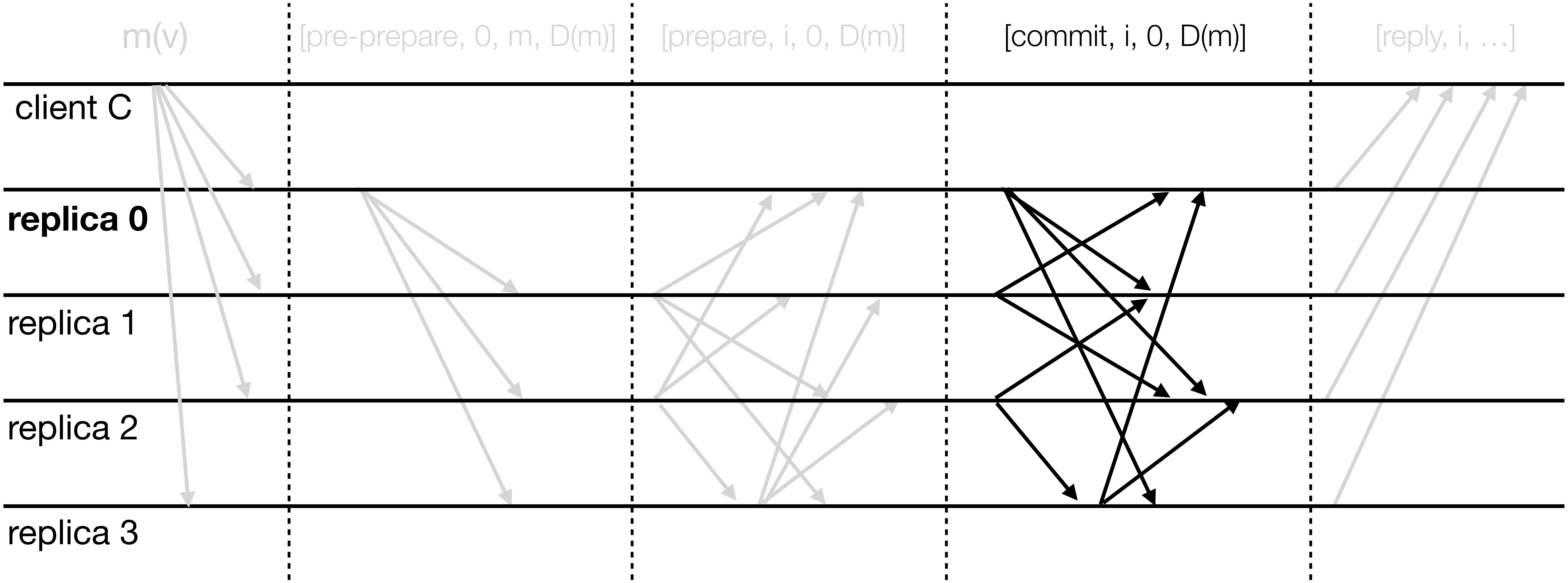
Prepare

- 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



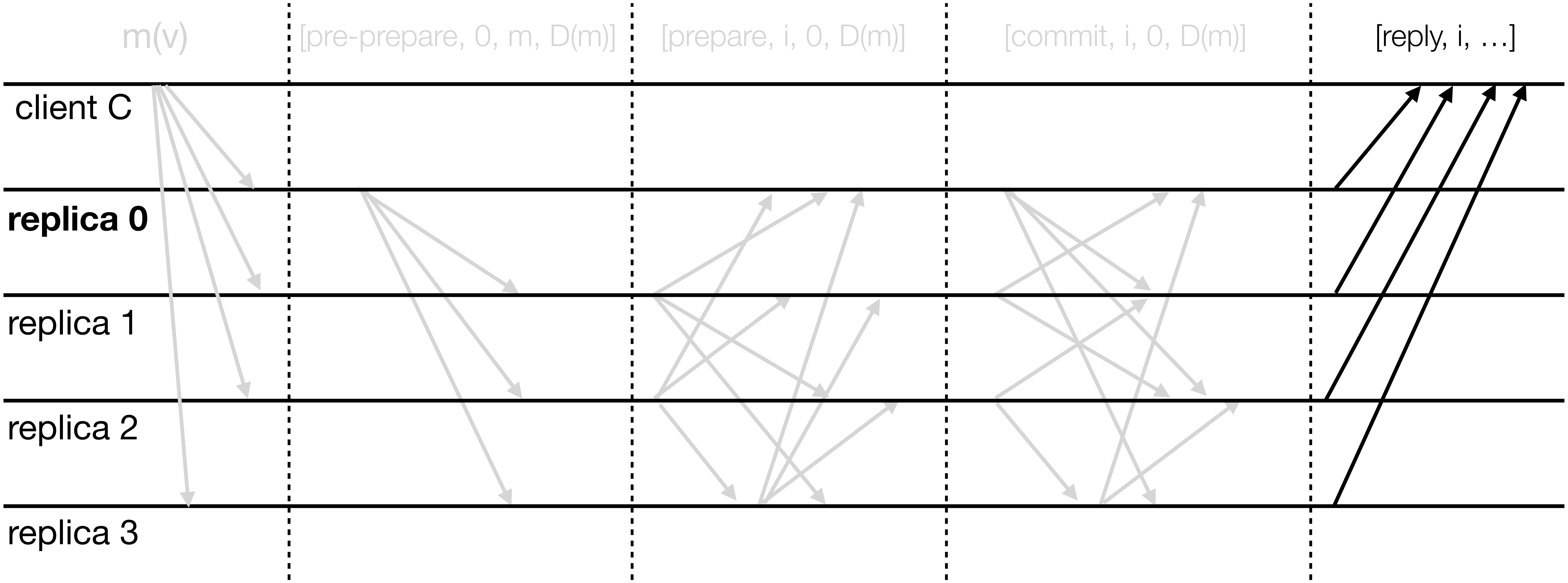
Commit

- 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 *sharding to speed-up* blockchain-based consensus
- Many blockchain solutions build on similar ideas
  - Stellar Consensus Protocol

PBFT and Formal Verification

- M. Castro's PhD Thesis
  Proof of the safety and liveness using I/O Automata (2001)
- L. Lamport:
  Mechanically Checked Safety Proof of a Byzantine Paxos Algorithm
  in TLA+ (2013)
- Velisarios by V. Rahli et al, ESOP 2018
  A version of *executable* PBFT verified in Coq

PBFT Shortcomings

- 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)

Reasoning about Blockchain Protocols

based on joint work with George Pîrlea

Motivation

1. Understand blockchain consensus
    - **what** it is
    - **how** it works: example
    - **why** it works: our formalisation

2. Lay foundation for *verified* practical implementation
    - verified Byzantine-tolerant consensus layer
    - platform for verified smart contracts

} **Future work**

What it does

$$\{tx_1, tx_3, tx_5, tx_4, tx_2\}$$

- transforms a **set** of transactions into a *globally-agreed* **sequence**
- "distributed timestamp server" (Nakamoto2008)

blockchain consensus protocol

transactions can be *anything*

$$tx_5 \rightarrow tx_3 \rightarrow tx_4 \rightarrow tx_1 \rightarrow tx_2$$

$$\{tx_1, tx_3, tx_5, tx_4, tx_2\}$$

$$[tx_5, tx_3] \rightarrow [tx_4] \rightarrow [tx_1, tx_2]$$

$$tx_5 \rightarrow tx_3 \rightarrow tx_4 \rightarrow tx_1 \rightarrow tx_2$$

$$\{tx_1, tx_3, tx_5, tx_4, tx_2\}$$

$$[tx_5, tx_3] \leftarrow [tx_4] \leftarrow [tx_1, tx_2]$$

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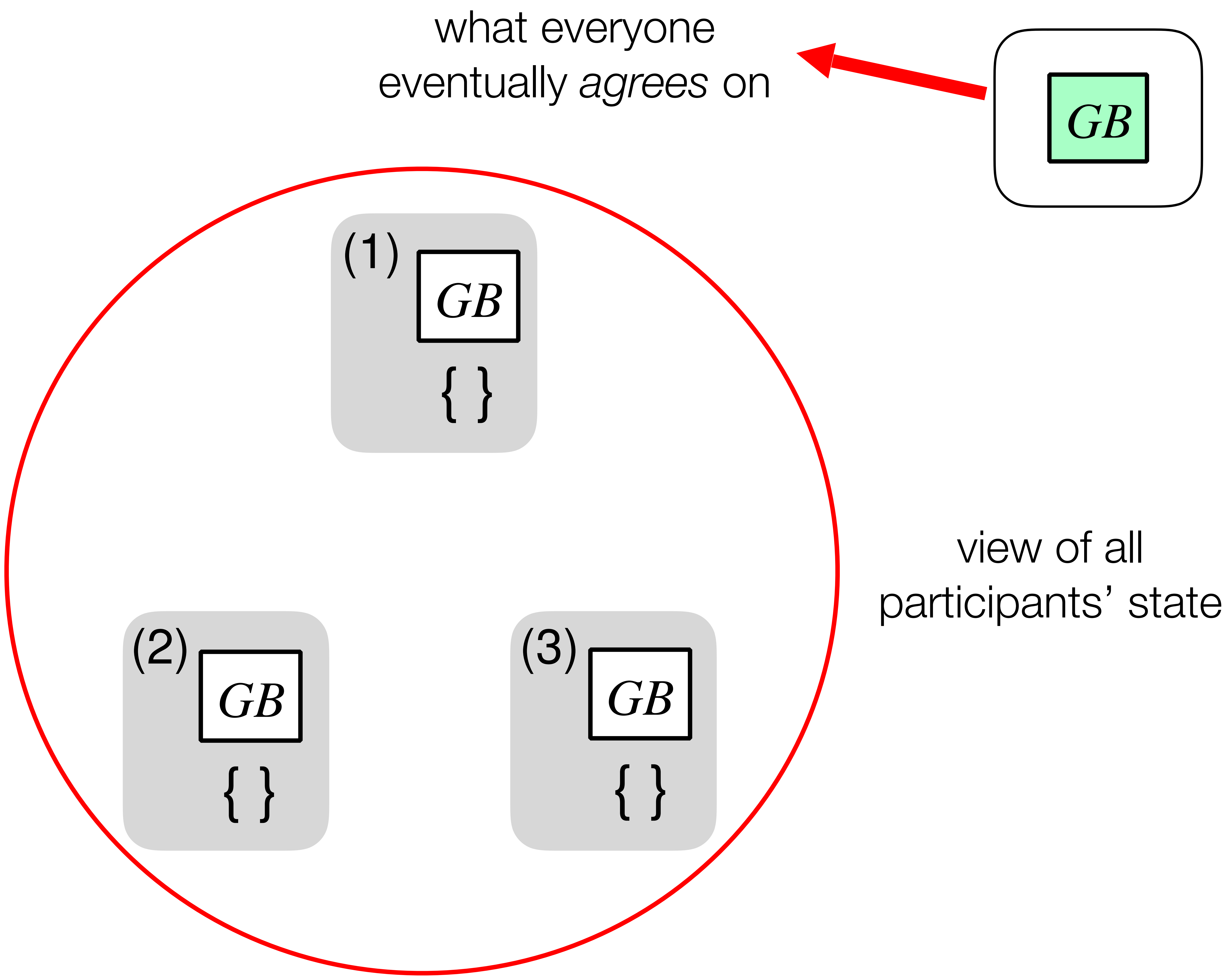
$$[] \leftarrow [tx_5, tx_3] \leftarrow [tx_4] \leftarrow [tx_1, tx_2]$$

