YSC3248: Parallel, Concurrent and Distributed Programming

Byzantine Fault Tolerance and Blockchains

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

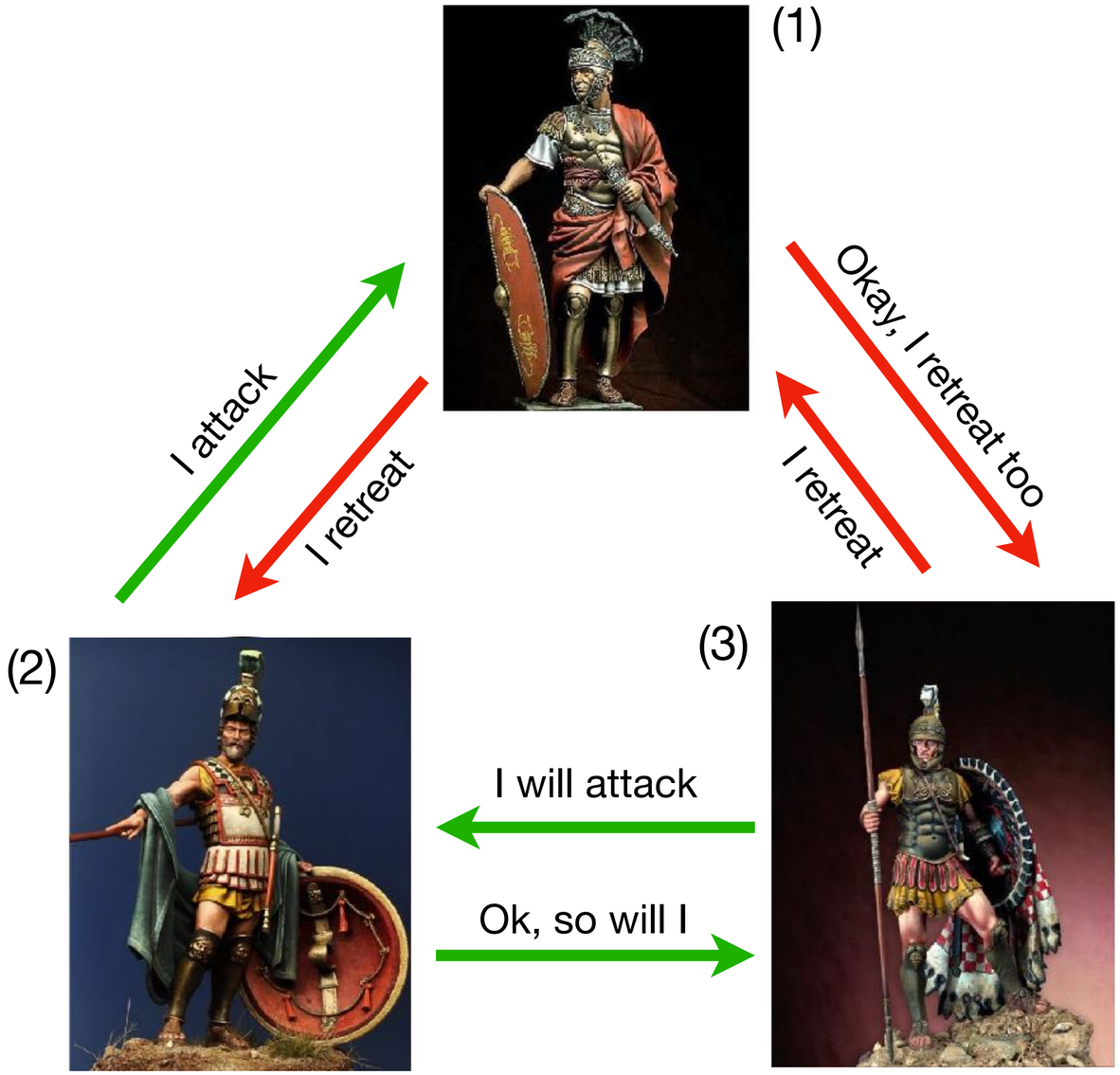
- A Byzantine army decides to attack/retreat
- N generals, f of them are *traitors* (can *collude*)
- Generals camp outside the battle field:
  decide individually based on their field information
- Exchange their plans by unreliable *messengers*
  - Messengers can be *killed*, can be *late*, *etc*.
  - 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/replica/node**
  - *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
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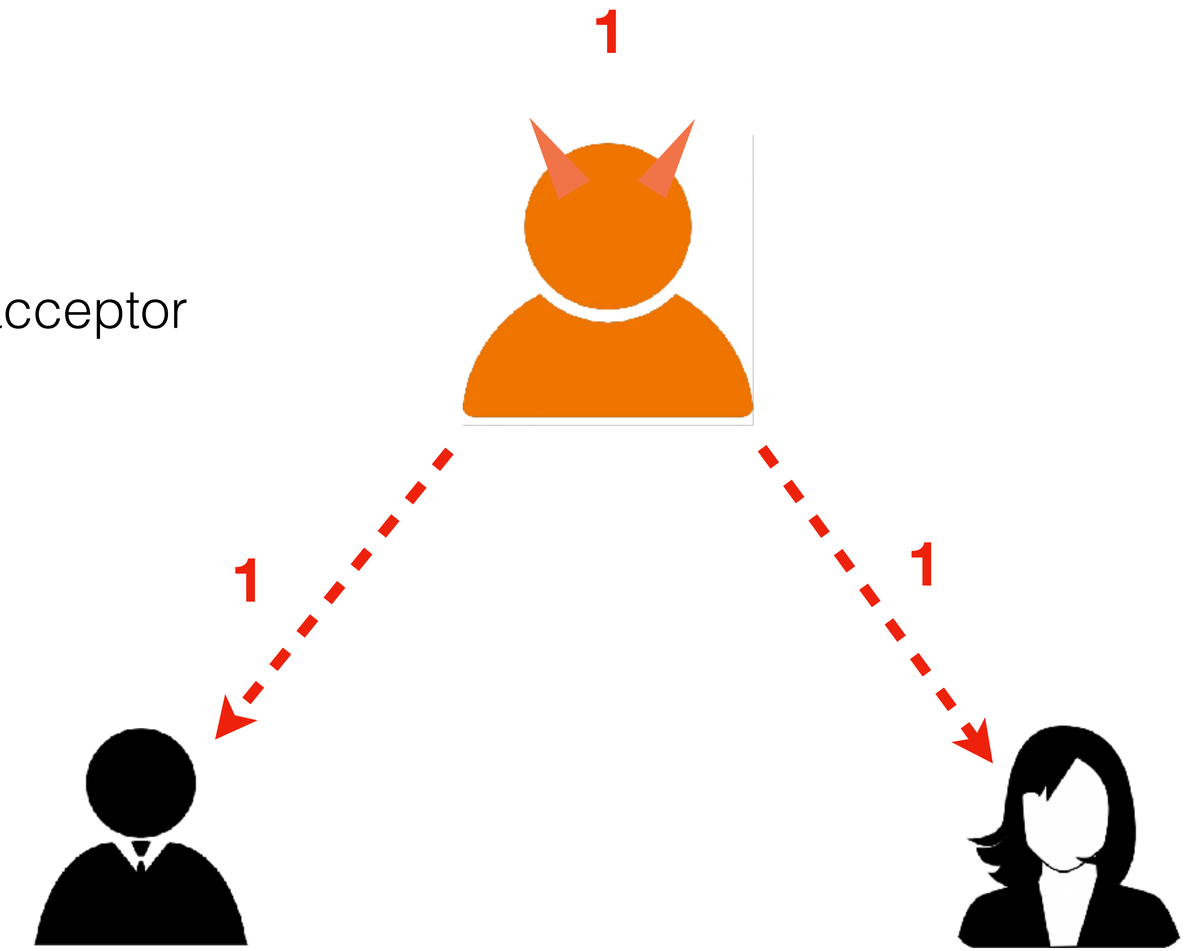

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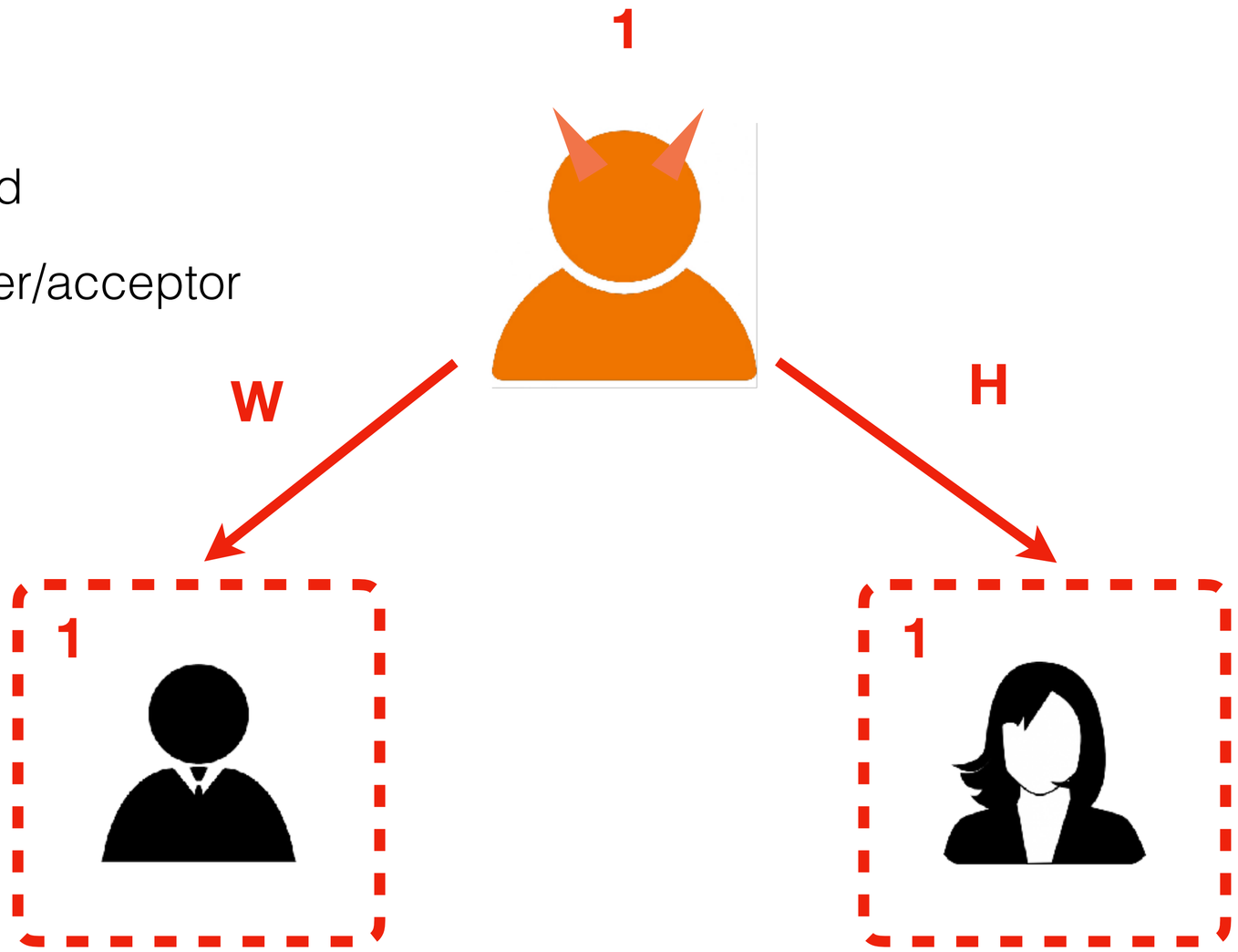


