Mechanising Blockchain Consensus

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Context

- Hundreds of deployed public blockchains
- $~~600~~ ~~625~~ ~~675~~ ~~735~~ ~~755~~ ~~780~~ 820 billion total market cap

  (7 day progression since Jan 1st)

This work

- Formalised a blockchain consensus protocol in Coq

- Proved eventual consistency in a clique topology

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*

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

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

$$\downarrow$$

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

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

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

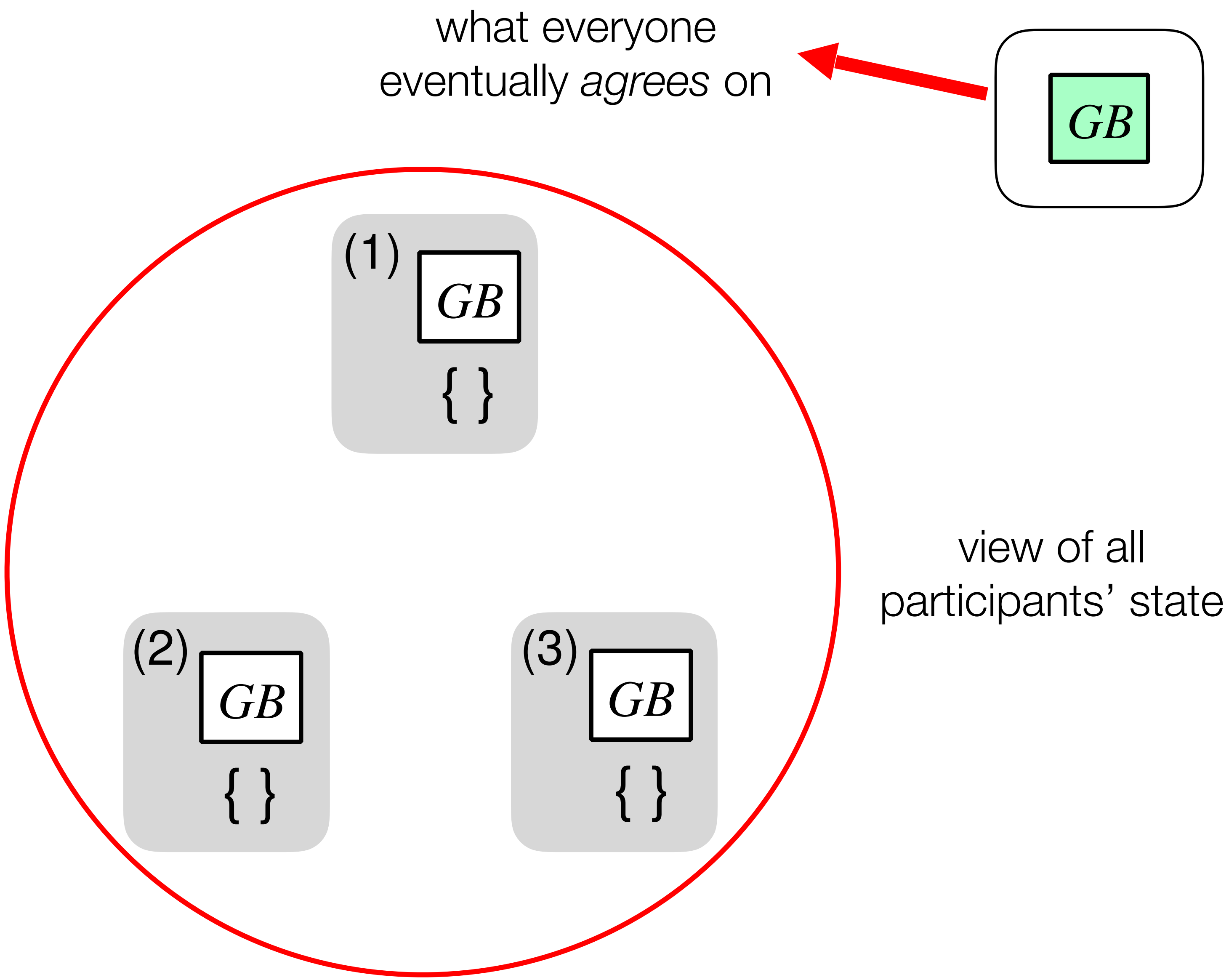
GB = genesis block

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

How it works

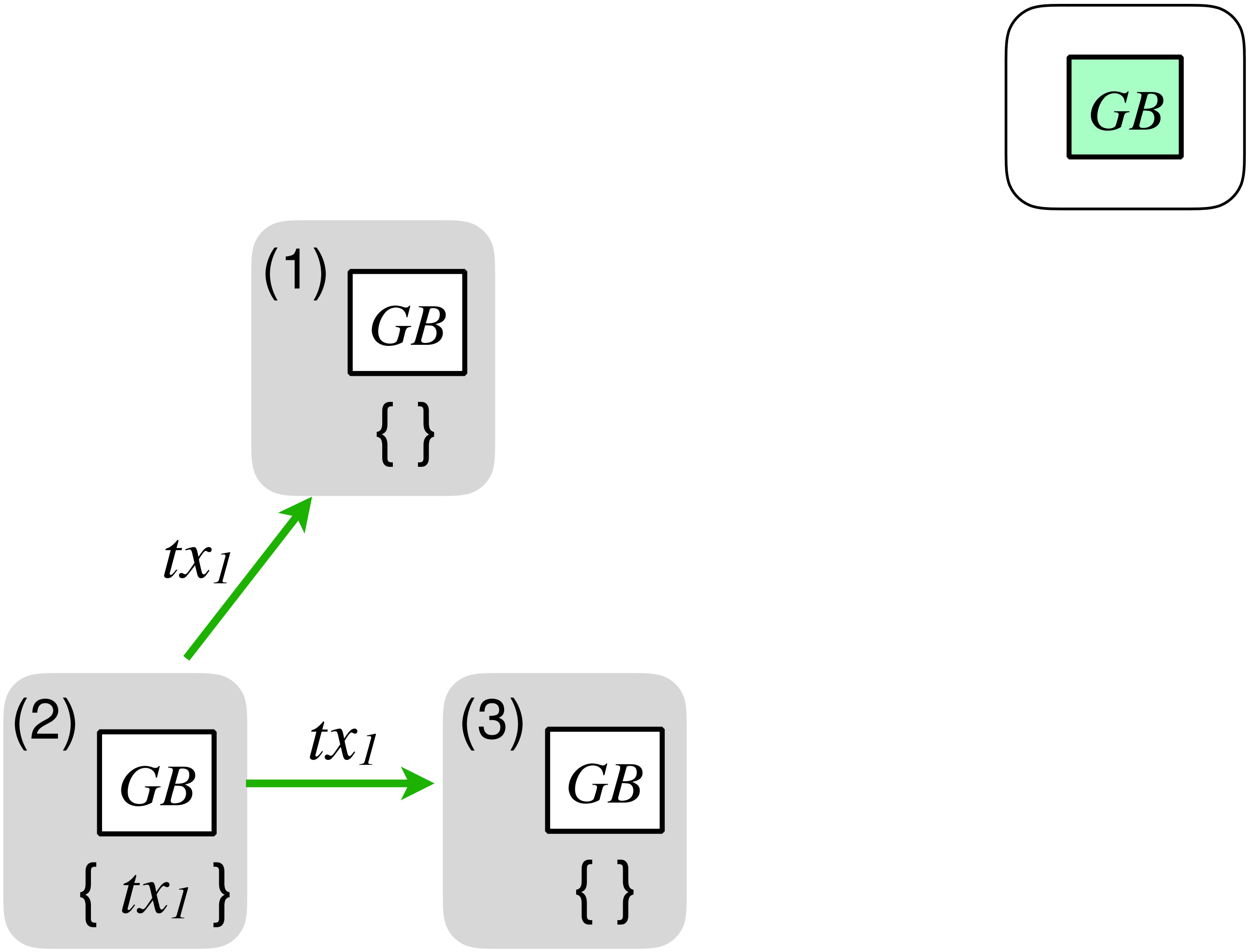
- **distributed**
  - multiple <u>nodes</u>