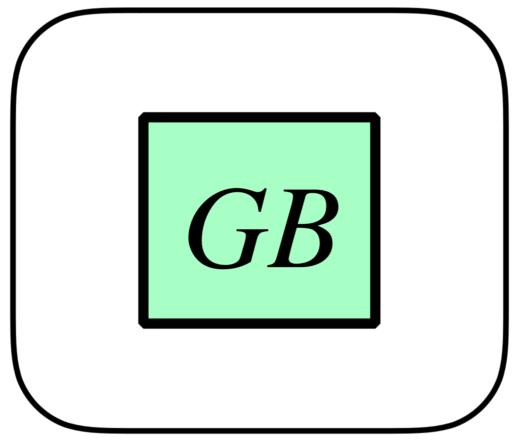
GB = genesis block

$$tx_5 \rightarrow tx_3 \rightarrow tx_4 \rightarrow tx_1 \rightarrow tx_2$$

How it works

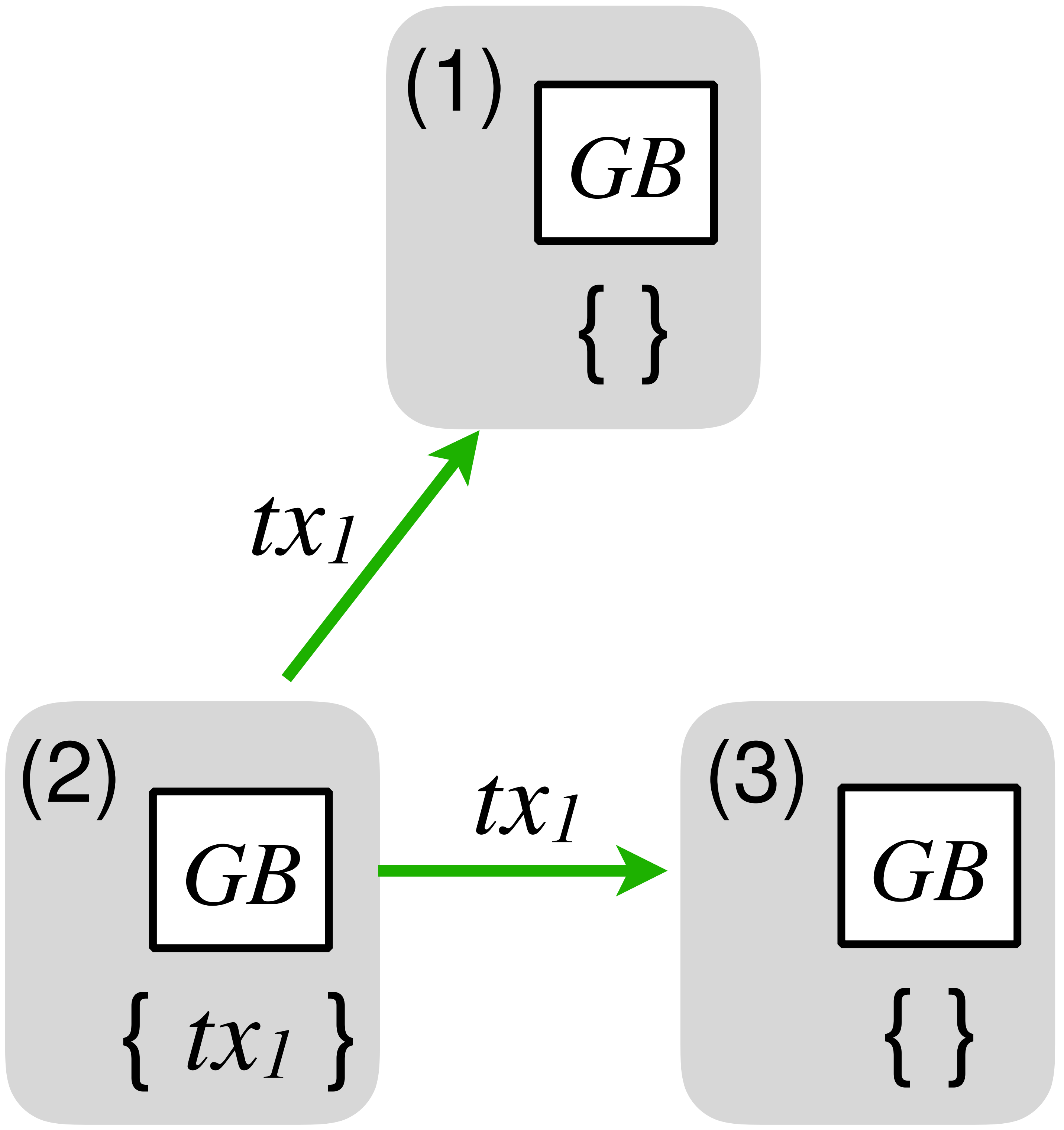
- **distributed**
  - multiple nodes
- all start with same GB





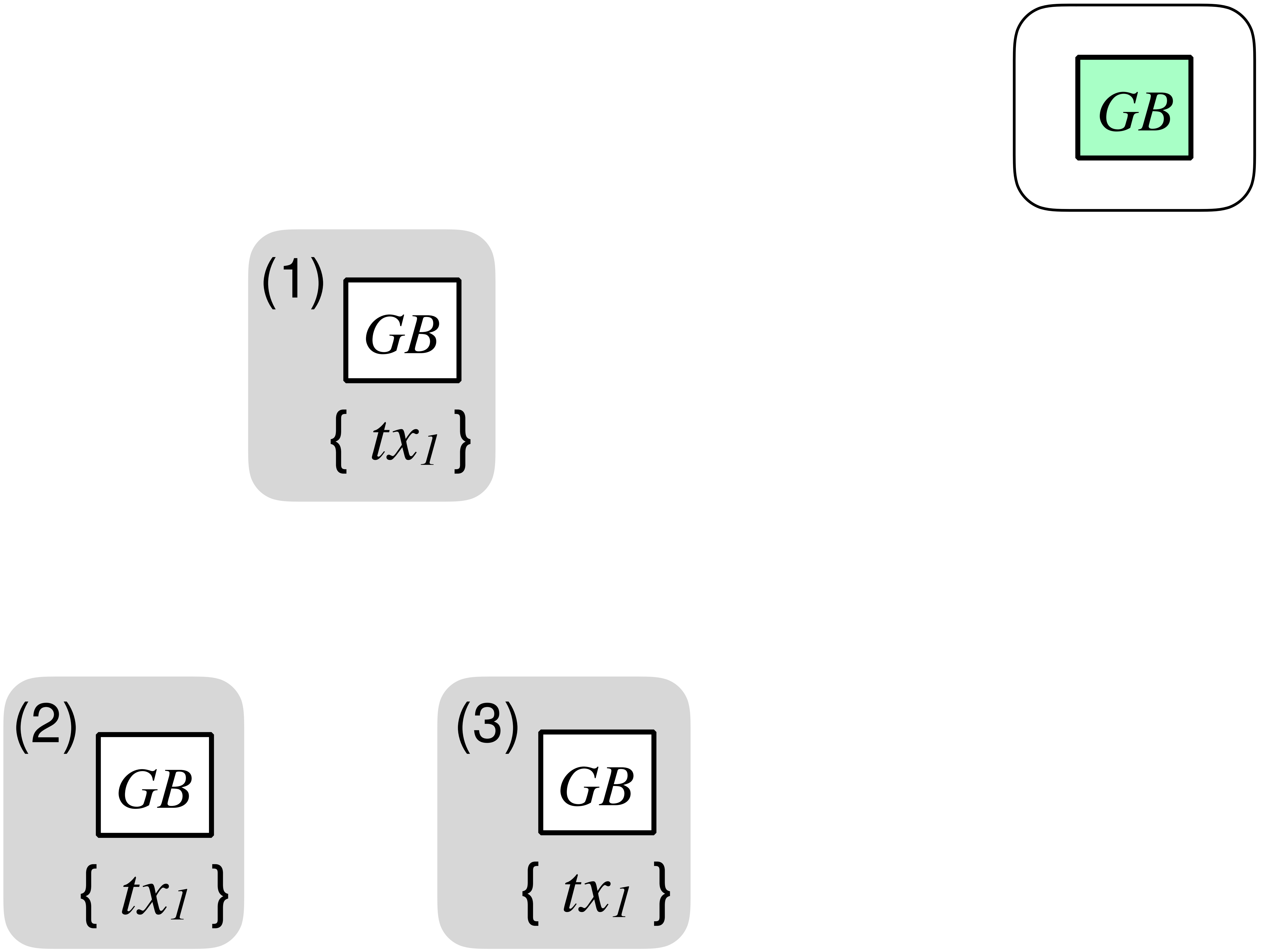
- **distributed**
  - multiple nodes
  - message-passing over a network