Paxos and Byzantine Faults

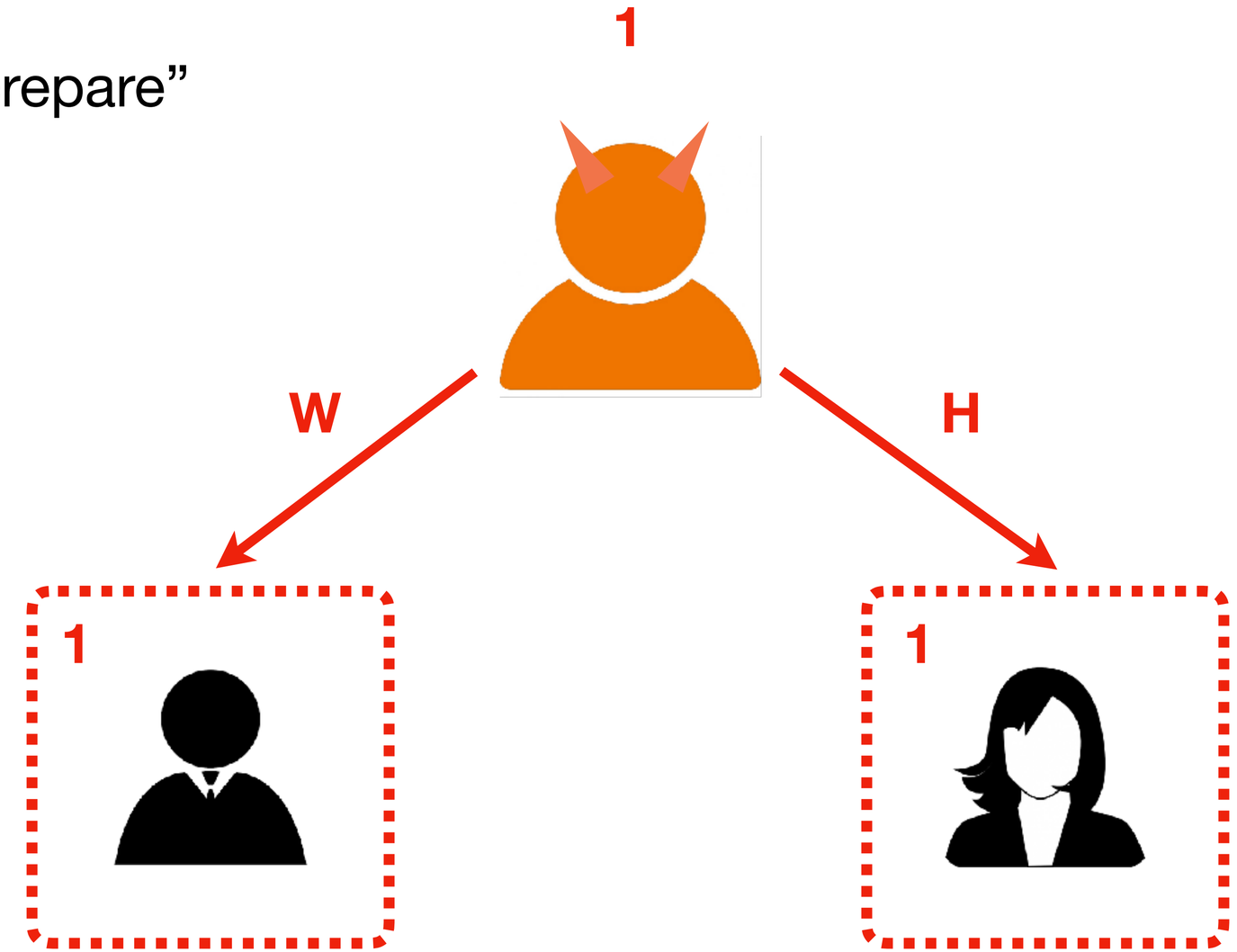
- N = 3, f = 1
- N/2 + 1 = 2 are good
- everyone is proposer/acceptor

What went wrong?

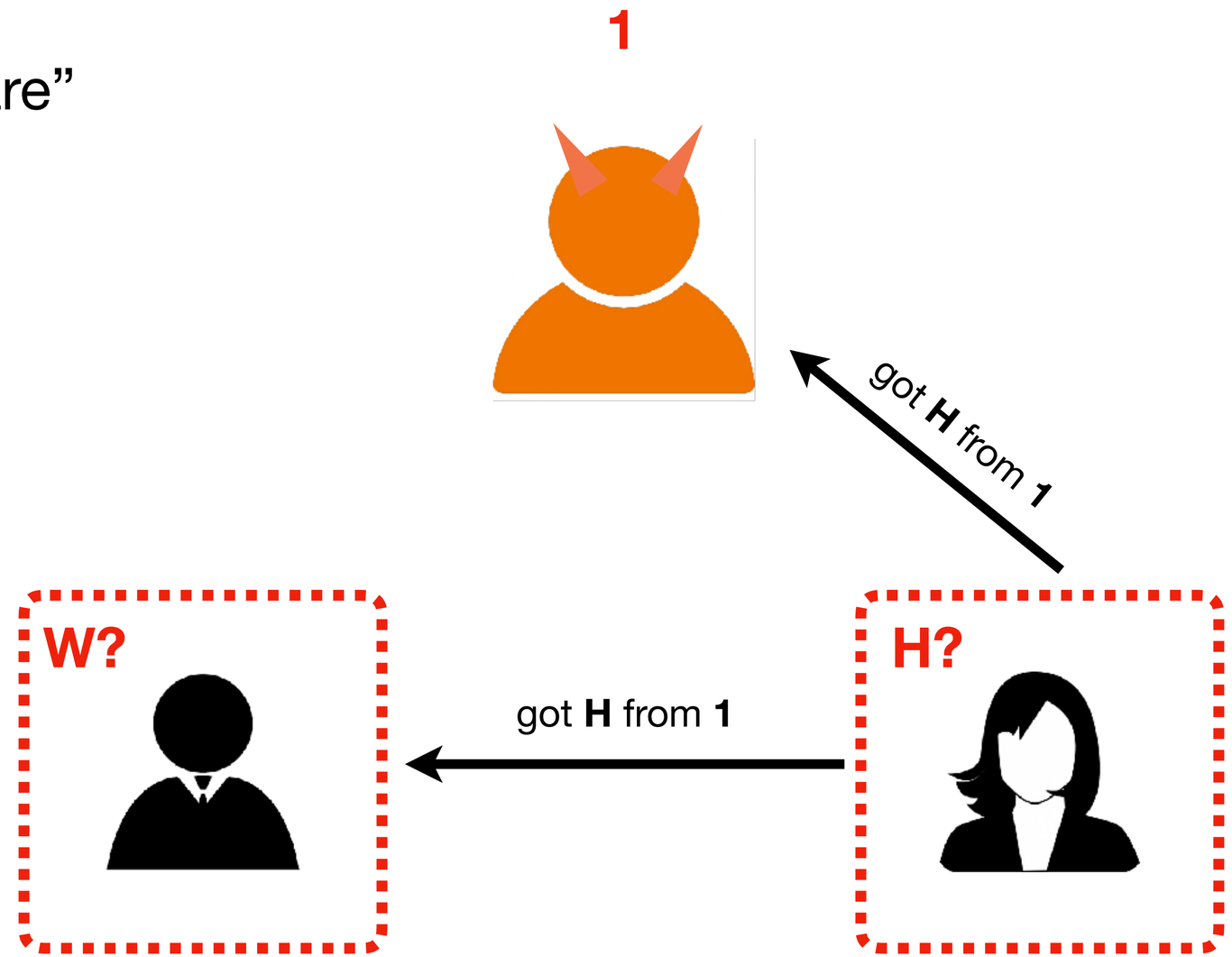
- Problem 1:
  Acceptors did not communicate with each other to check the consistency of the values proposed to everyone.

- 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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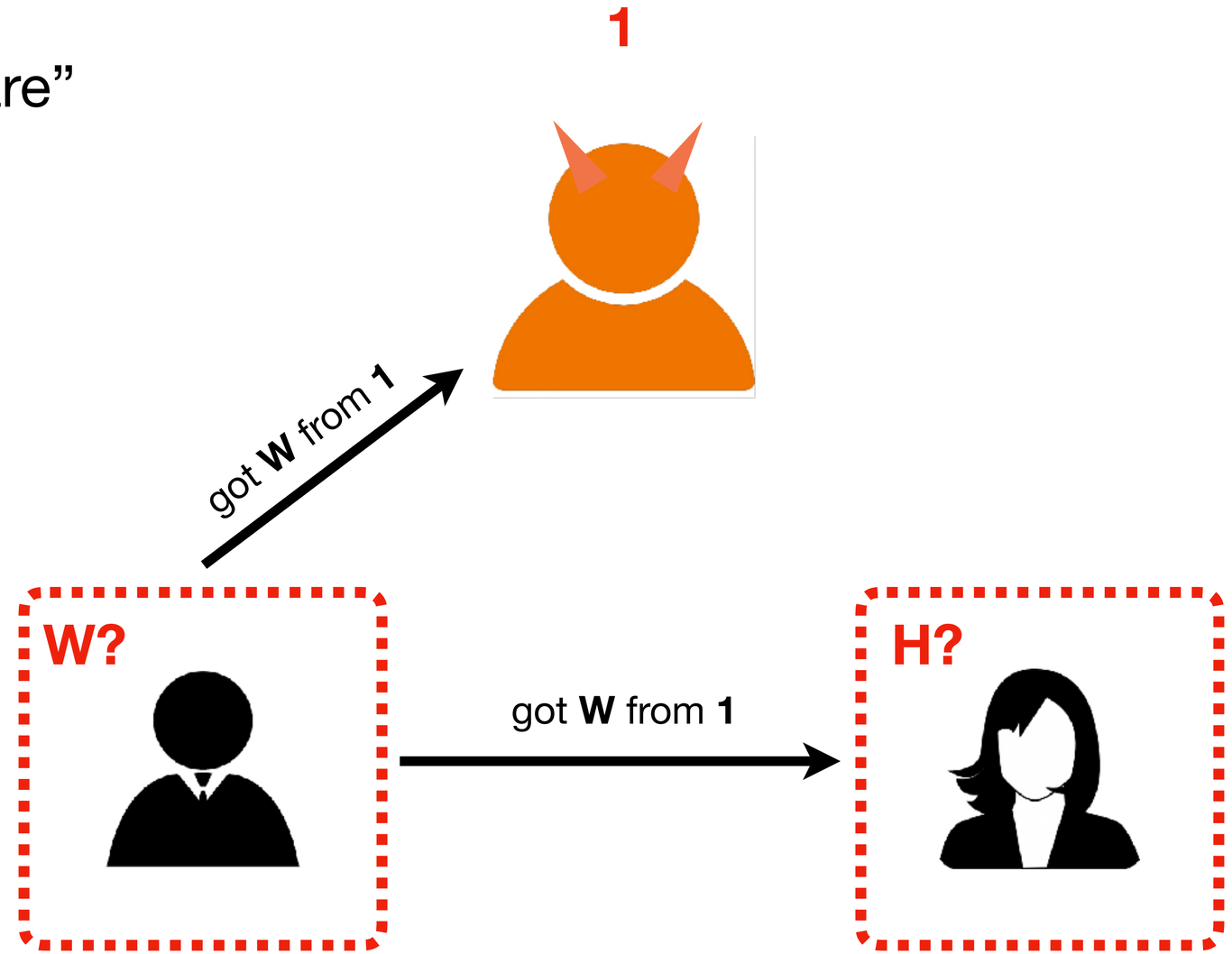