- all start with same GB



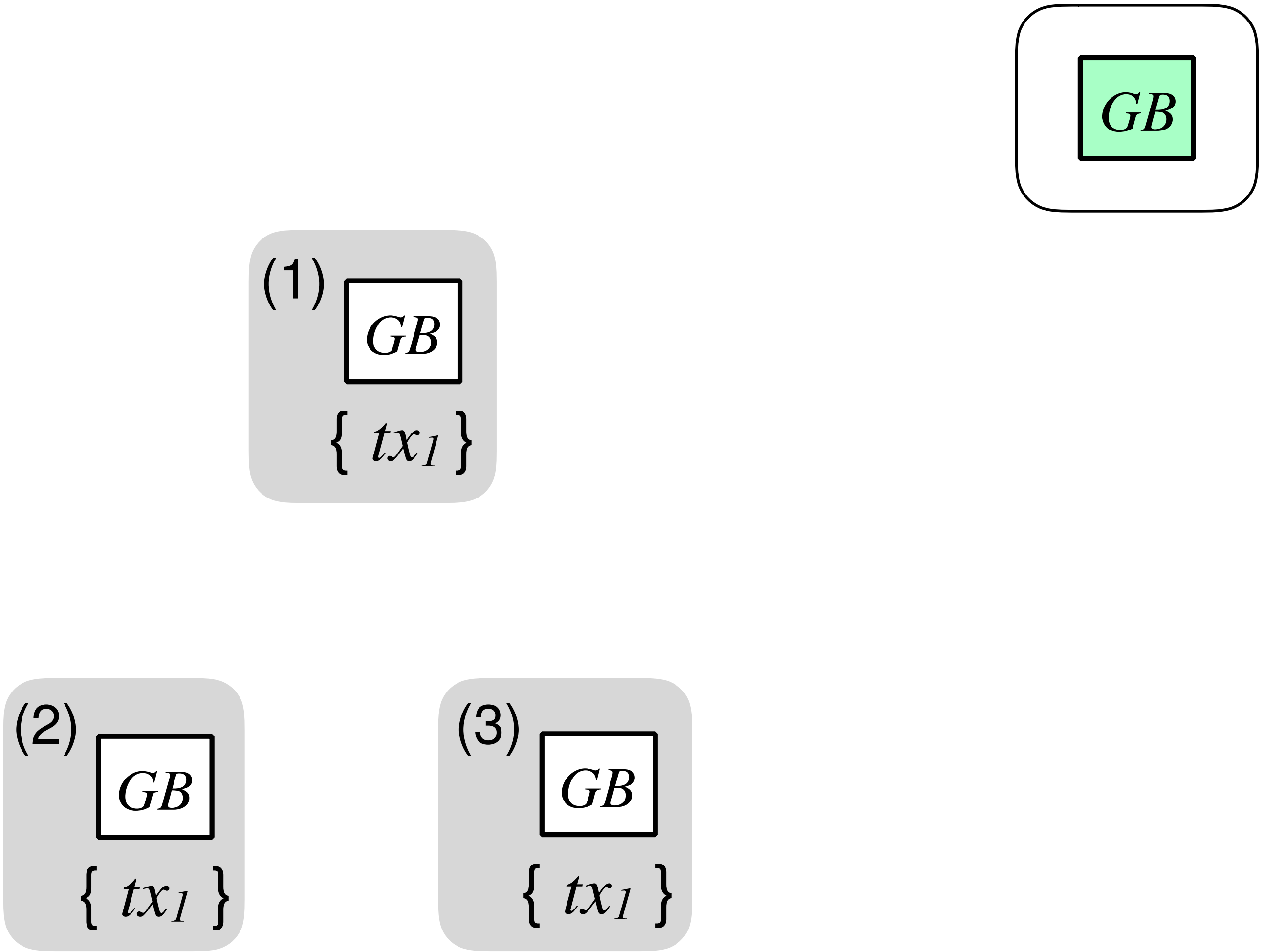
- **distributed**
  - multiple nodes
  - message-passing over a network

- all start with same GB



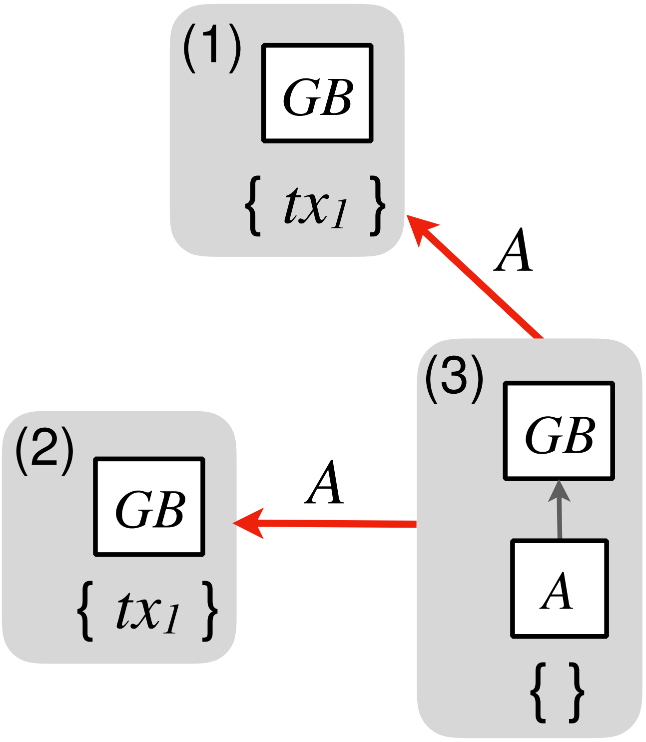
- **distributed**
  - multiple nodes
  - message-passing over a network

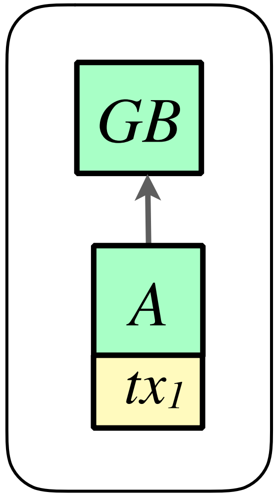
- all start with same GB
- have a transaction pool



