

Blockchain and Distributed Ledgers

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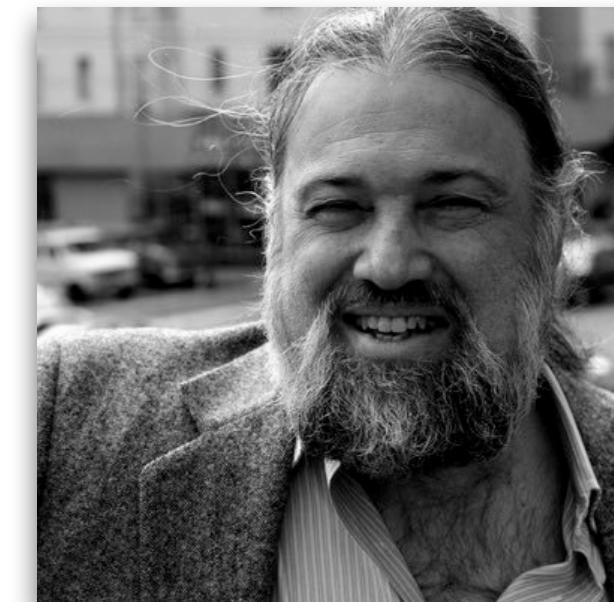
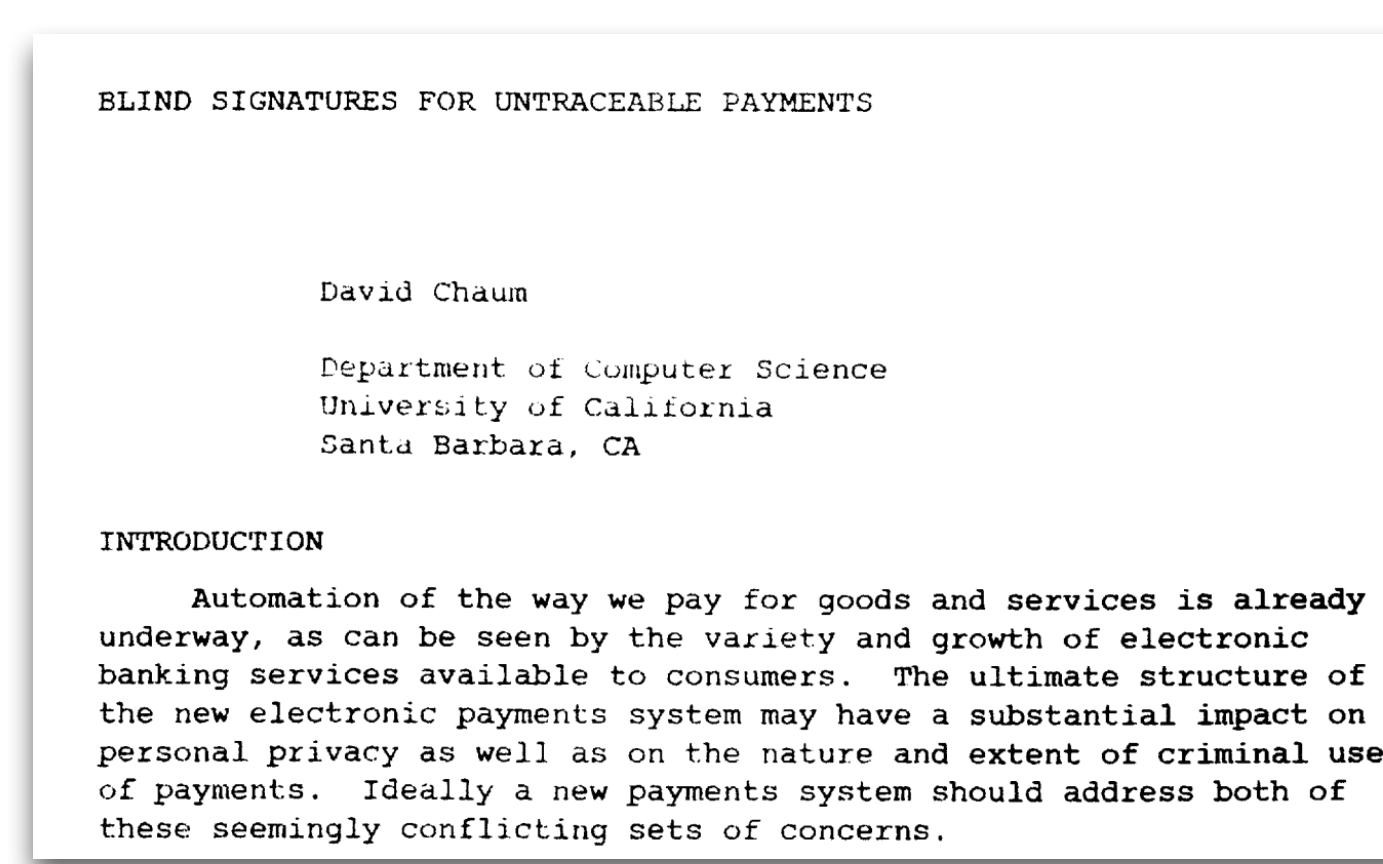
Course topics