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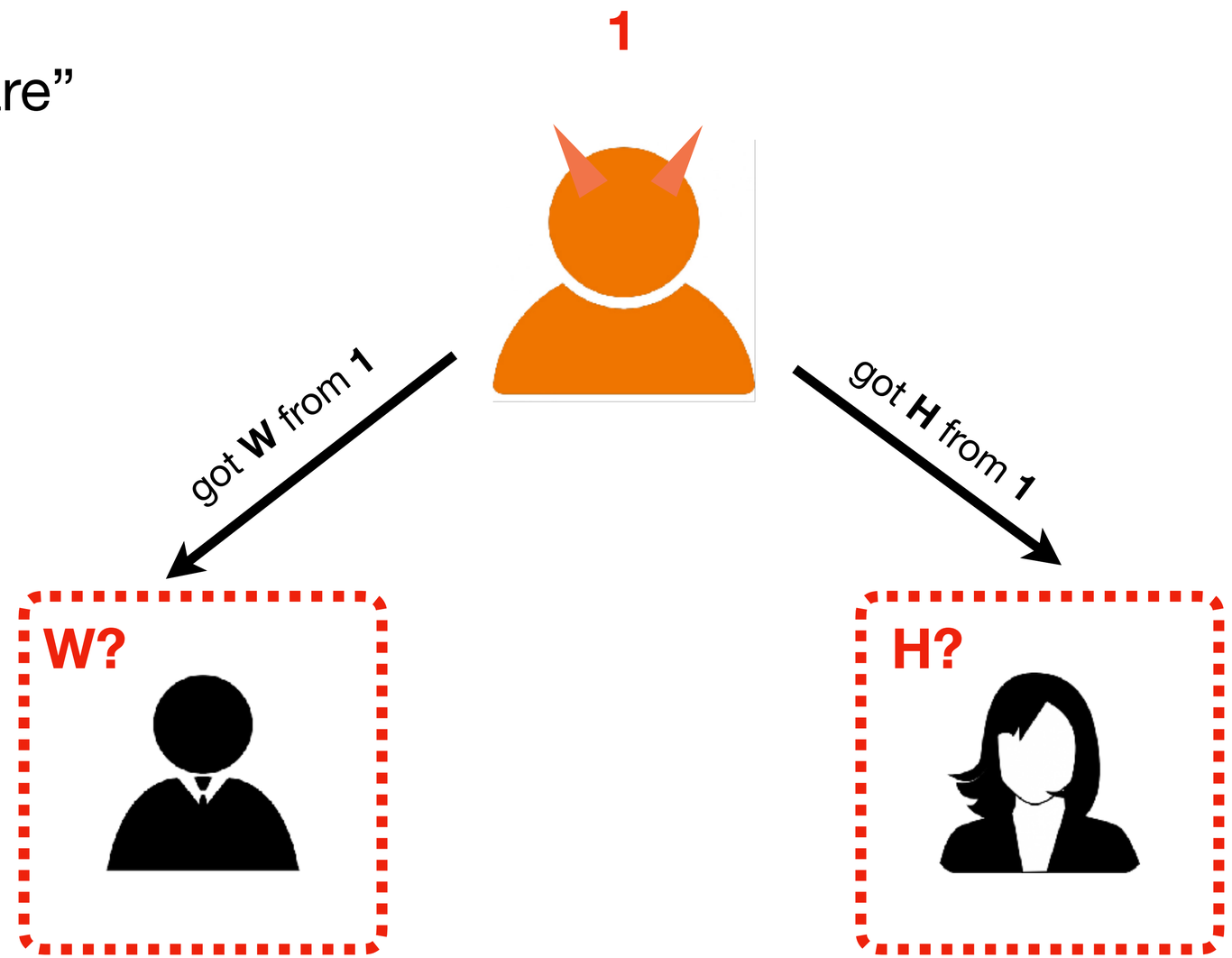

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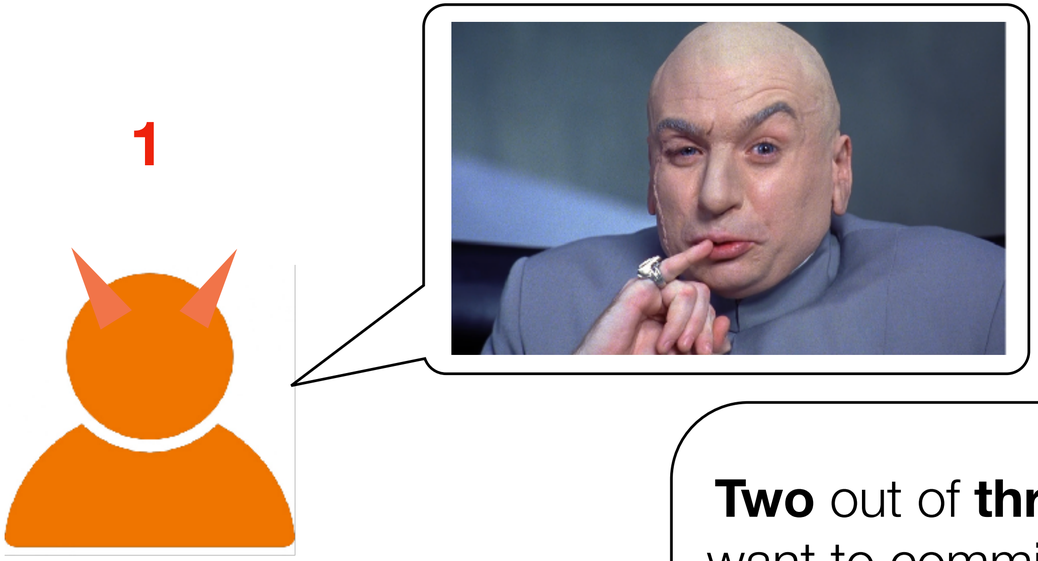


Phase 3: “Commit”

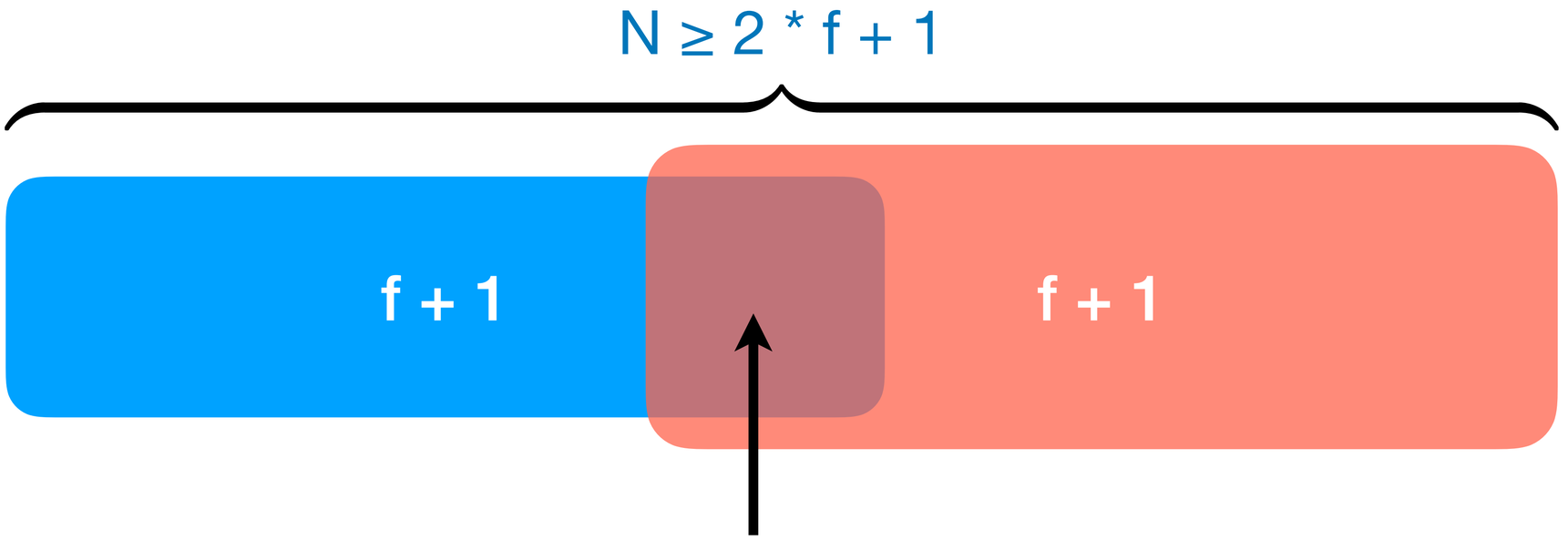
What went wrong now?