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

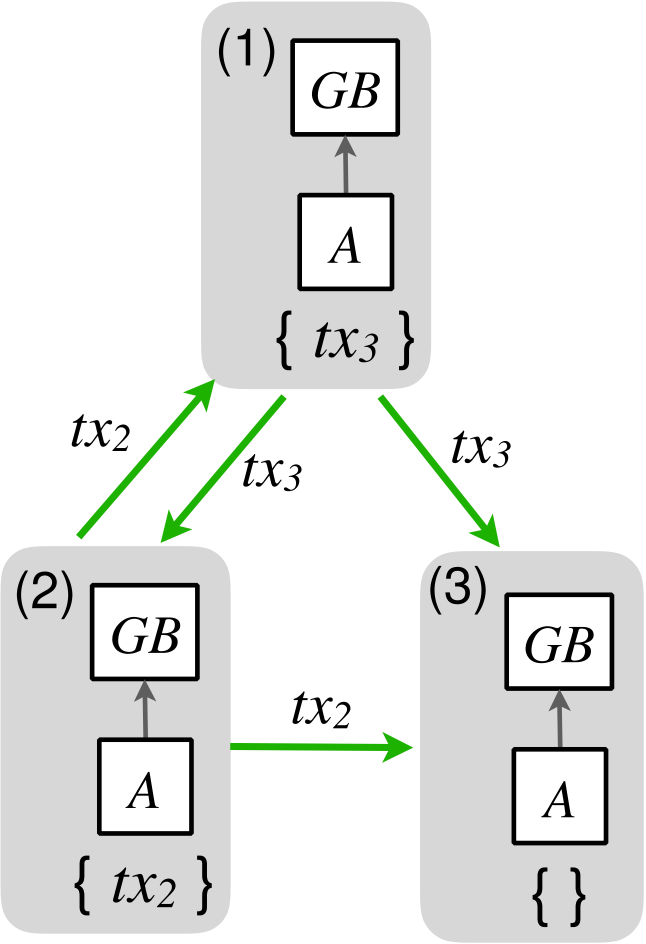
- all start with same GB
- have a transaction pool
- can <u>mint blocks</u>

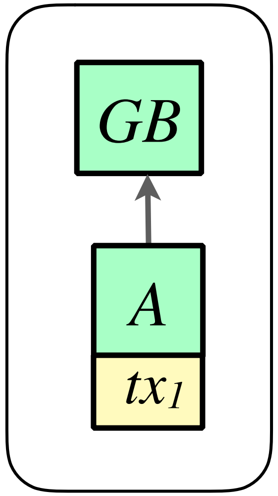




- **distributed** => <u>concurrent</u>
  - multiple nodes
  - message-passing over a network

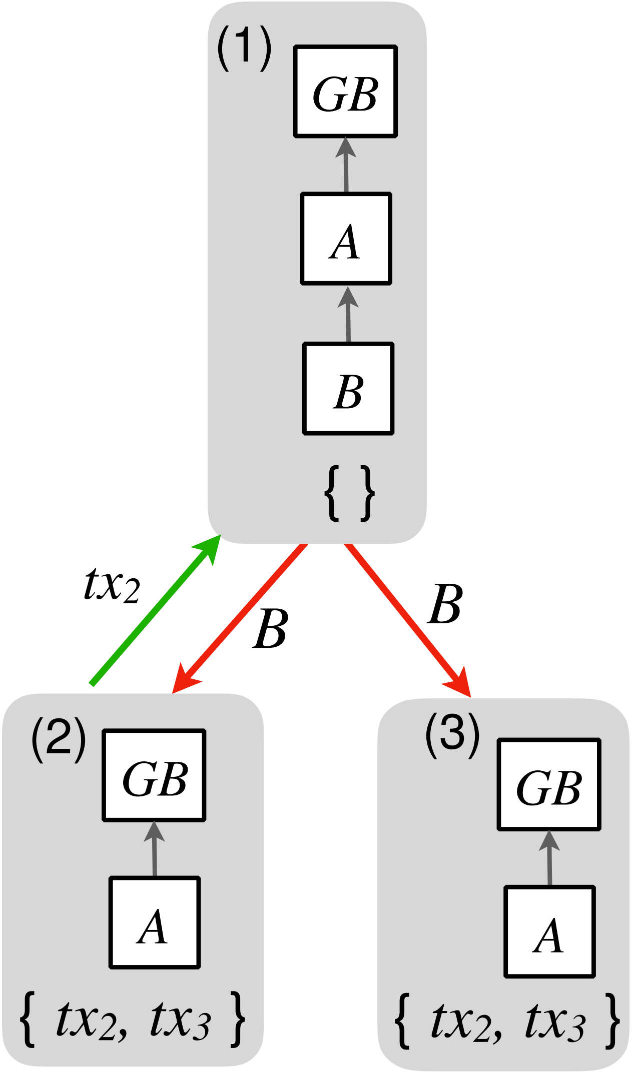
- multiple transactions can be issued and propagated concurrently