- all start with same GB



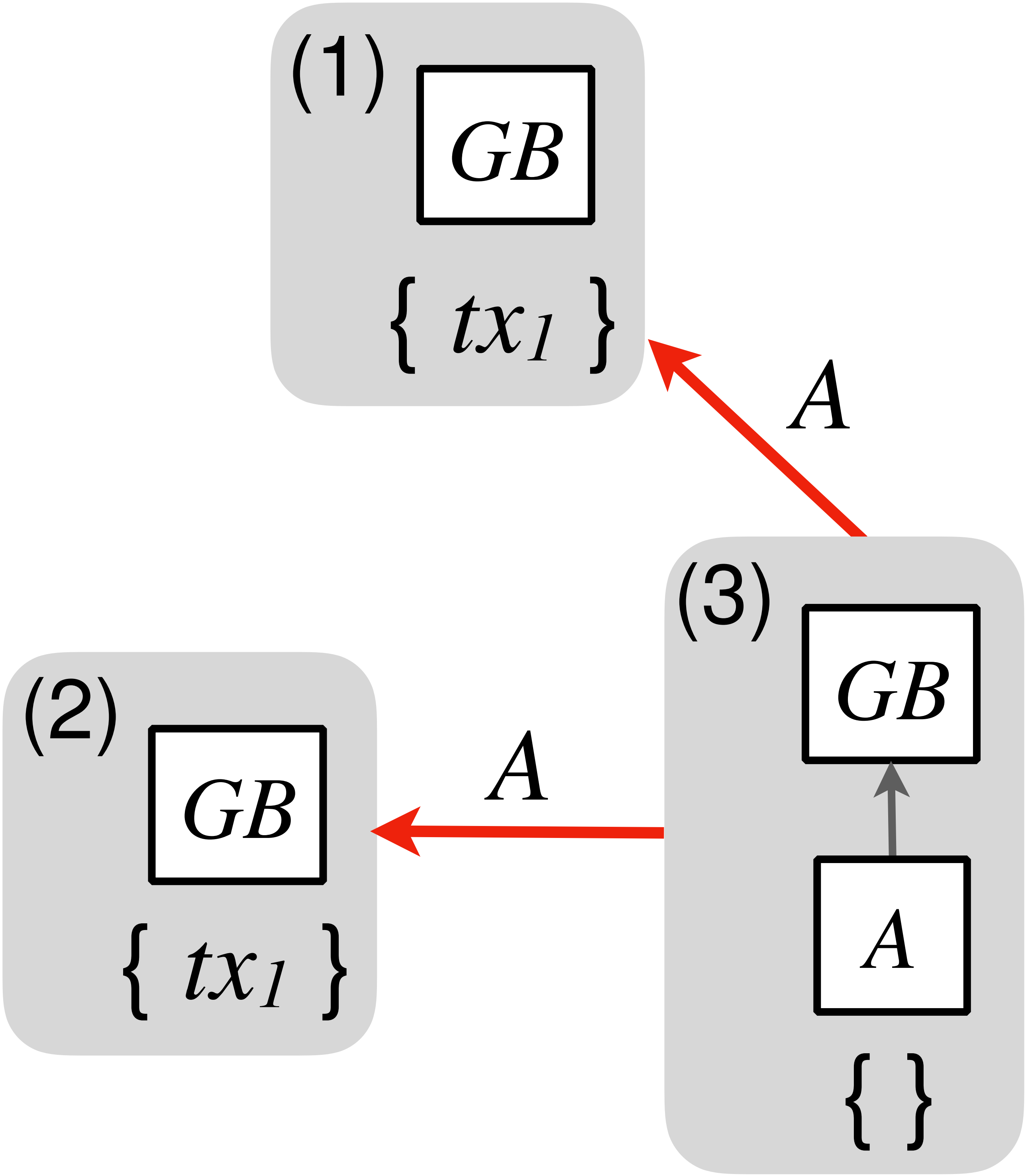
- **distributed**
  - multiple nodes
  - message-passing over a network

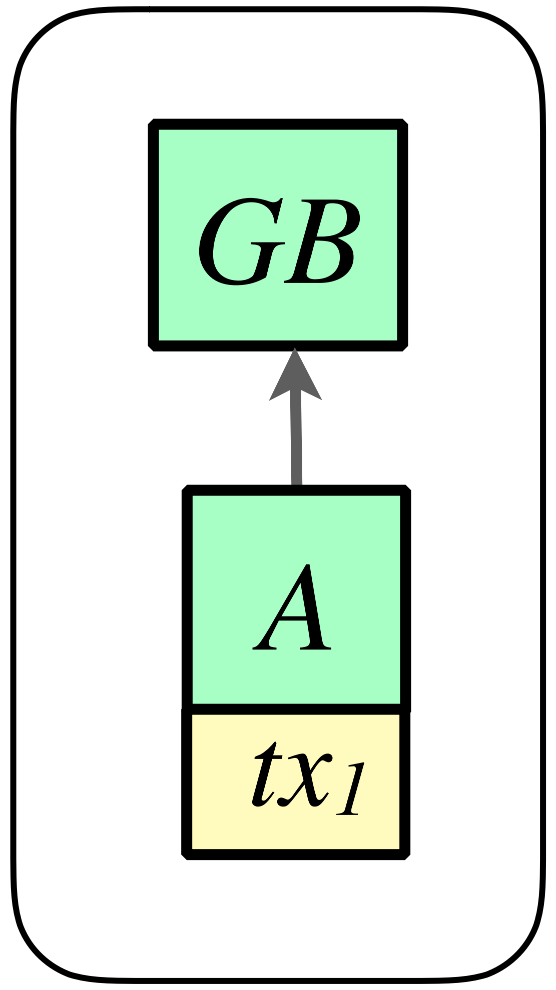
- all start with same GB
- have a <u>transaction pool</u>



- **distributed**
  - multiple nodes
  - message-passing over a network

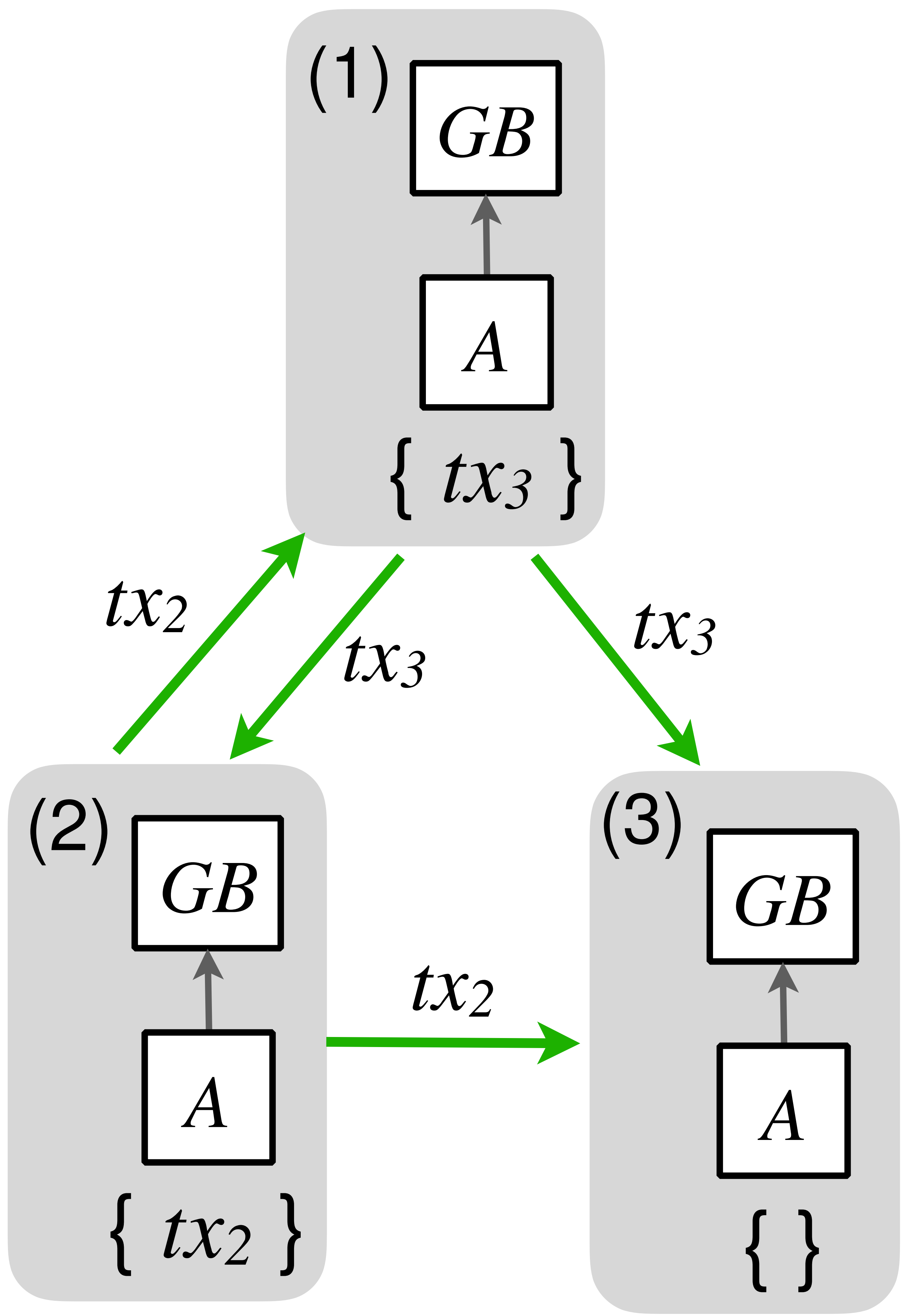
- all start with same GB
- have a transaction pool
- can <u>mint blocks</u>