- **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



Sharing *at least one* node: must agree on the value

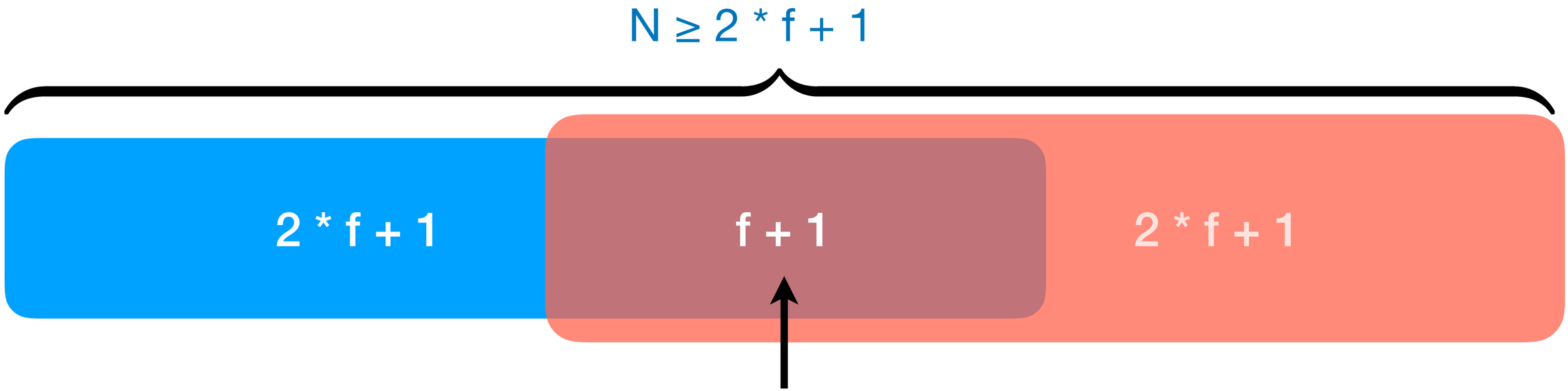
Choosing the Quorum Size

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)

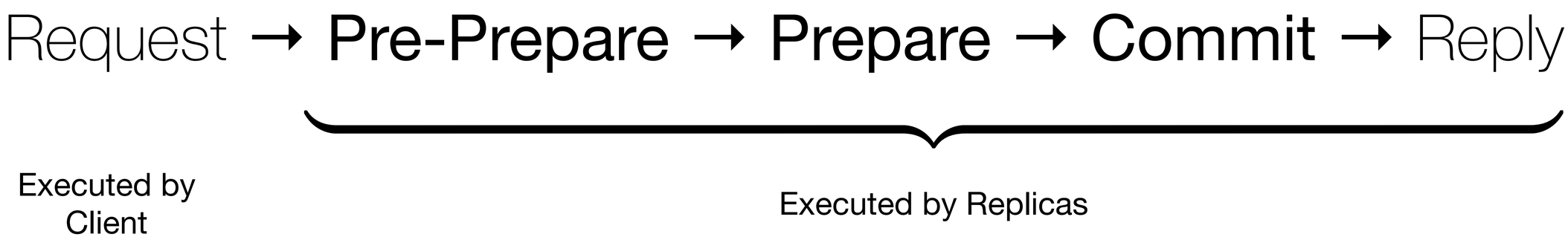
PBFT Terminology and Layout

- 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

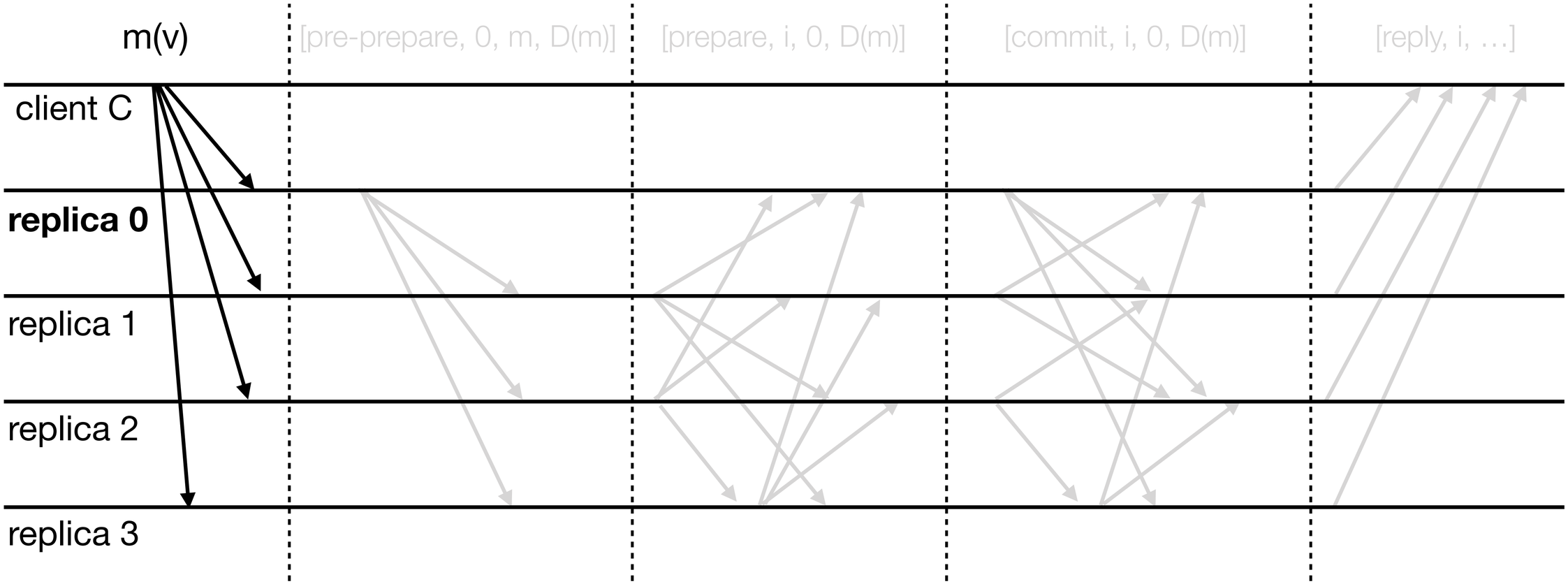
- Clients — communicate directly with primary/replicas
- The protocol uses *time-outs* (partial synchrony) to *detect faults*
  - *E.g.*, a primary not responding *for too long is considered compromised*