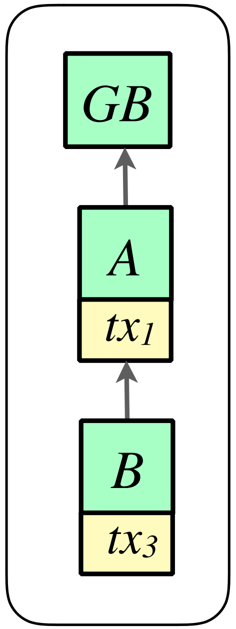




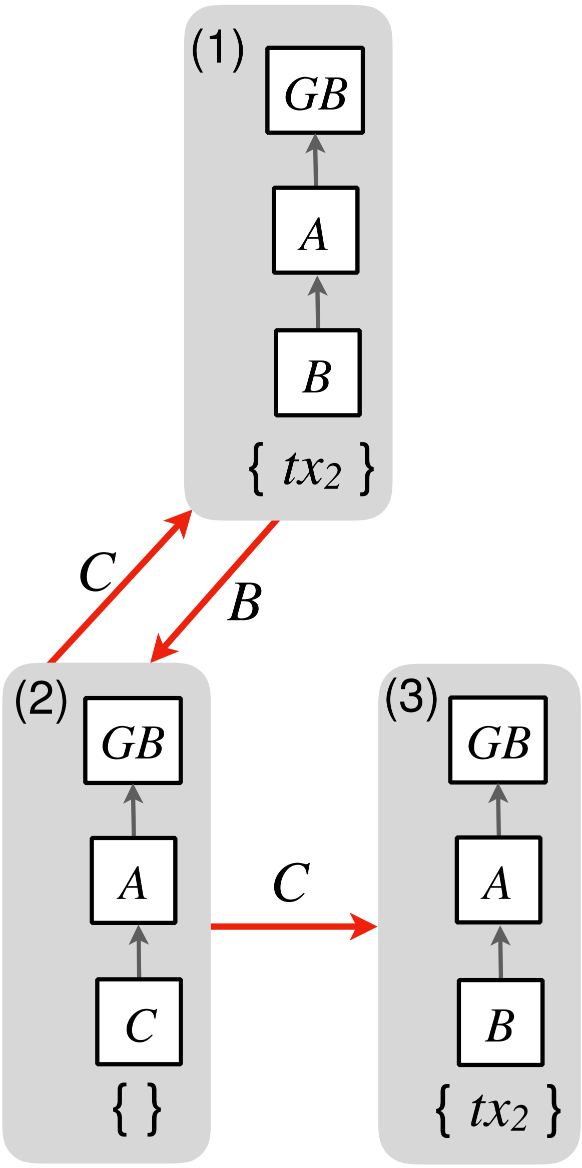
- **distributed** => <u>concurrent</u>
    - multiple nodes
    - message-passing over a network

- blocks can be minted without full knowledge of all transactions

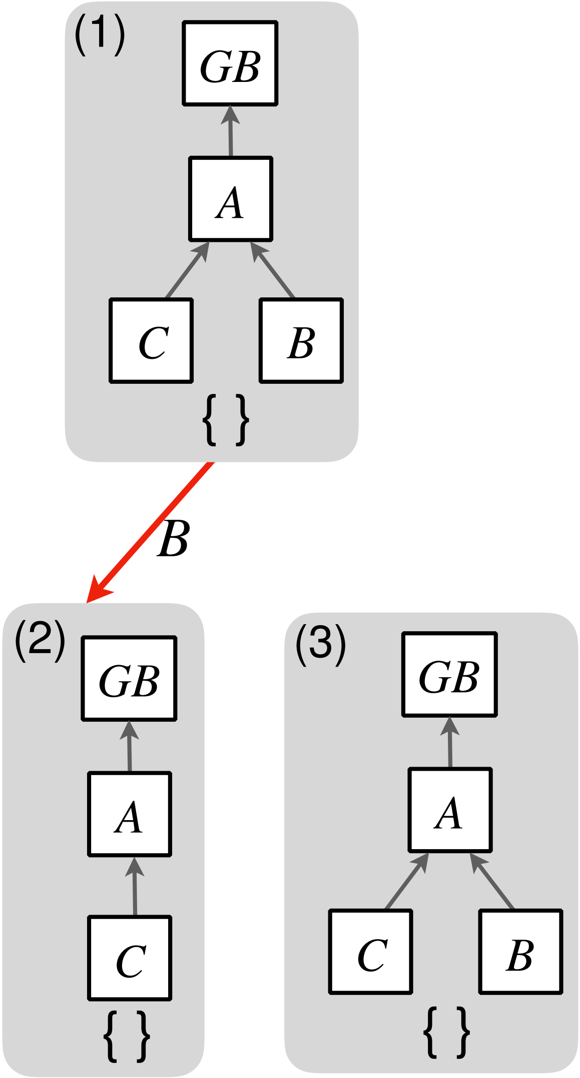




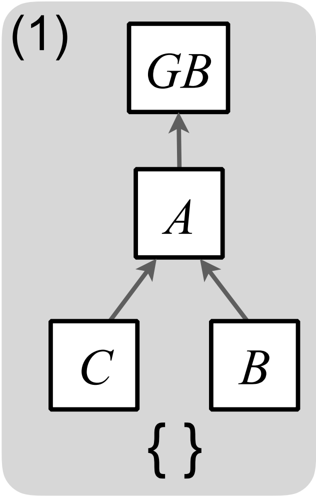
- <u>chain fork</u> has happened, but nodes don't know