- The **origins** of Blockchain
- What are the **cryptographic building blocks** of a blockchain?
- How does a blockchain process transactions? **Life of a blockchain transaction.**
- **Consensus** in blockchain networks: Proof-of-Work, Proof-of-Stake, BFT Consensus
- **Permissioned** versus **Permissionless** blockchain networks
- Blockchains as trusted computers: **smart contracts** and **Ethereum**
- Building **decentralized applications** using blockchains
- **Conclusion** and latest trends

Blockchain: origins

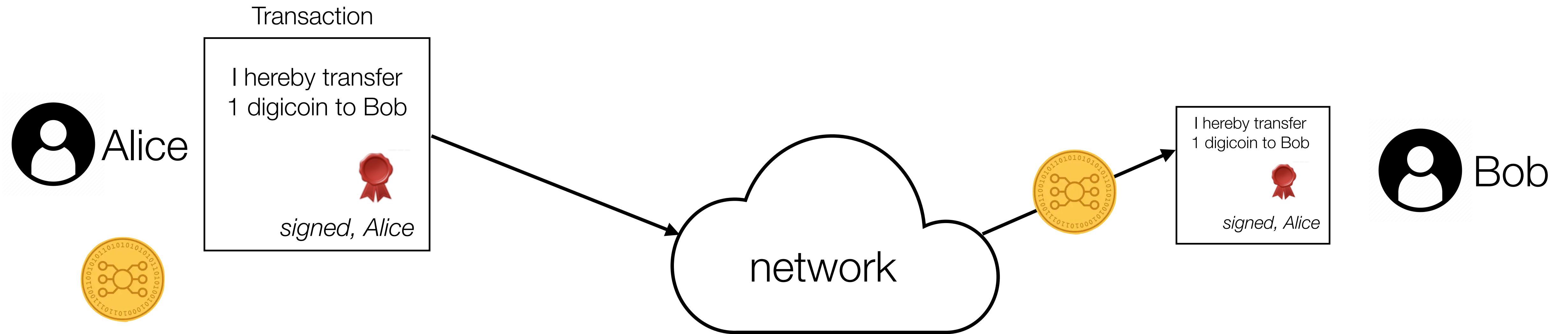
Electronic cash

- Since the dawn of the Internet, cryptographers have tried to create digital currencies that are more similar to physical cash or coins
- Money as a “bearer instrument” token: whoever holds the token can spend it
- Payments are anonymous and untraceable
- Example: e-cash (Digicash)