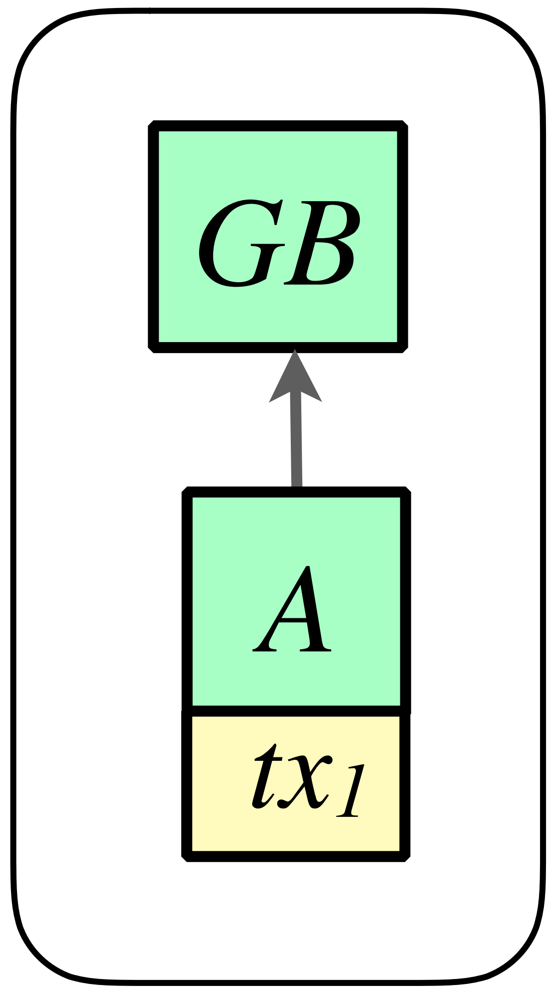




- **distributed** => <u>concurrent</u>
  - multiple nodes
  - message-passing over a network

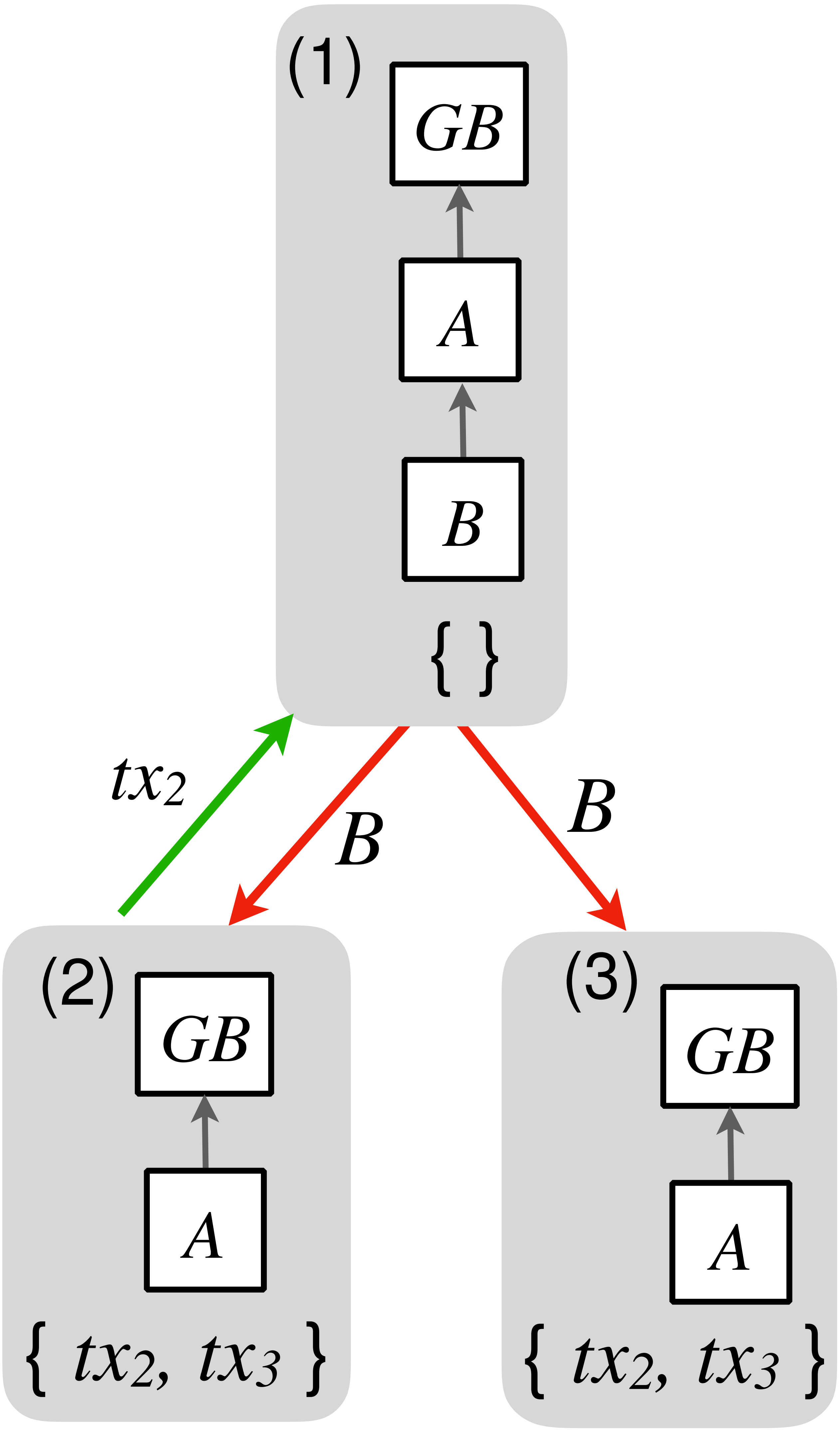
- multiple transactions can be issued and propagated concurrently

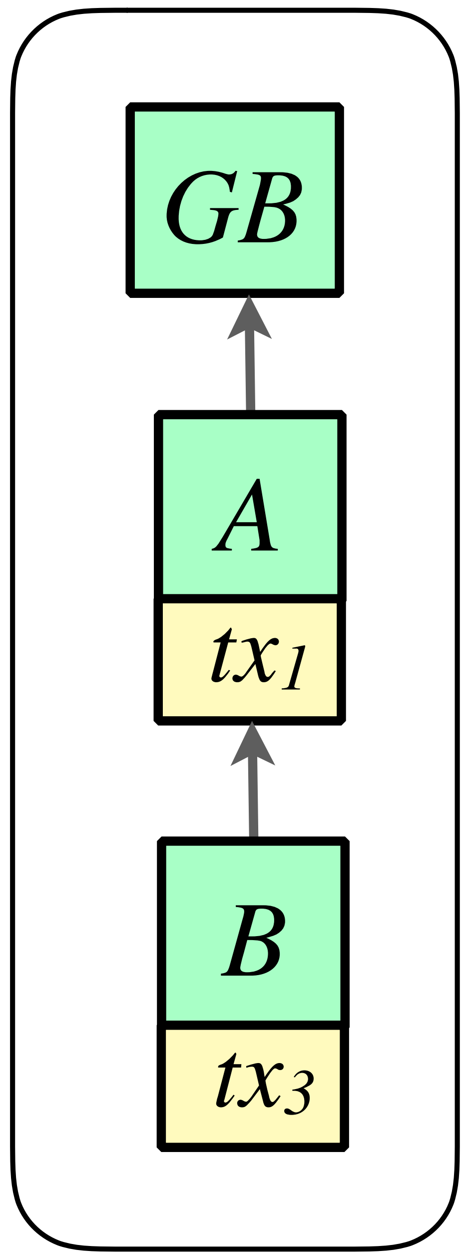




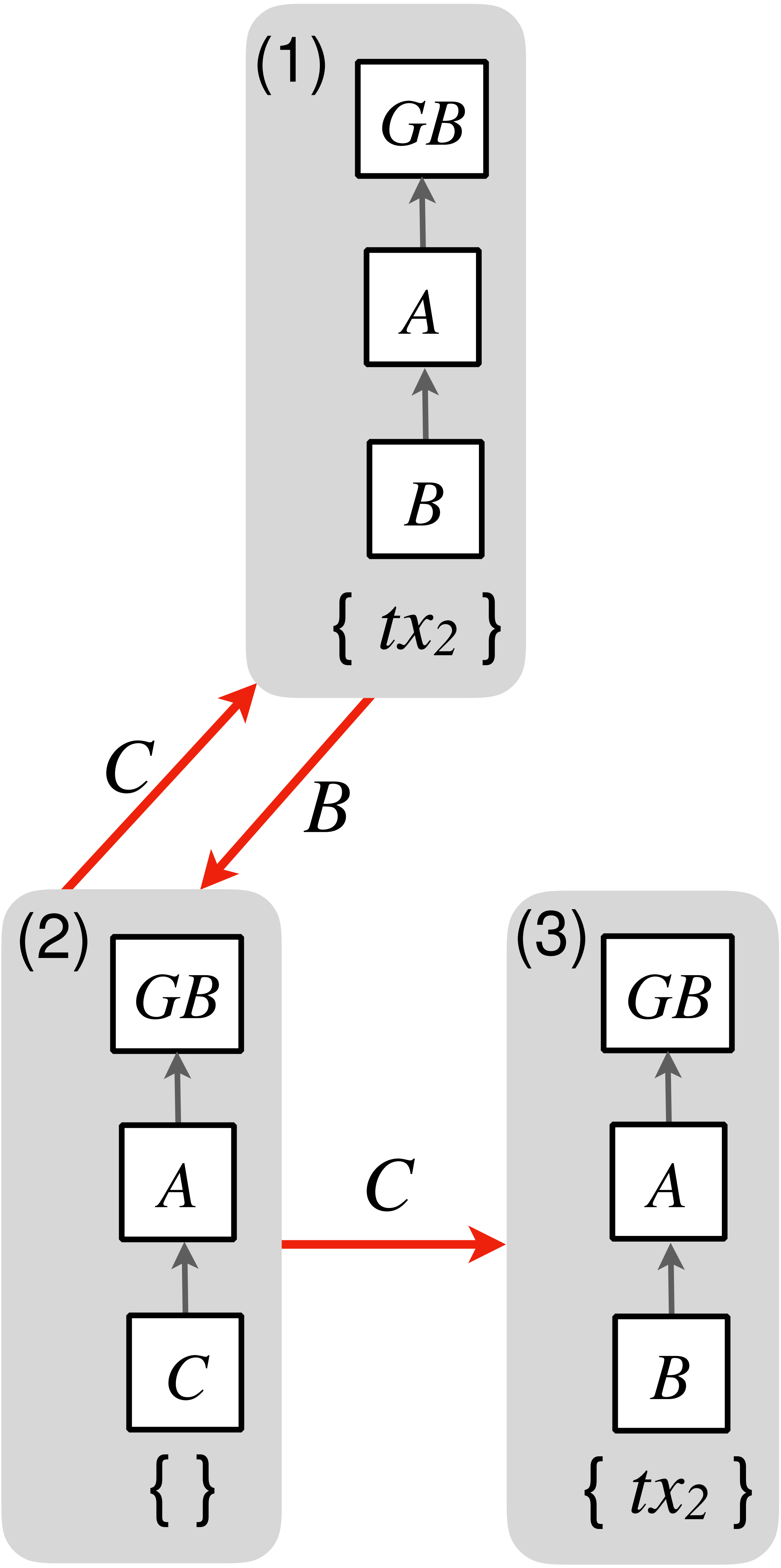
- **distributed** => concurrent
  - multiple nodes
  - message-passing over a network