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

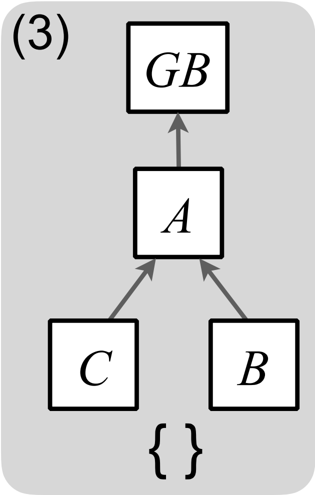


Problem: need to choose



- 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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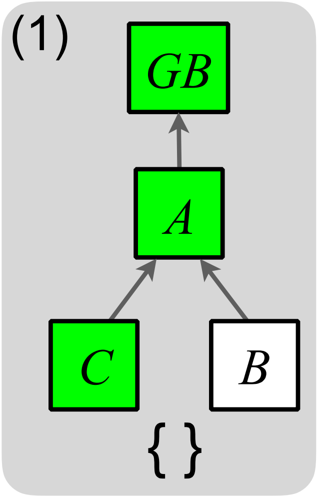

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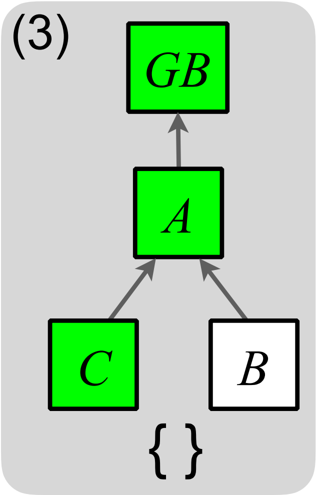

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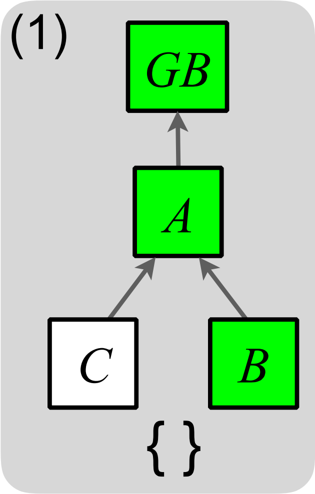

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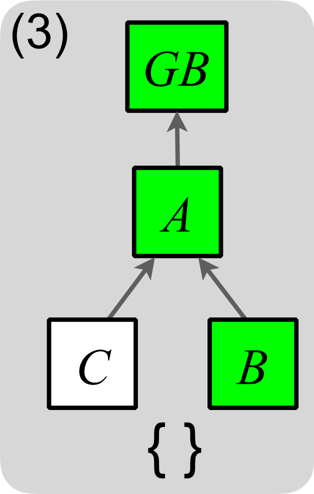

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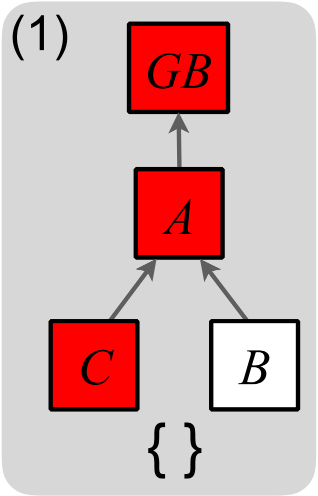

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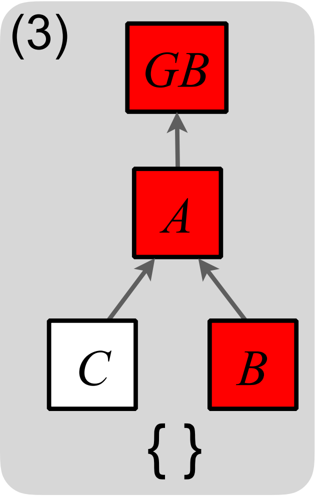
  - each node must choose <u>one</u> chain
  - nodes with the same information must choose <u>the same</u> chain



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 (>)