Overview of the Core PBFT Algorithm



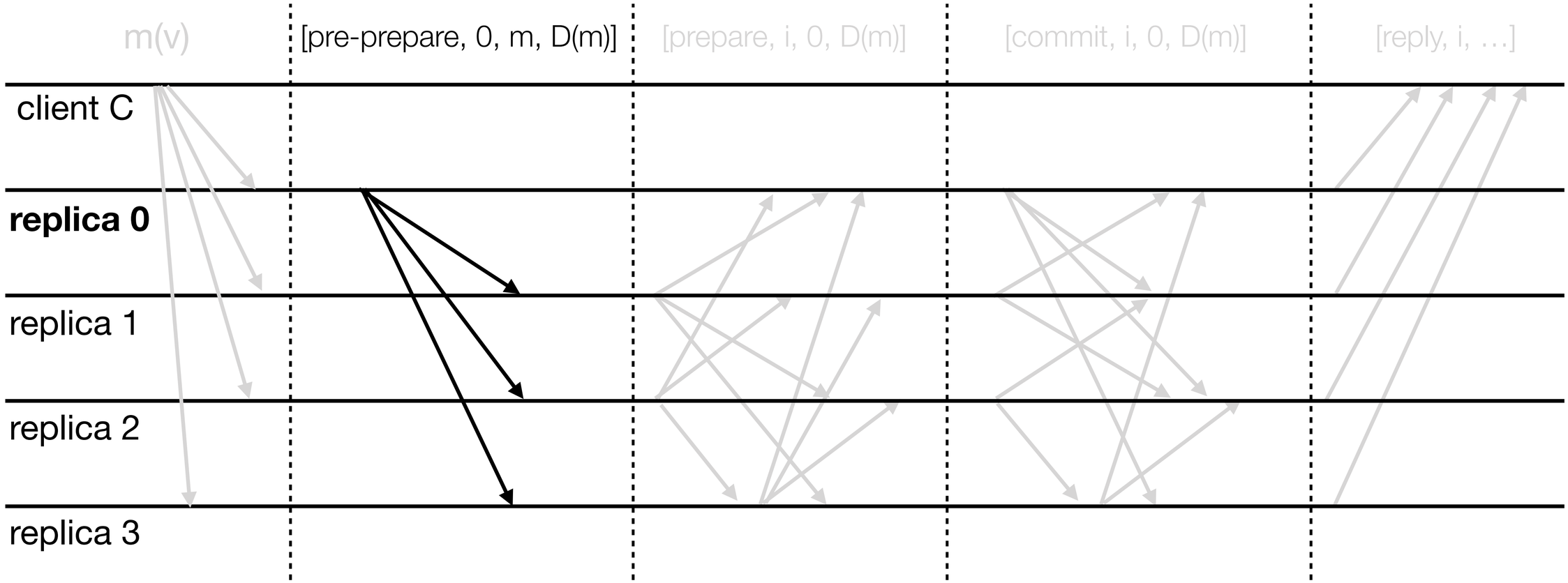
Request

Client C sends a message to *all* replicas



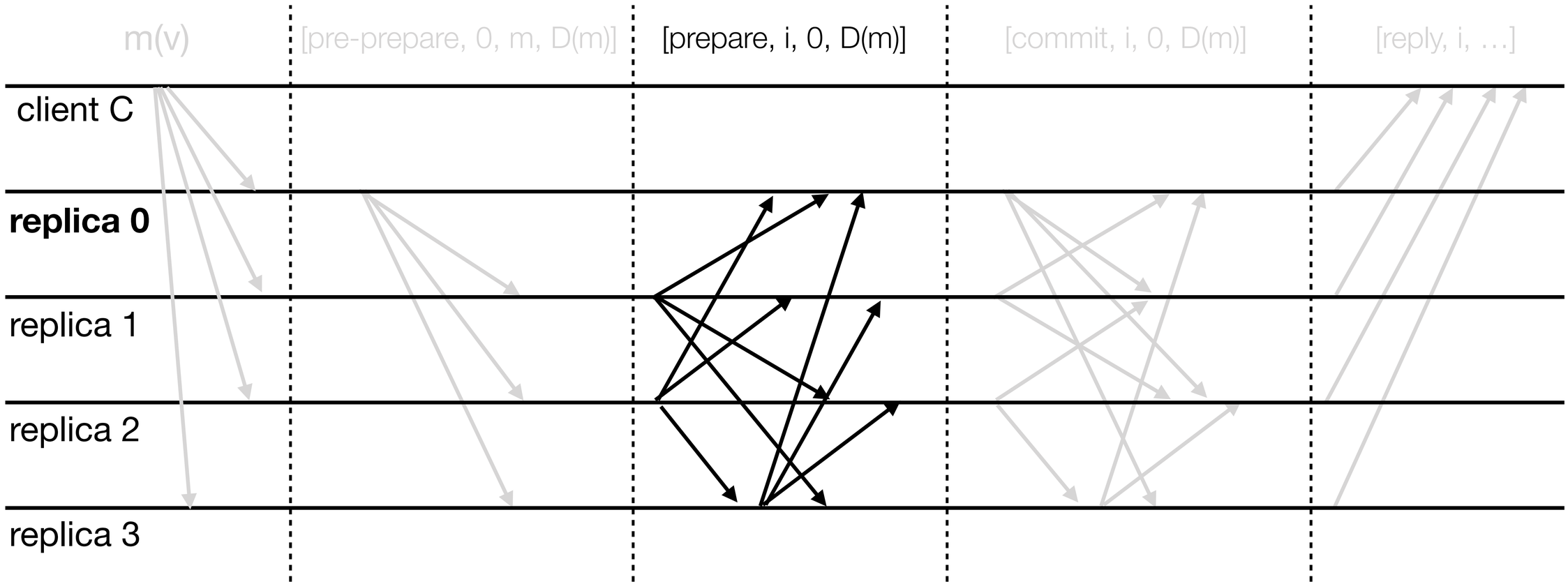
Pre-prepare

- 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



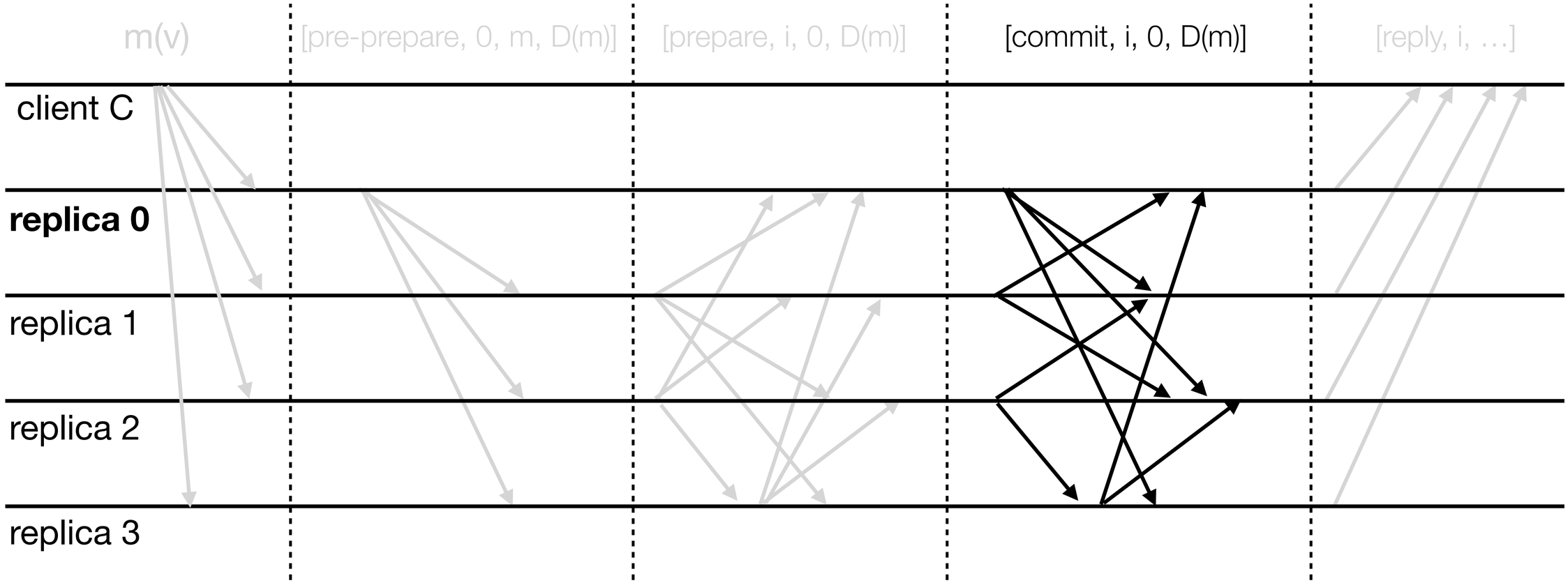
Prepare

- 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



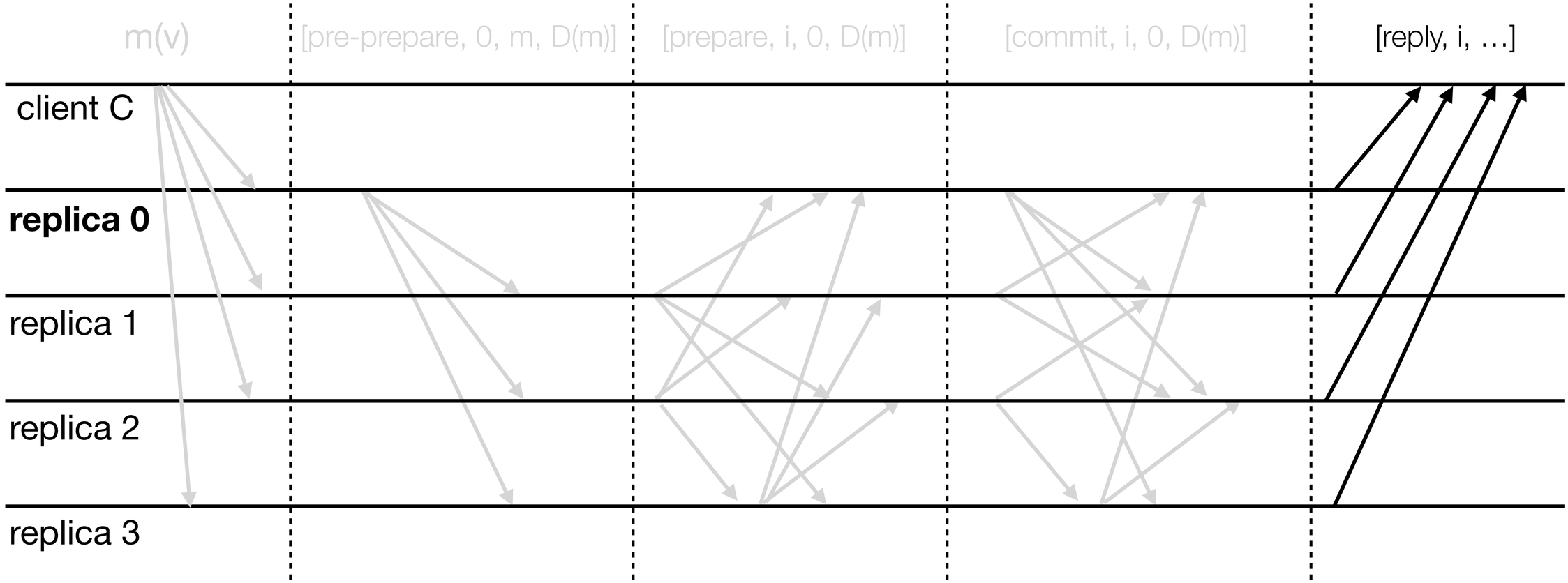
Commit

- 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

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)

Blockchain Consensus Protocols

What blockchain does

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

- transforms a **set** of transactions into a *globally-agreed* **sequence**
- "distributed timestamp server" (Nakamoto 2008)

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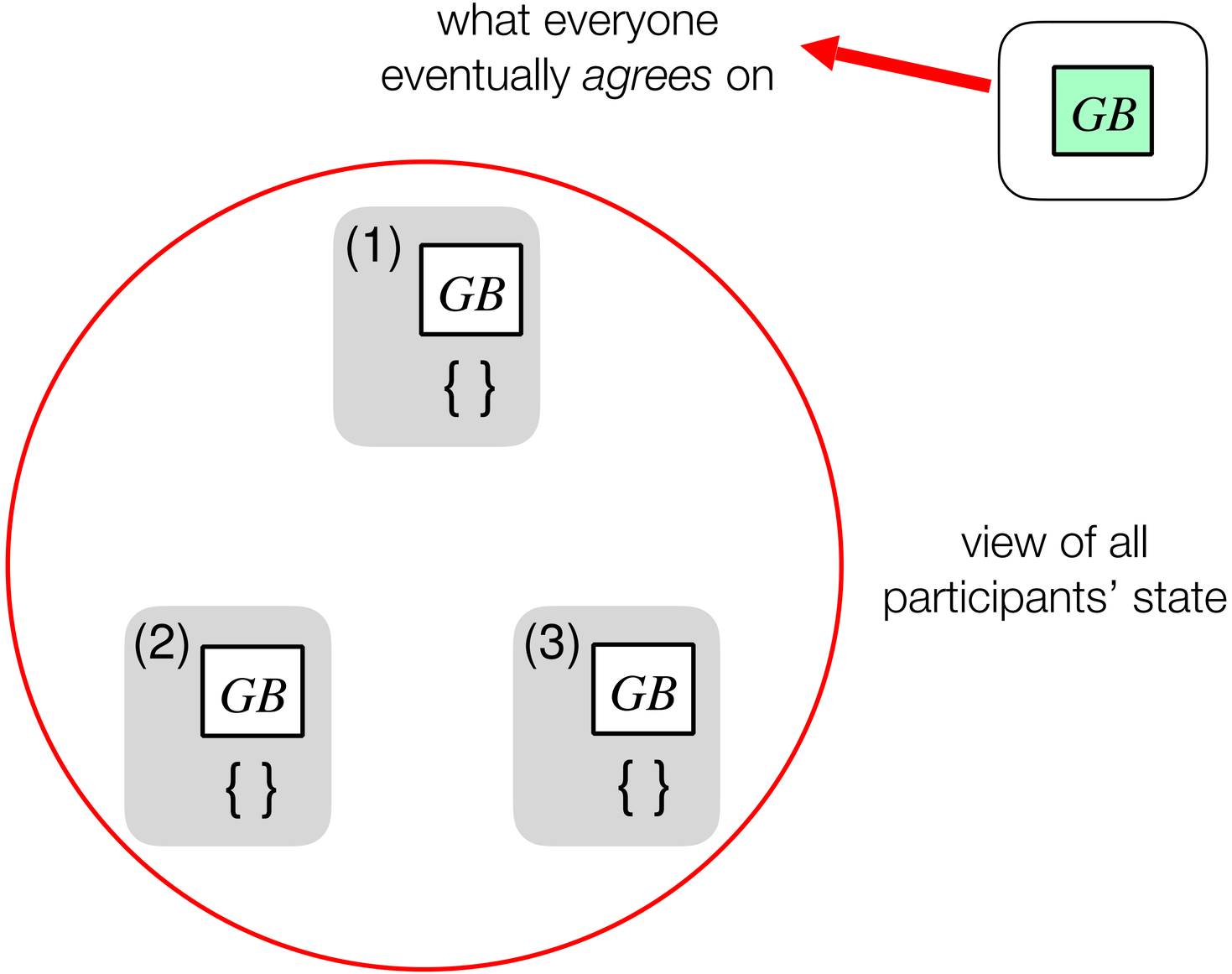
$$[] \leftarrow [tx_5, tx_3] \leftarrow [tx_4] \leftarrow [tx_1, tx_2]$$