- blocks can be minted without full knowledge of all transactions

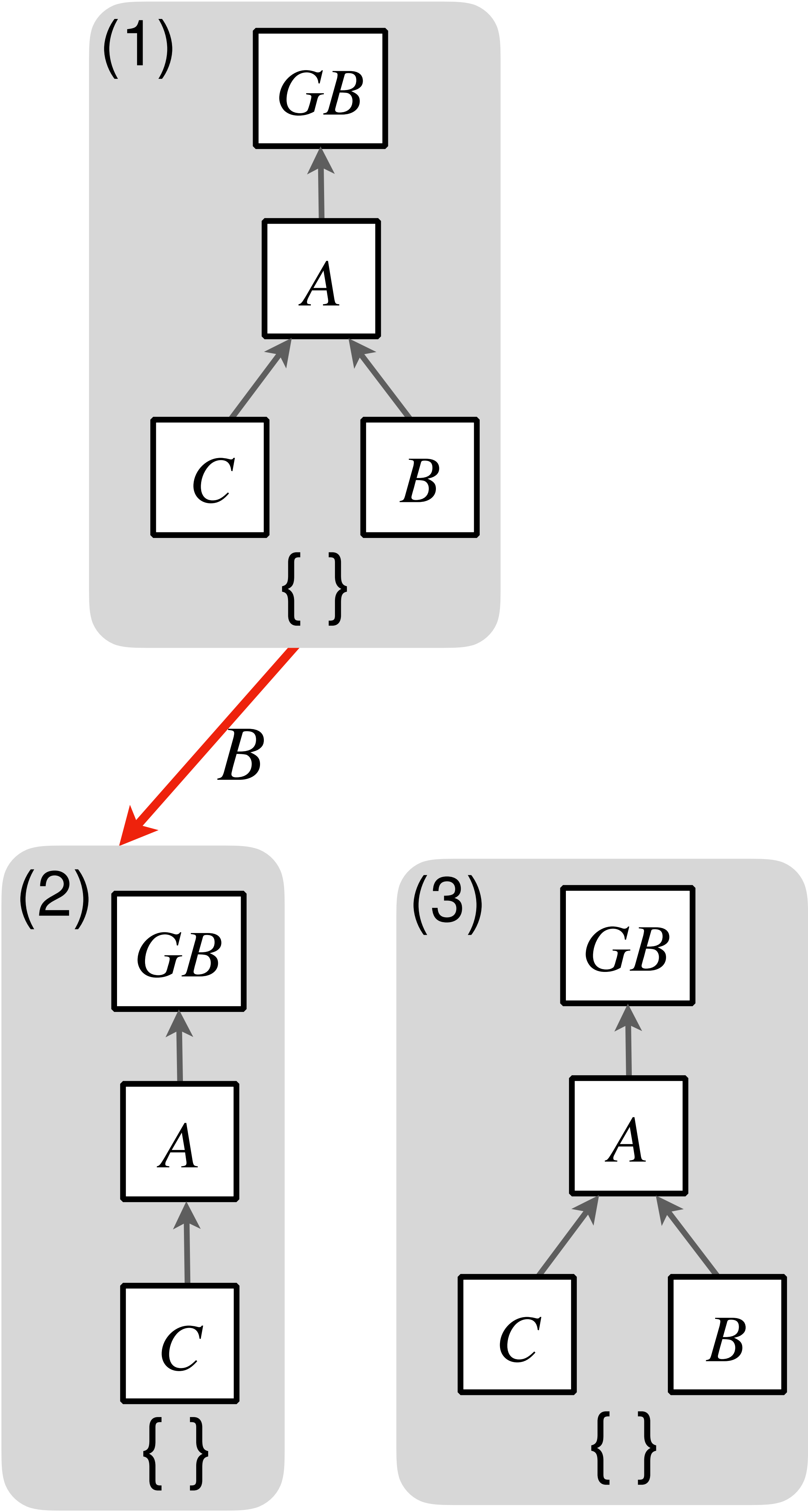




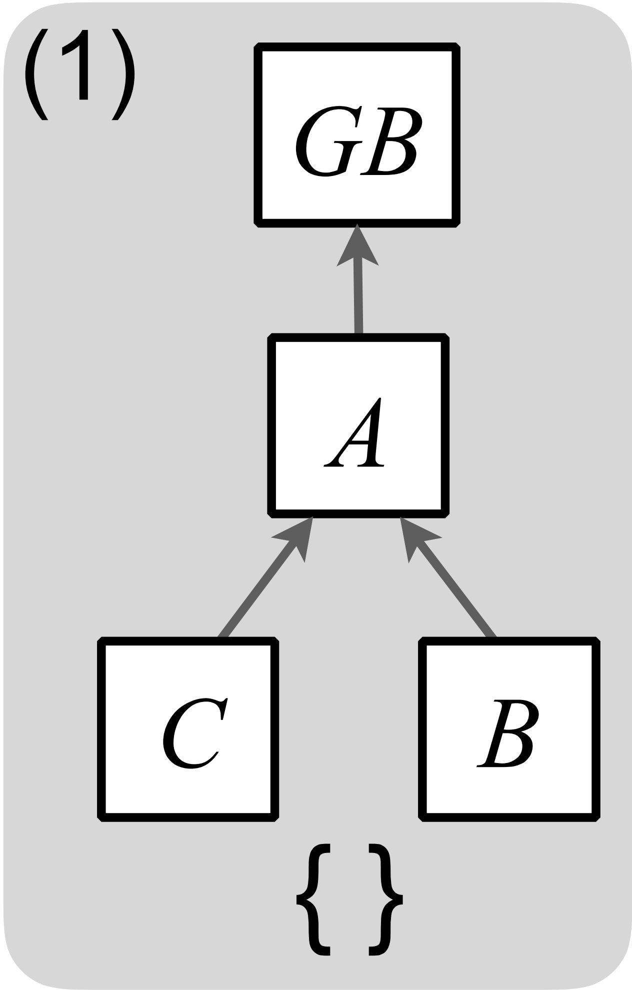
- <u>chain fork</u> has happened, but nodes don't know



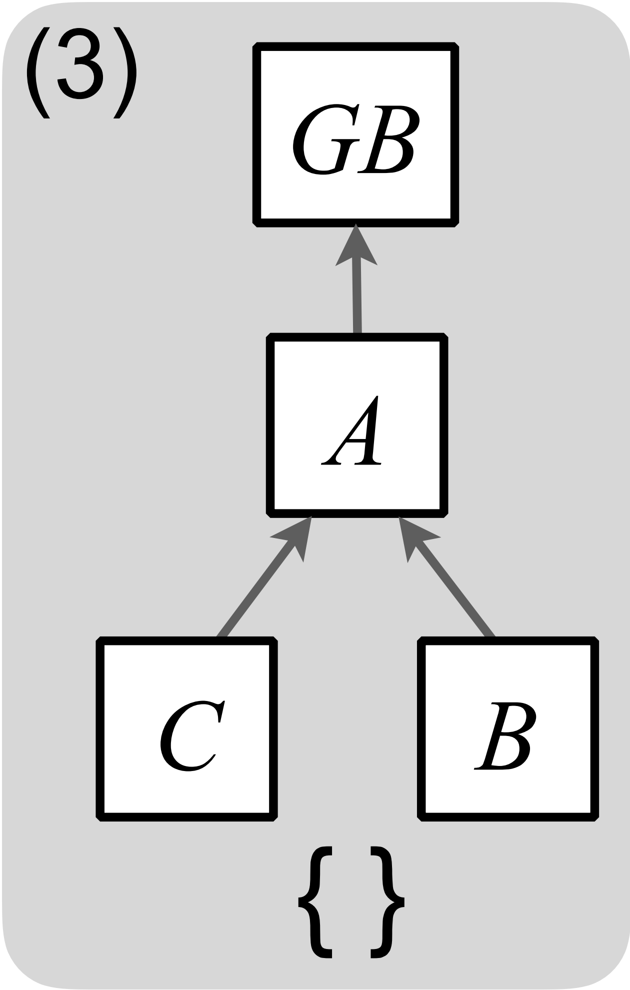
- as block messages propagate, nodes become aware of the fork



Problem: need to choose



- blockchain “promise” =
  one globally-agreed chain
  - each node must choose one chain
  - nodes with the same information must choose the same chain