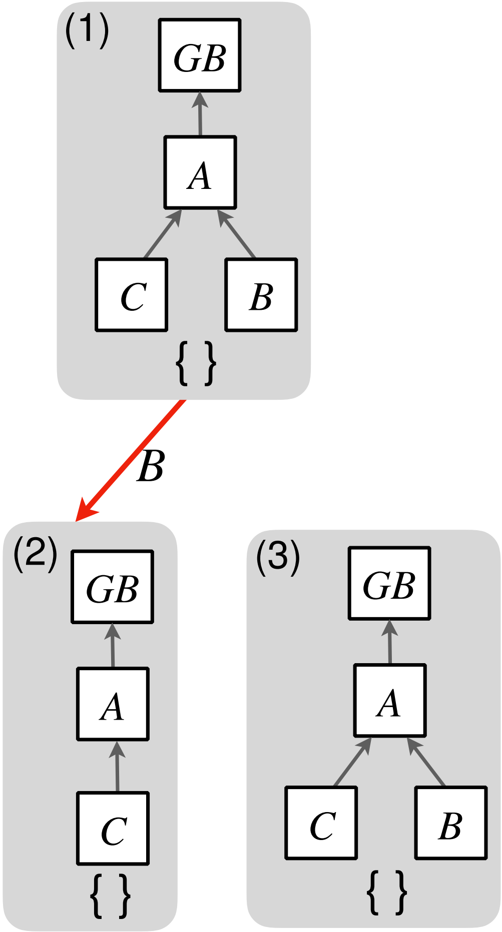
… > [GB, A, C] > … > [GB, A, B] > … > [GB, A] > … > [GB] > …

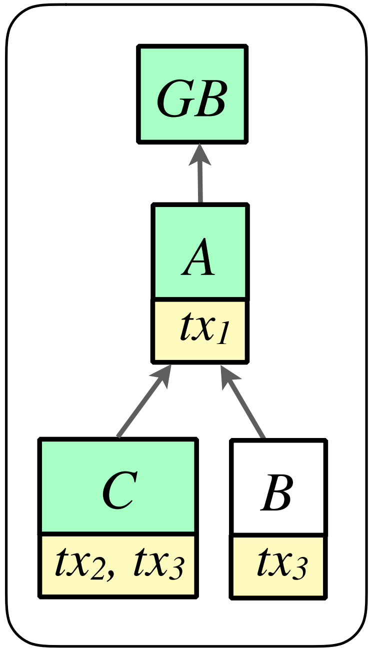
Bitcoin: FCR based on “most cumulative work”

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

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

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

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

$$GB : \mathrm{Block}$$

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

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

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

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

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

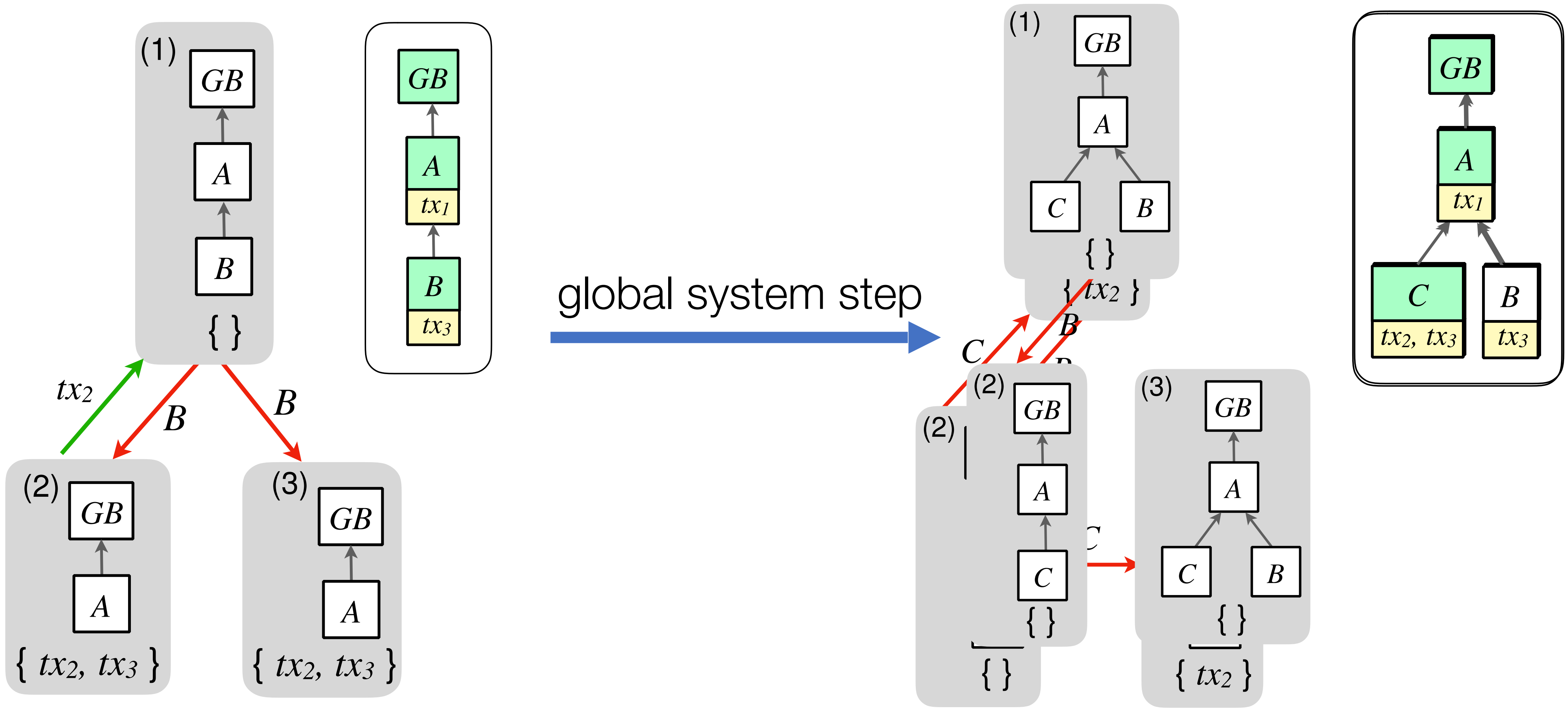
- FCR imposes a *strict total order* on all blockchains