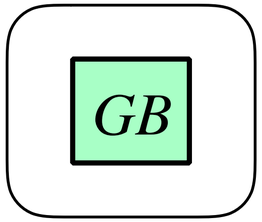
GB = genesis block

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

How blockchain protocols work

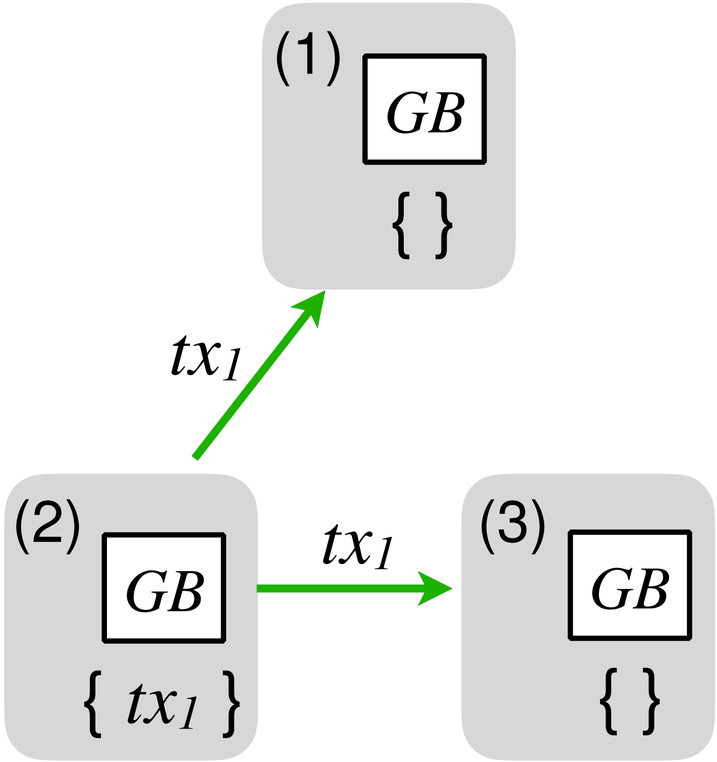
- **distributed**
  - multiple *nodes*
- all start with same GB

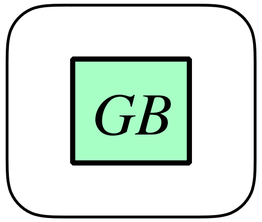




- **distributed**
  - multiple nodes
  - *message-passing* over a network

- all start with same GB





- **distributed**
  - multiple nodes
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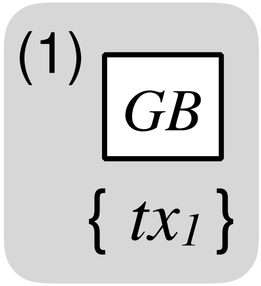
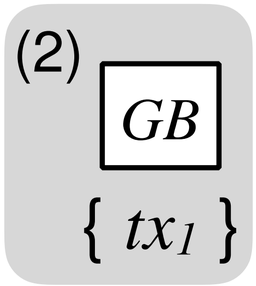
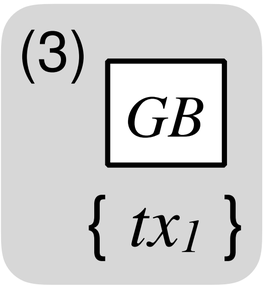


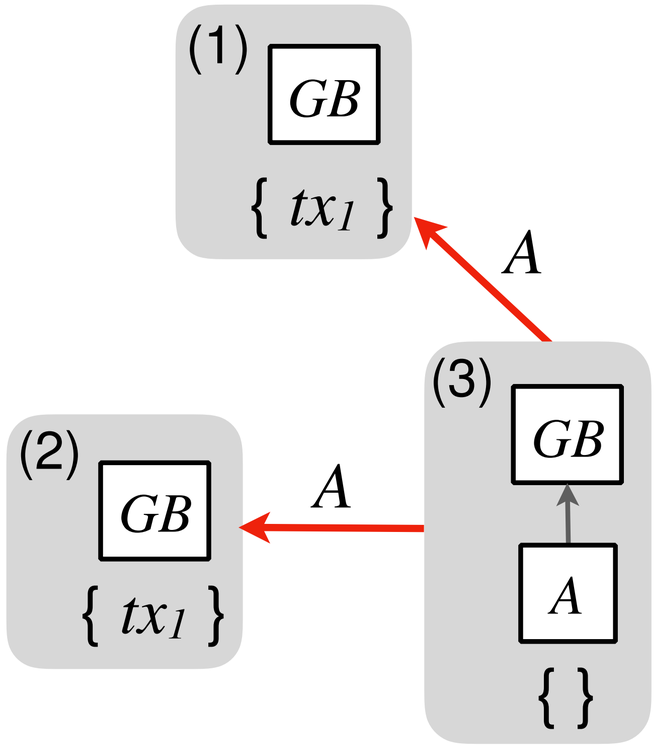
- all start with same GB
- have a transaction pool

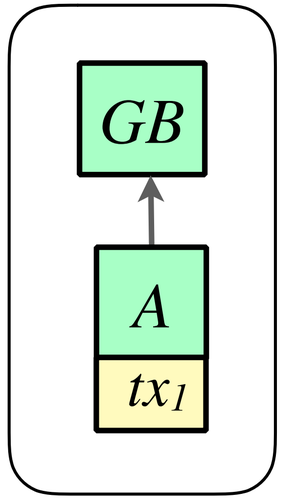




- **distributed**
  - multiple nodes
  - message-passing over a network

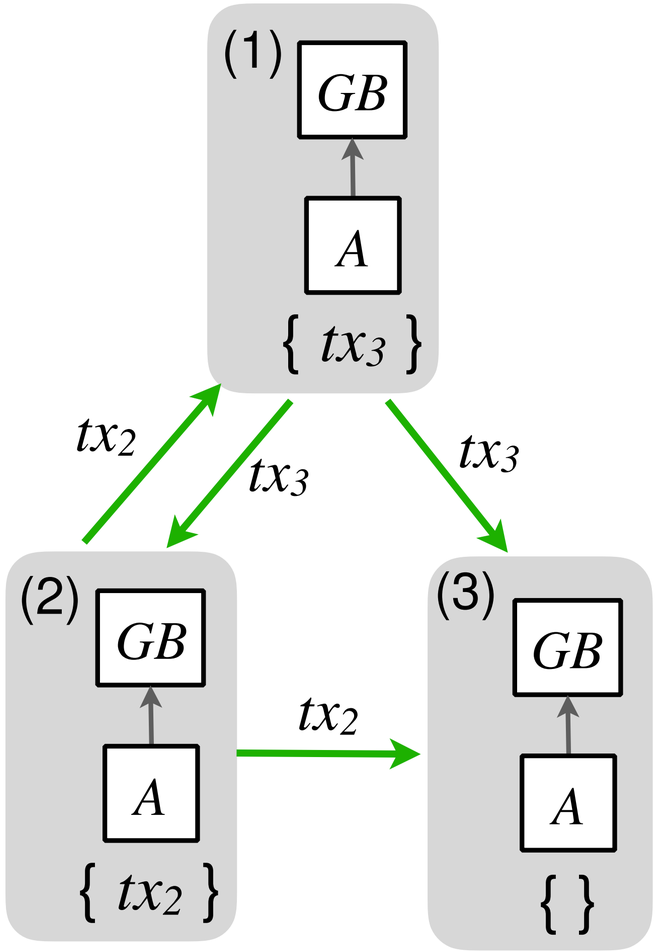
- all start with same GB
- have a transaction pool
- can *create (mint) blocks*

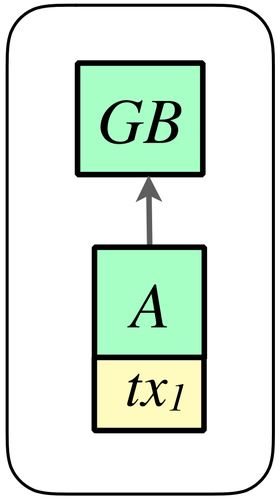




- **distributed** ⇒ *concurrent*
  - multiple nodes
  - message-passing over a network

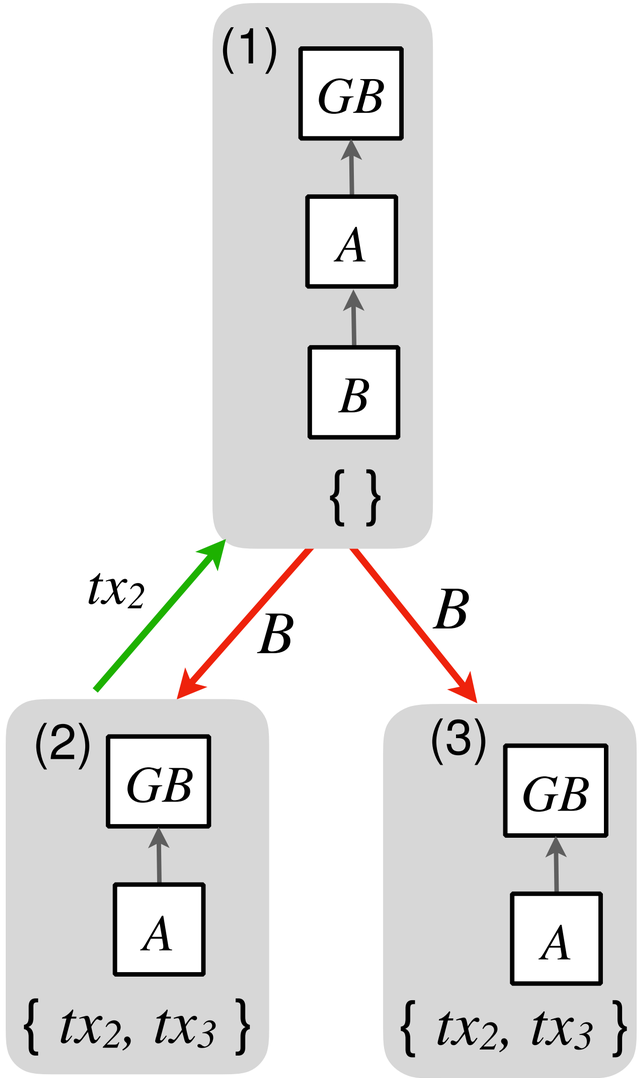
- multiple transactions can be issued and propagated *concurrently*