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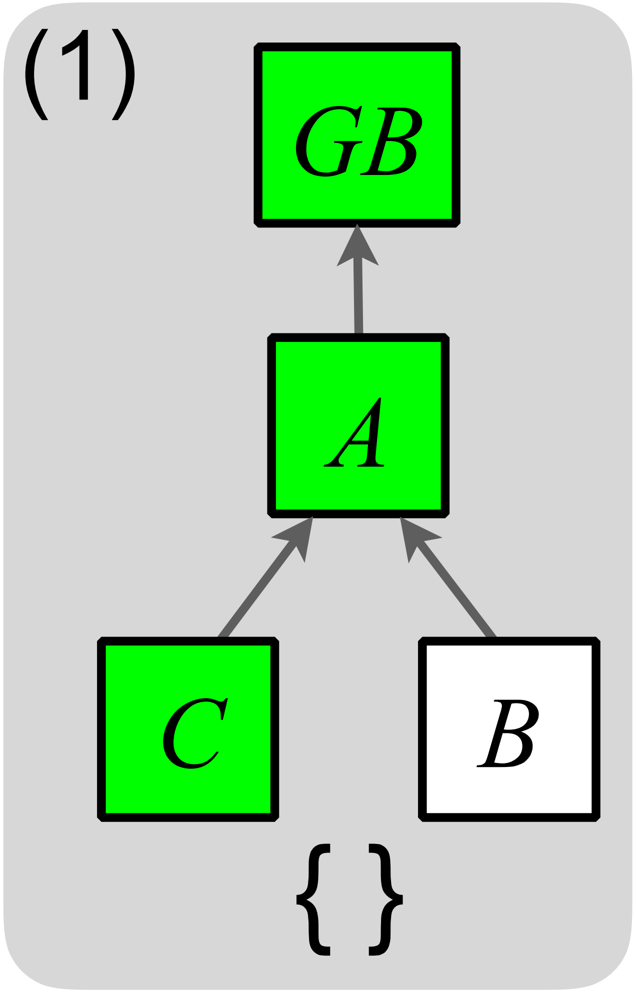

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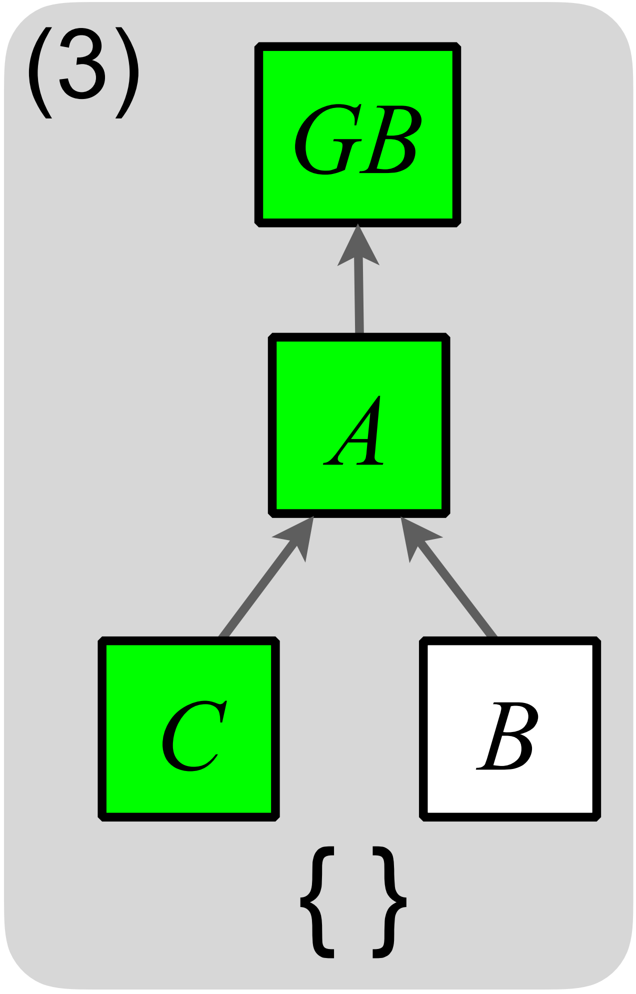

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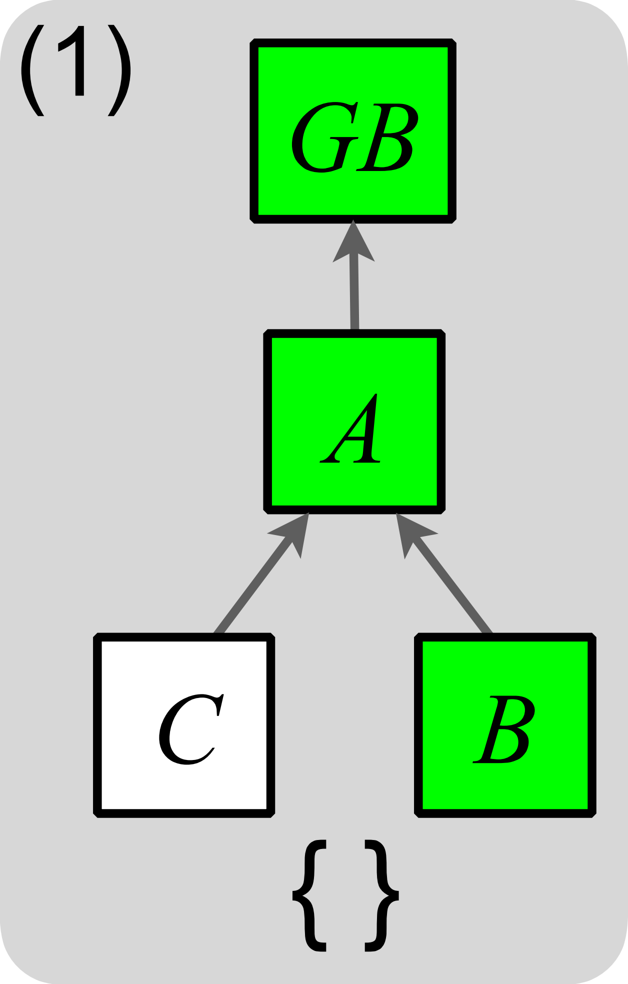

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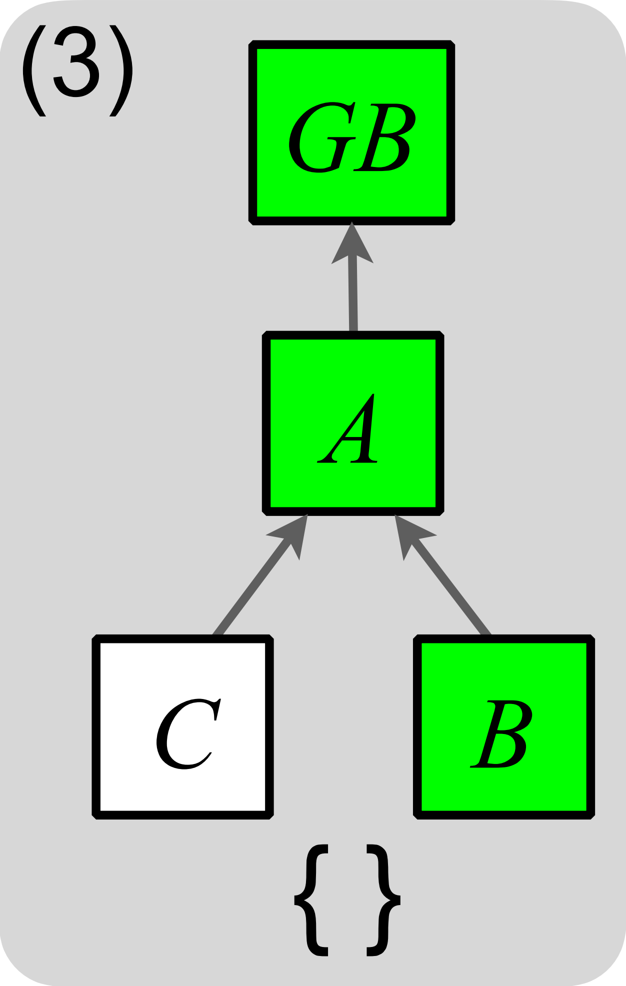

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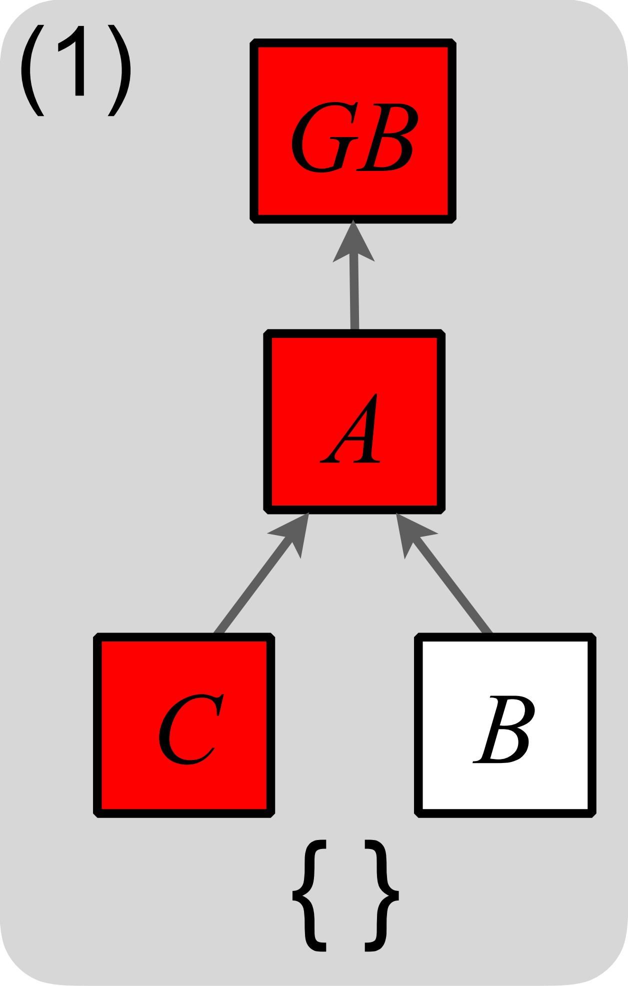