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

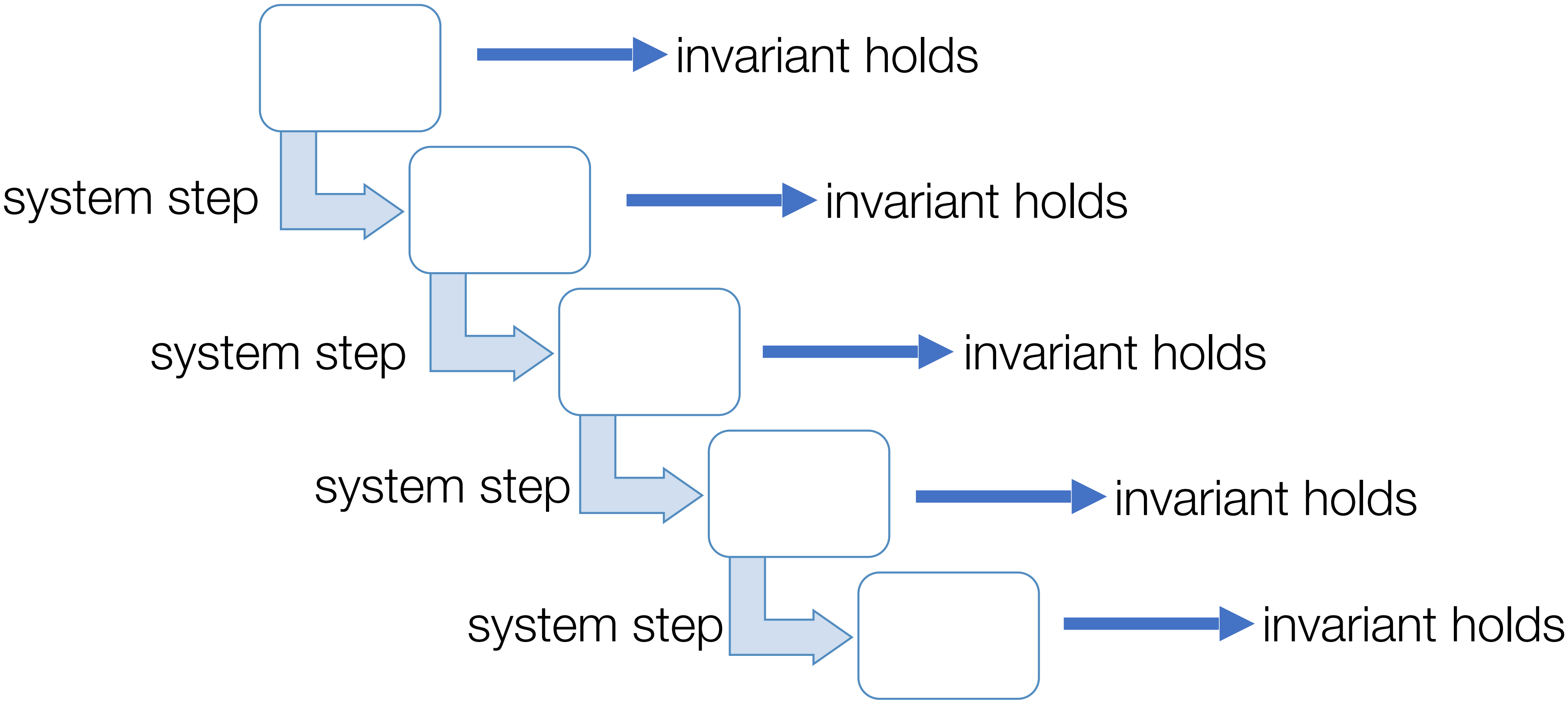
$$FCR\_trans \quad : \forall c_1\ c_2\ c_3, c_1 > c_2 \land c_2 > c_3 \implies c_1 > c_3$$

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

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 of block forests
- Per-node protocol logic
- Network semantics
- Clique invariant, QC property, various theorems

https://github.com/certichain/toychain

Future work

- Network semantics with nodes joining/leaving at will
- Improved invariants:
  - non-clique topologies
  - network partitions
  - Byzantine faults
- Verified smart contracts platform

Take away

- Formalisation of a blockchain consensus protocol in Coq:
  - minimal set of required security primitives
  - per-node protocol logic & data structures
  - network semantics

  - global eventual consistency in a clique topology

https://github.com/certichain/toychain