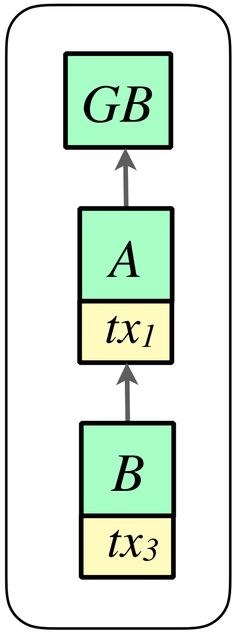




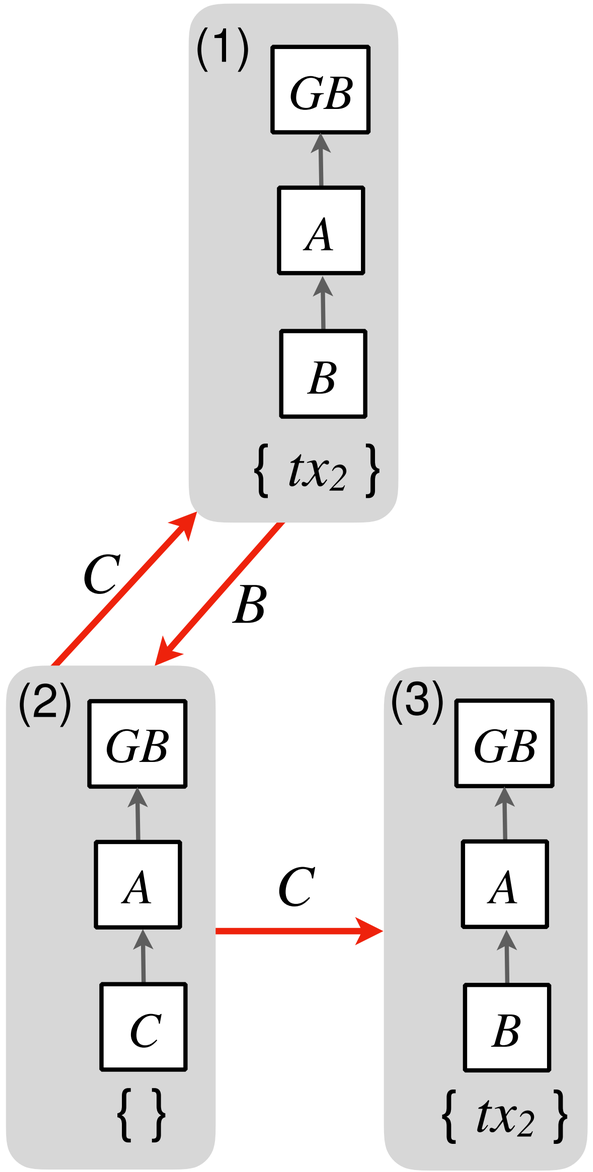
- **distributed** ⇒ *concurrent*
  - multiple nodes
  - message-passing over a network

- blocks can be created *without full knowledge* of all transactions

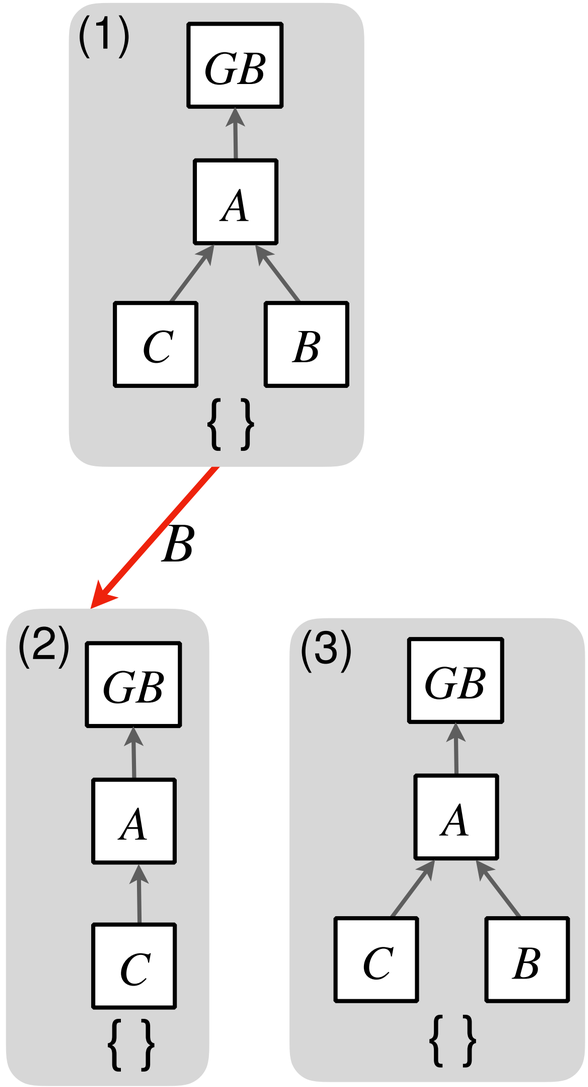




- *chain fork* has happened, but nodes don't know about it



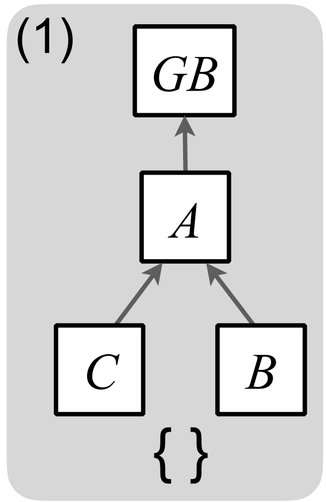
- as block messages propagate, nodes become aware of the *fork*

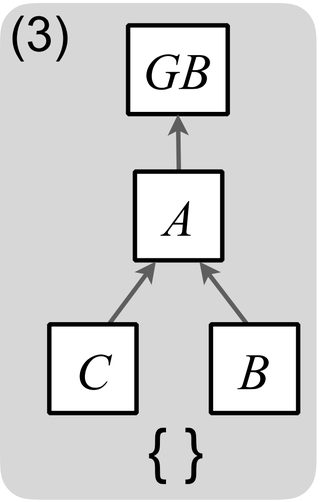


Problem: need to choose

- 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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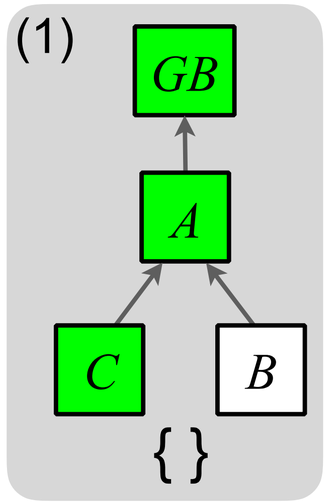

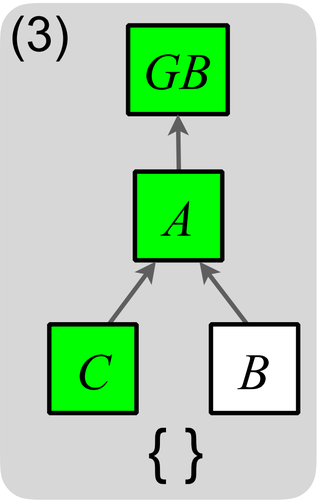

Problem: need to choose

- blockchain “promise” =
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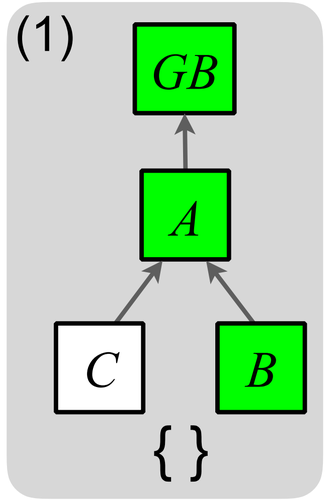

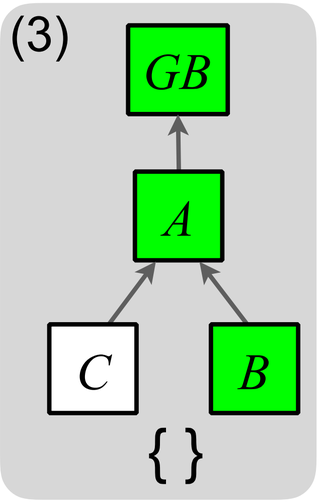

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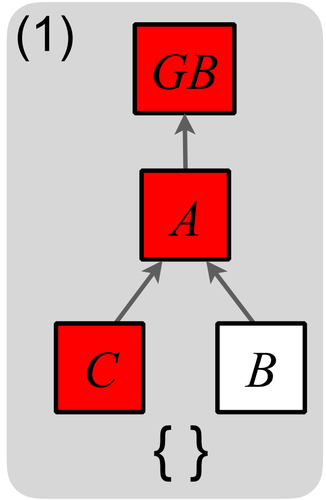
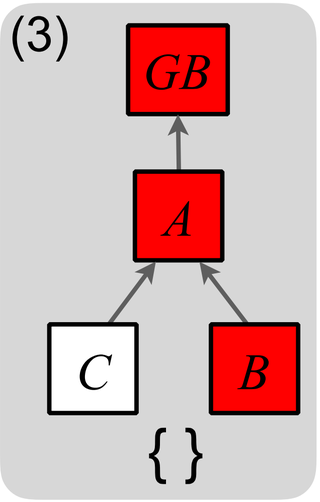




Solution: *fork choice rule*

- **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

- "Lying" to different nodes is computationally *very expensive* and *cannot* be done for *multiple subsequent blocks*

FCR (>)

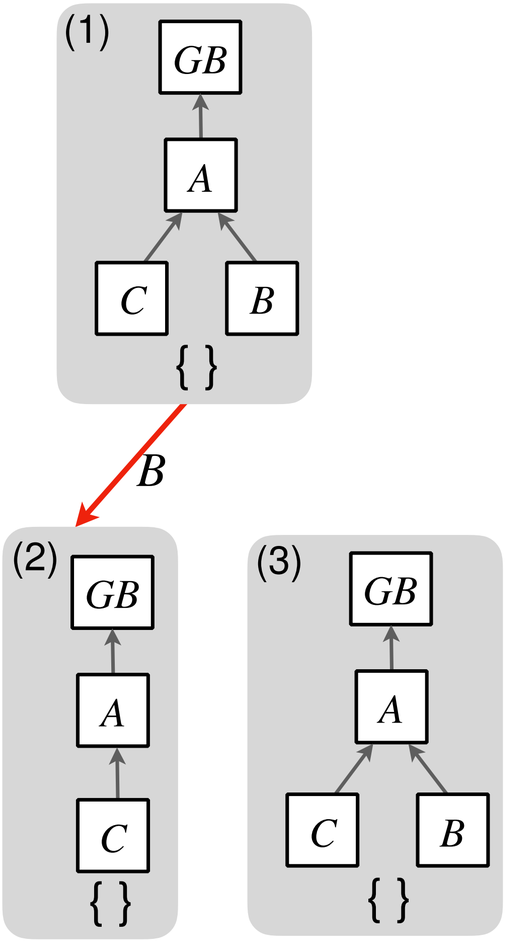
… > [GB, A, C] > … > [GB, A, B] > … > [GB, A] > … > [GB] > …

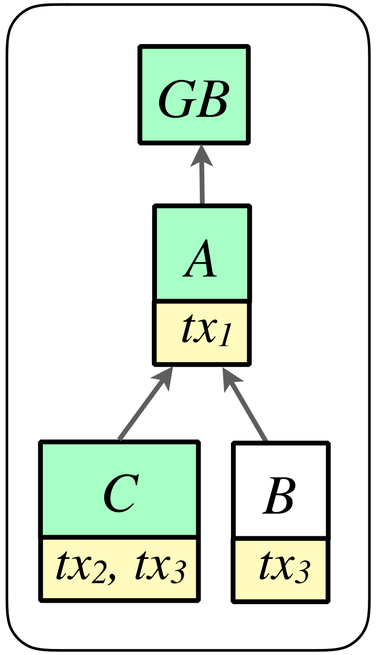
Bitcoin: FCR based on “most cumulative work”.
New blocks take *a lot of time and CPU* to create.