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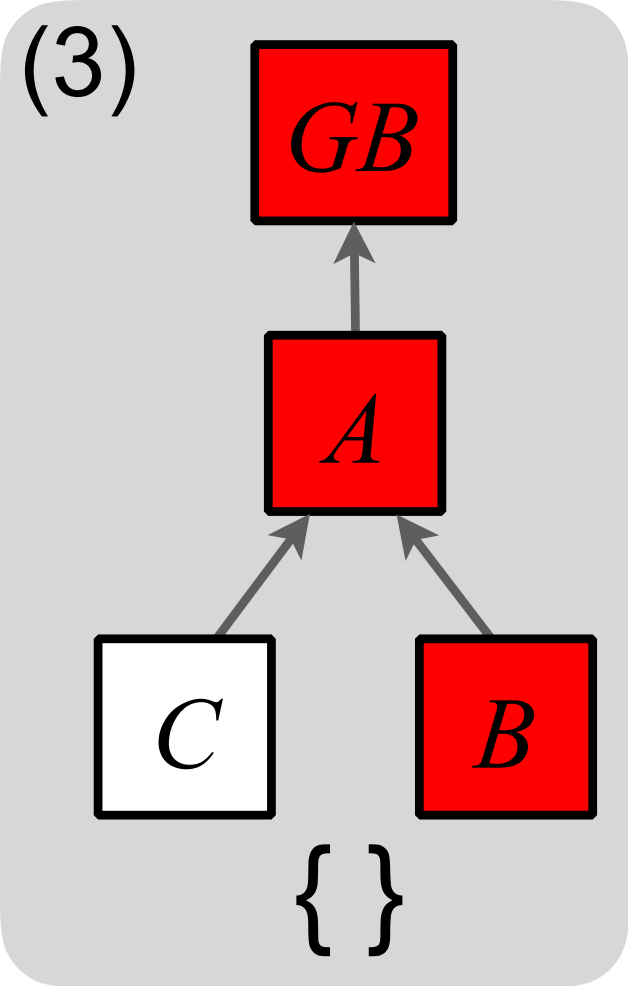


Solution: fork choice rule

- Fork choice rule (FCR, >):
  - given two blockchains, says which one is “heavier”
  - imposes a *strict total order* on all possible blockchains
  - same FCR shared by all nodes

- Nodes adopt “heaviest” chain they know

FCR (>)

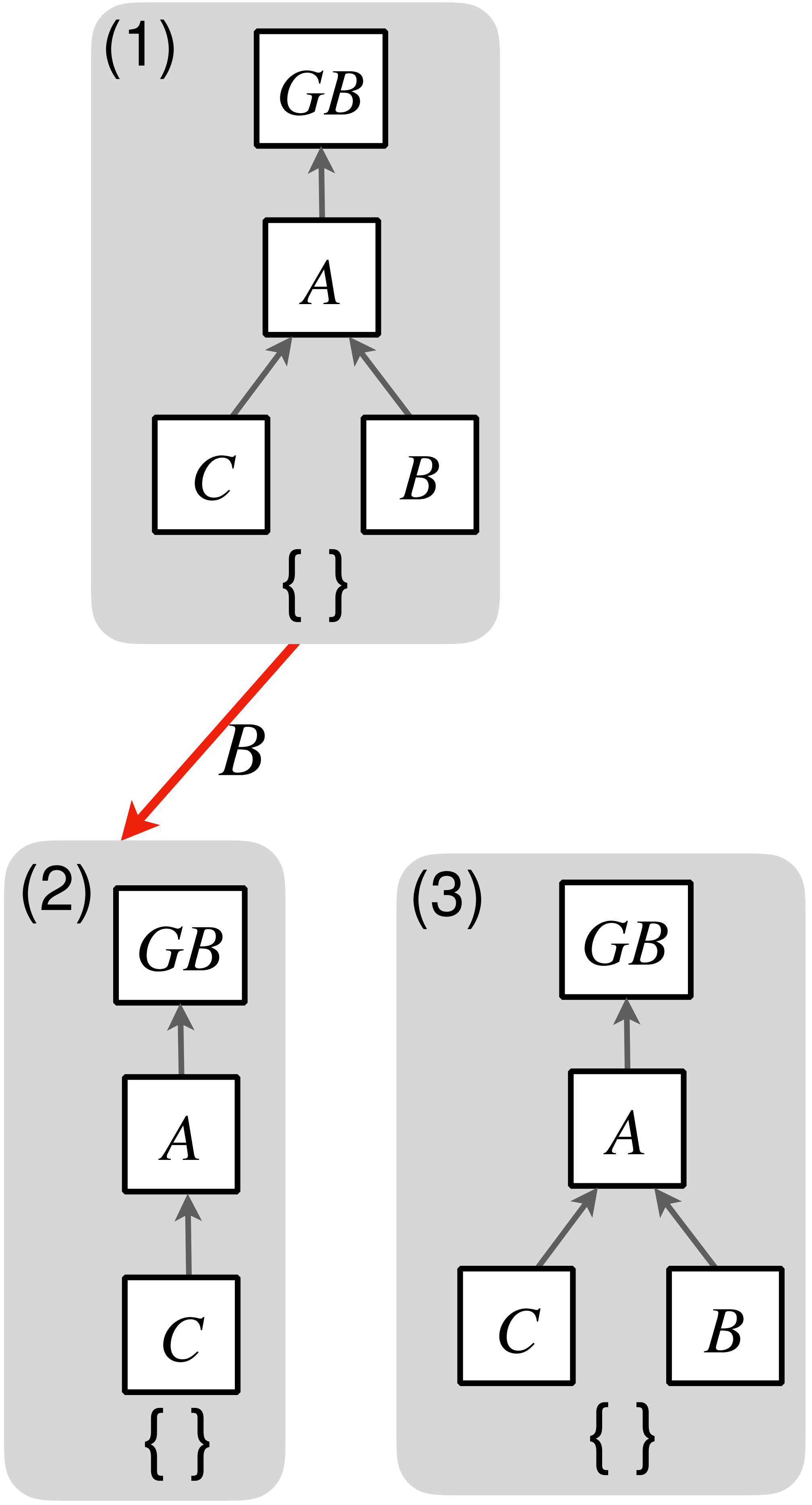
… > [GB, A, C] > … > [GB, A, B] > … > [GB, A] > … > [GB] > …

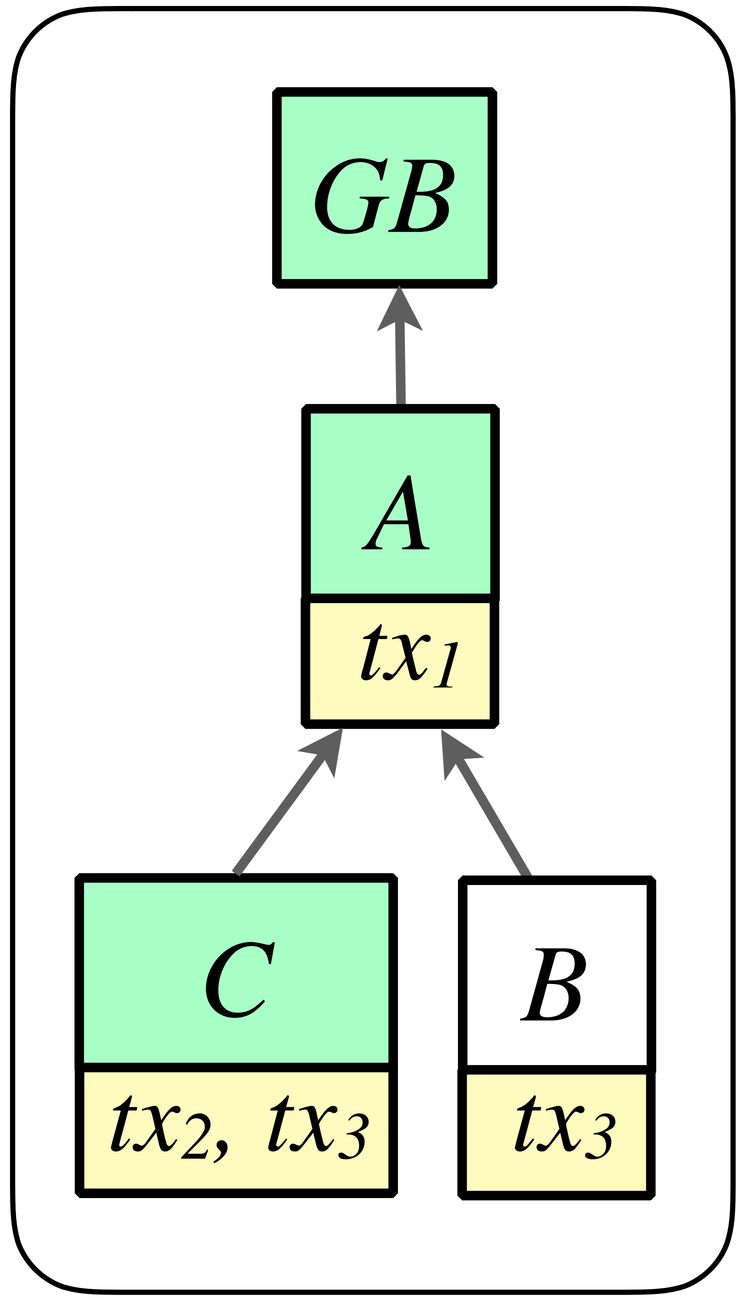
Bitcoin: FCR based on “most cumulative work”

Quiescent consistency

- **distributed**
  - multiple nodes
  - all start with GB
  - message-passing over a network
  - equipped with same FCR

- quiescent consistency: when all block messages have been delivered, everyone agrees