Quiescent consistency

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

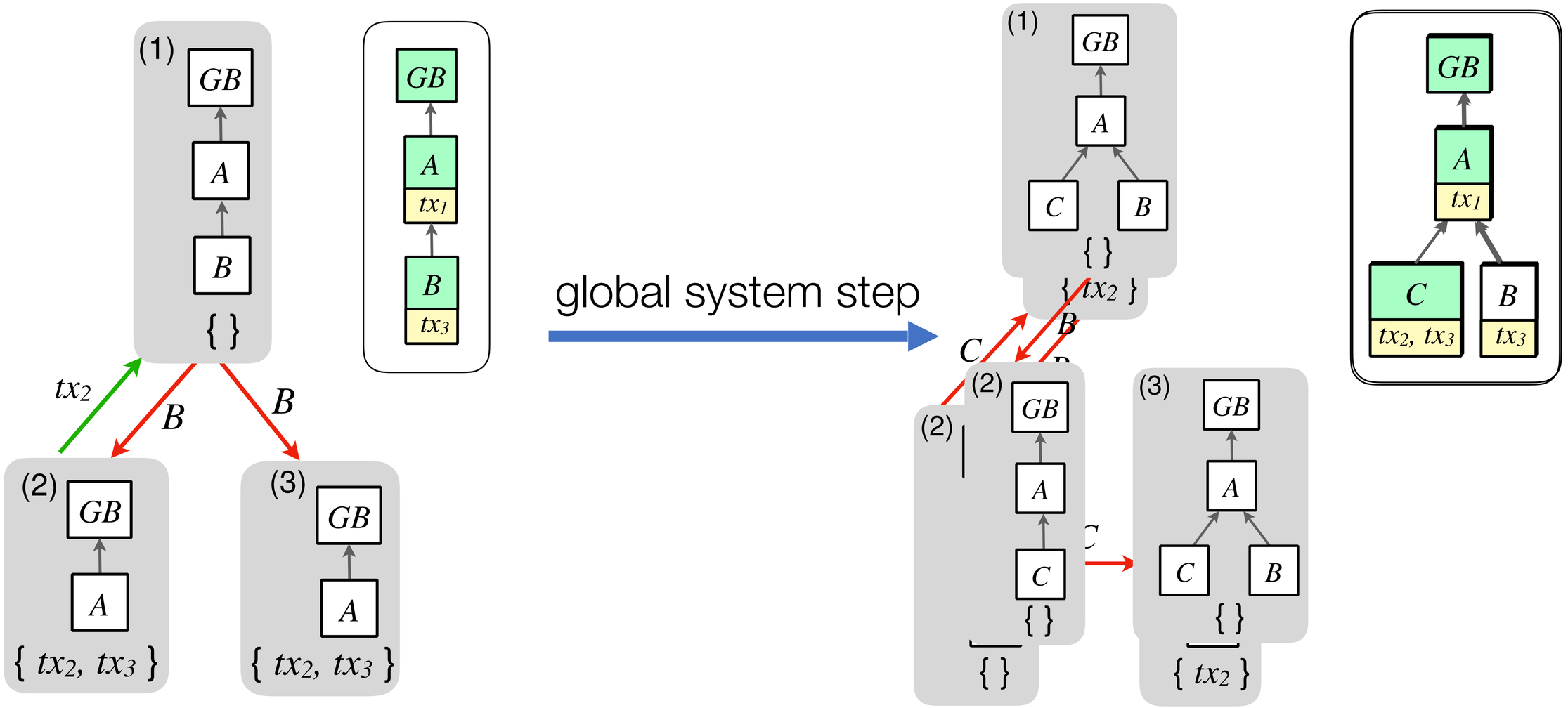
- *Quiescent Consistency*:
  when *all* block messages have been delivered, *everyone (good) agrees*



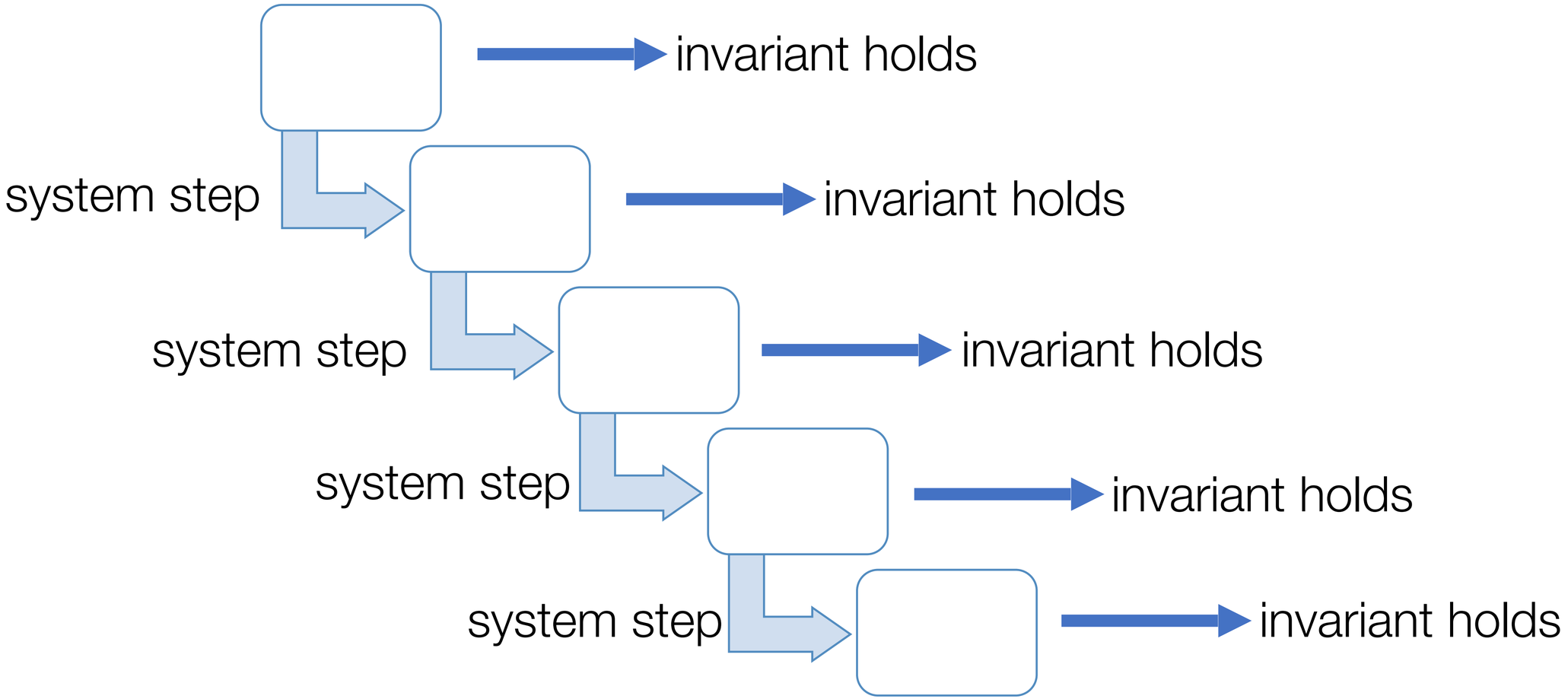


Why it works

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



Invariant is inductive



Invariant implies Quiescent Consistency

- 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 initial state* & *same FCR*

  ➢consensus

Blockchain Transactions

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

- Executed by each node *locally*, alter the *replicated* state.
- Simplest variant: *transferring funds* from ***A*** to ***B***,
  consensus: *no* double spending.
- More interesting: deploying and executing *replicated computations*

Smart Contracts

Smart Contracts

- *Stateful mutable* objects replicated via a consensus protocol
- State typically involves a stored amount of *funds/currency*
- One or more entry points: invoked *reactively* by a client *transaction*
- Main usages:
  - crowdfunding and ICO
  - multi-party accounting
  - voting and arbitration
  - puzzle-solving games with distribution of rewards
- Supporting platforms: **Ethereum**, **Tezos**, **Zilliqa**, **Concordium**, **Libra**,…

Smart Contracts are Like Concurrent Objects

```
contract Accounting {
  /* Define contract fields */
  address owner;
  mapping (address => uint) assets;

  /* This runs when the contract is executed */
  function Accounting(address _owner) {
    owner = _owner;
  }

  /* Sending funds to a contract */
  function invest() returns (string) {
    if (assets[msg.sender].initialized()) { throw; }
    assets[msg.sender] = msg.value;
    return "You have given us your money";
  }
}
```

Mutable fields

Constructor

Entry point

- `msg` argument is implicit
- funds accepted implicitly
- can be called as a function from another contract

Smart Contracts are Like Concurrent Objects

A Concurrent Perspective on Smart Contracts

Ilya Sergey[1] and Aquinas Hobor[2]

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Abstract. In this paper, we explore remarkable similarities between multi-transactional behaviors of smart contracts in cryptocurrencies such as Ethereum and classical problems of shared-memory concurrency. We examine two real-world examples from the Ethereum blockchain and analyzing how they are vulnerable to bugs that are closely reminiscent to those that often occur in traditional concurrent programs. We then elaborate on the relation between observable contract behaviors and well-studied concurrency topics, such as atomicity, interference, synchronization, and resource ownership. The described *contracts-as-concurrent-objects* analogy provides deeper understanding of potential threats for smart contracts, indicate better engineering practices, and enable applications of existing state-of-the-art formal verification techniques.

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 relies on *cryptographically signed* messages and *partial synchrony*.
- In *open* systems (blockchains), consensus can be reached via a universally accepted ***Fork-Chain-Rule***:
  - It measures the *amount of work*, while comparing two “conflicting” proposals

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YSC3248: Parallel, Concurrent and Distributed Programming

Conclusion

Concurrency is Tricky

Concurrency is Tricky

- It can be *very confusing*

Concurrency is Tricky

- It can be *very confusing*
- It takes *a lot of* time to get right
- … but we simply *cannot get away without it*
- … because we want our programs to be *fast*
- … and we want our systems to be *reliable*

We learned to *understand* concurrency and to implement it *correctly* and *efficiently*

- Amdahl's Law
- Safety, Liveness
- Programming with Threads
- Event Orderings and Mutual Exclusion
- Linearizability and Sequential Consistency
- RMW operations, consensus numbers, CAS
- Spin-locks and contention
- Monitors: waiting and signalling
- Design of concurrent objects
- Fine-grained, lazy, and optimistic locking
- Concurrent Elimination, ABA problem
- Skiplists
- Thread pools
- Data race detection
- Futures and Promises
- Data parallelism, splitters and combiners
- Actors and message-passing
- Distributed consensus protocols

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Now you know Kung Fu

Show me

The final project assignment will be posted right after this lecture

Fin