Why it works

Definitions	• blocks, chains, block forests
Parameters and assumptions	• *hashes* are collision-free • *FCR* imposes strict total order
Invariant	• local state + messages "in flight" = global
Quiescent consistency	• when all block messages are delivered, everyone agrees

Blocks and chains

links blocks together

$hash_b : \text{Block} \to \text{Hash}$

$$b \in \text{Block} ::= \{\, \texttt{prev} : \text{Hash};\ \underline{\texttt{txs} : \text{Tx}^*};\ \texttt{pf} : \text{Proof} \,\}$$

$$c \in \text{Chain} \triangleq \text{Block}^*$$

$$GB : \text{Block}$$

proof-of-work

proof-of-stake

proof that this block was minted in accordance to the rules of the protocol

Minting and verifying

try to generate a proof = “ask the protocol for permission” to mint

$$mkProof : \mathrm{Addr} \to \mathrm{Chain} \to \mathrm{option\ Proof}$$

$$VAF : \mathrm{Proof} \to \mathrm{Time} \to \mathrm{Chain} \to \mathrm{bool}$$

validate a proof = ensure protocol rules were followed

Resolving conflict

$$FCR : \mathrm{Chain} \to \mathrm{Chain} \to \mathrm{bool}$$

Assumptions

- Hash functions are collision-free

$$hash\_inj \quad : \forall x\ y,\ \#x = \#y \implies x = y$$

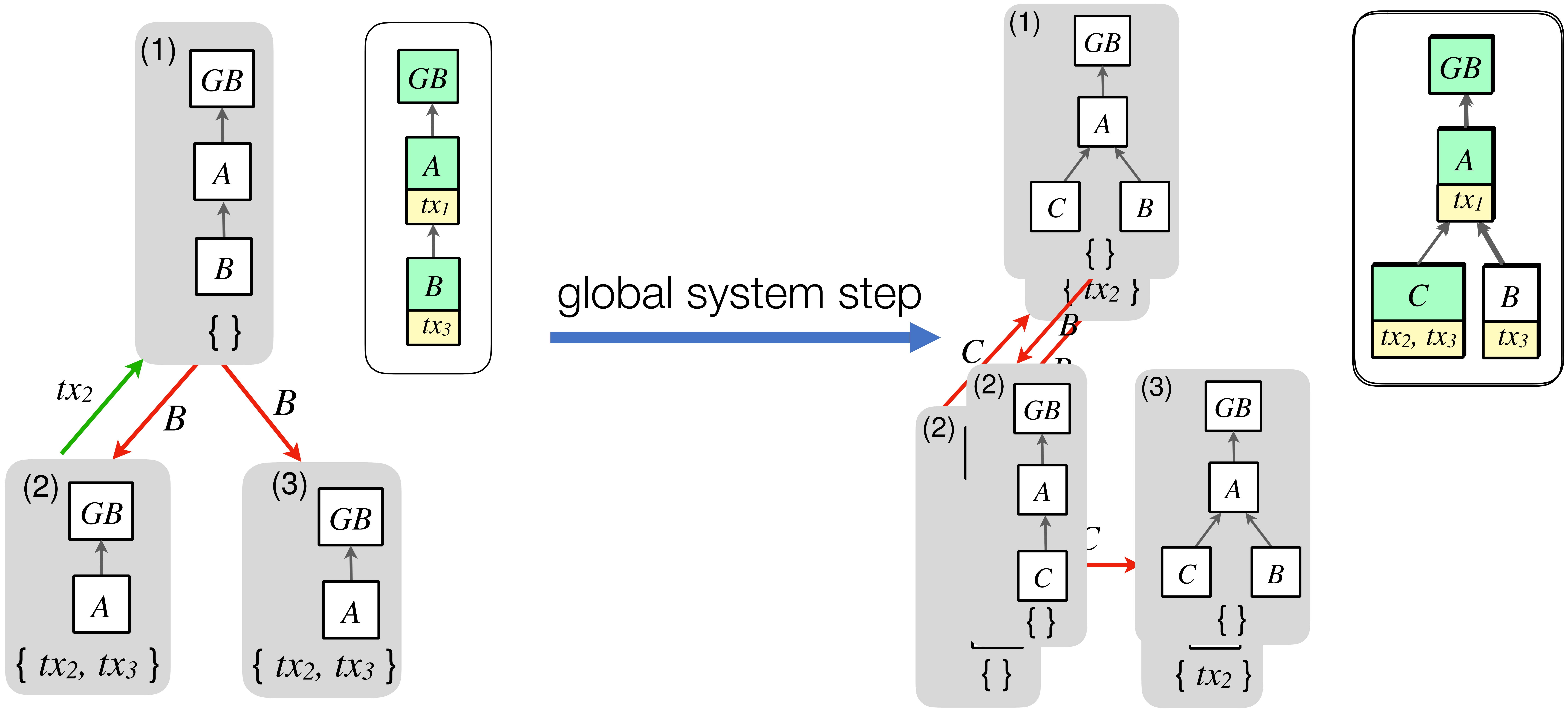
- FCR imposes a *strict total order* on all blockchains

$$FCR\_rel \quad : \forall c_1\ c_2, c_1 = c_2 \lor c_1 > c_2 \lor c_2 > c_1$$

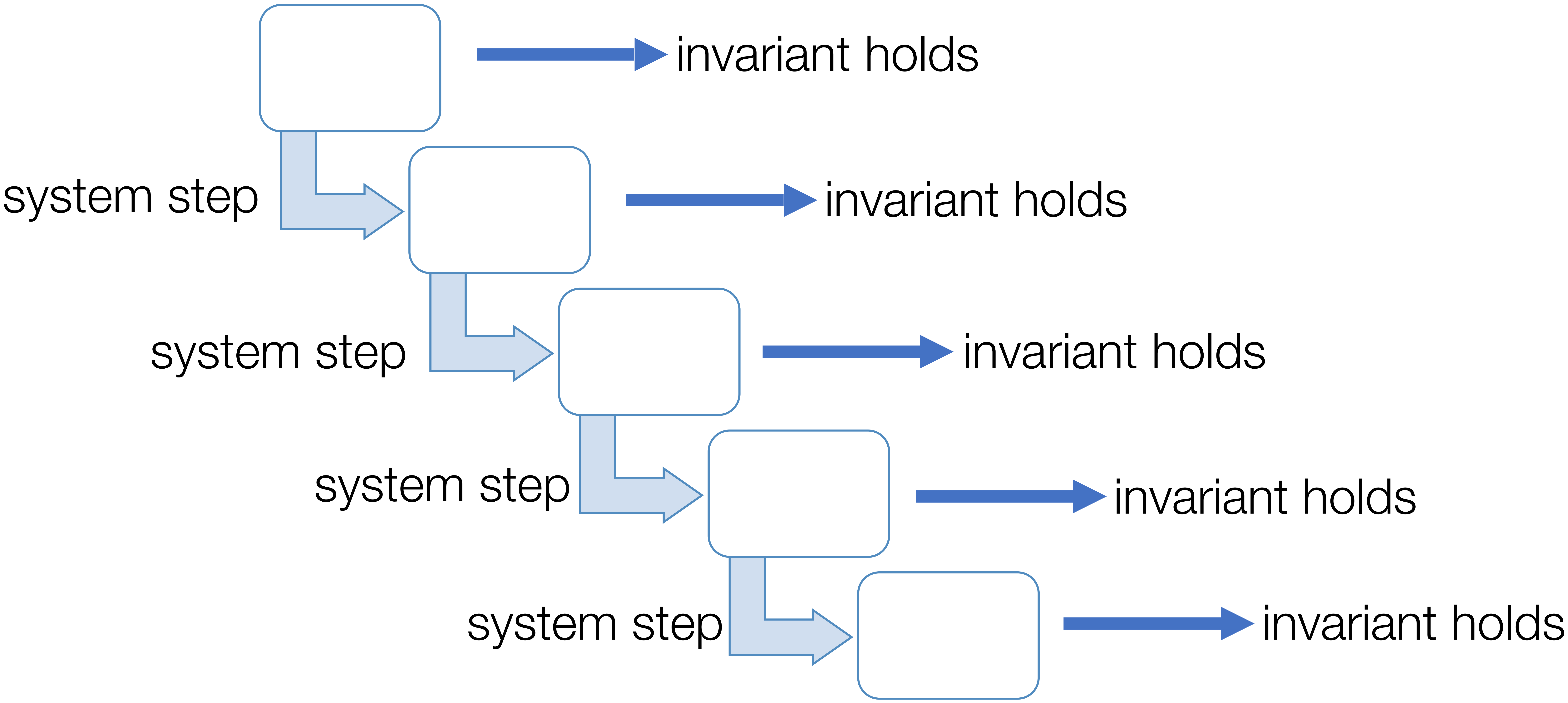
$$FCR\_trans \quad : \forall c_1\ c_2\ c_3, c_1 > c_2 \land c_2 > c_3 \implies c_1 > c_3$$

$$FCR\_nrefl \quad : \forall c, c > c \implies \text{False}$$

Invariant: local state + “in-flight” = global



Invariant is inductive



Invariant implies QC

- QC: when all blocks *delivered*, everyone *agrees*

How:

- local state + ~~“in-flight”~~ = global
- use FCR to extract “heaviest” chain out of local state

- since everyone has same state & same FCR
  - ➢consensus

Reusable components

- Reference implementation in Coq
- Per-node protocol logic
- Network semantics
- Clique invariant, QC property, various theorems

https://github.com/certichain/toychain

To Take Away

- *Byzantine Fault-Tolerant Consensus* is a common issue addressed in distributed systems, where participants *do not trust each other*.
- For a *fixed set* of nodes, a Byzantine consensus can be reached via
  - (a) making an agreement to proceed in *three phases*
  - (b) increasing the *quorum size*
  - These ideas are implemented in **PBFT**, which also relies on *cryptographically signed* messages and *partial synchrony*.
- In *open* systems (such as those used in Proof-of-X blockchains), consensus can be reached via a universally accepted ***Fork-Chain-Rule***:
  - It measures the *amount of work*, while comparing two "conflicting" proposals

To be continued…

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