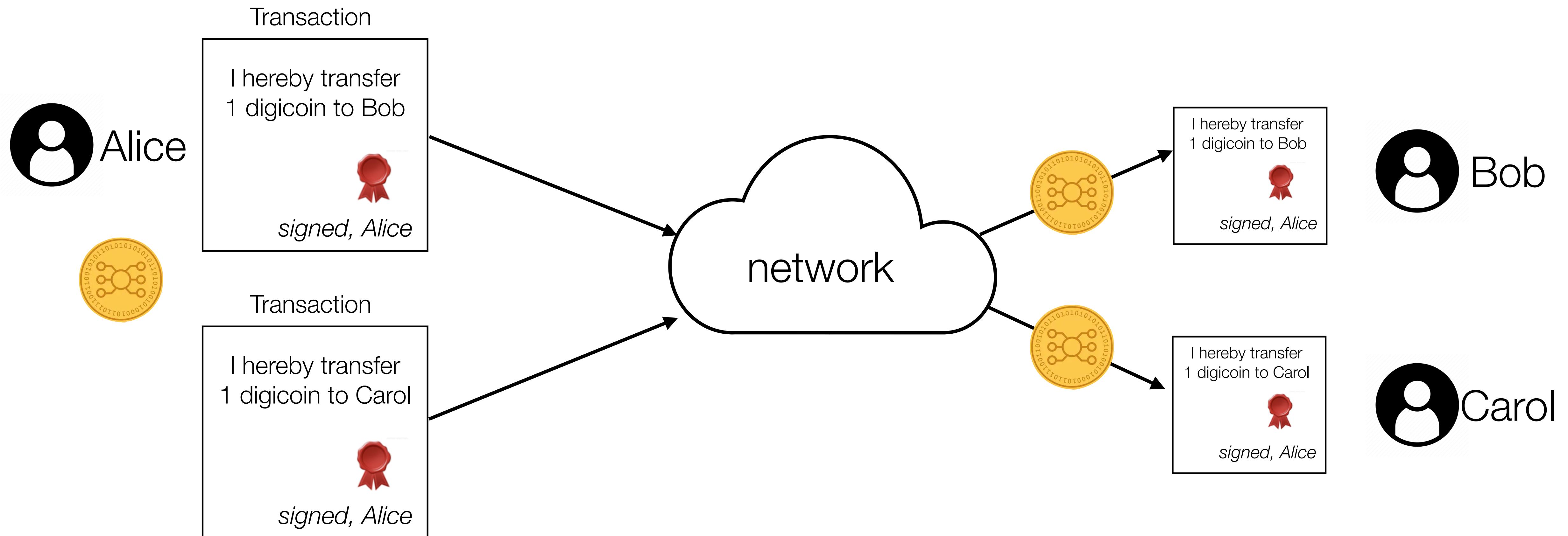


David Chaum
Electronic cash (1982)

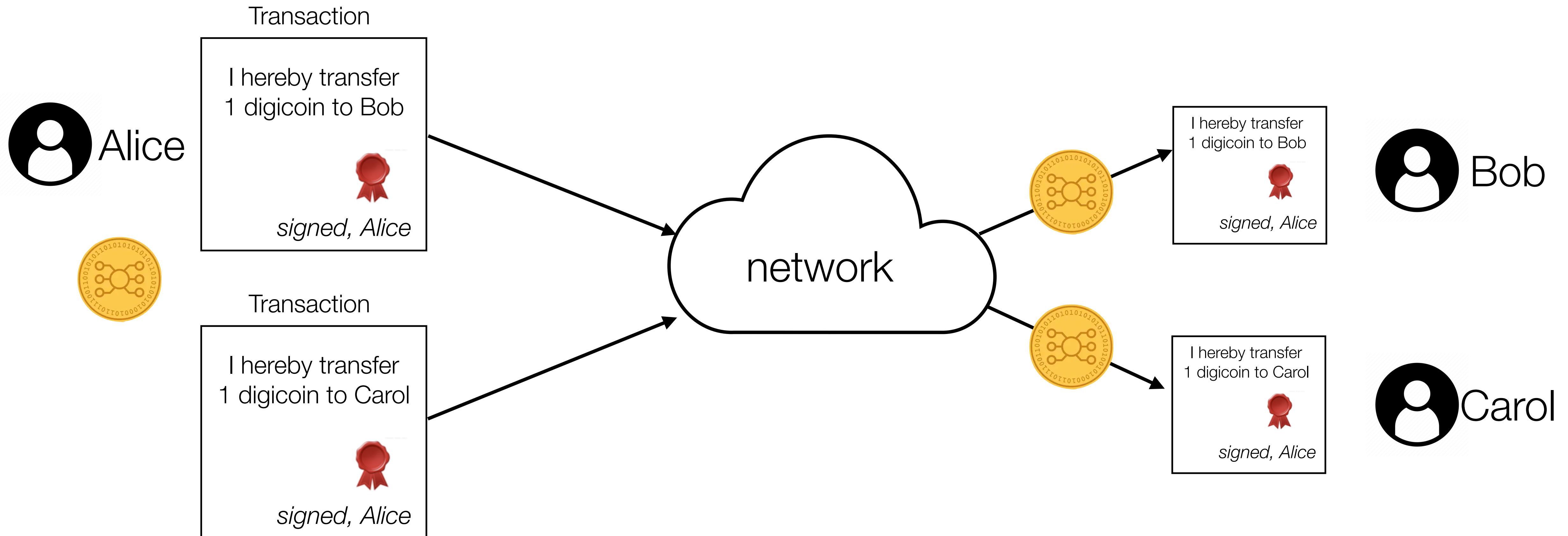
The problem with electronic cash: the Double Spending Problem



The problem with electronic cash: the Double Spending Problem



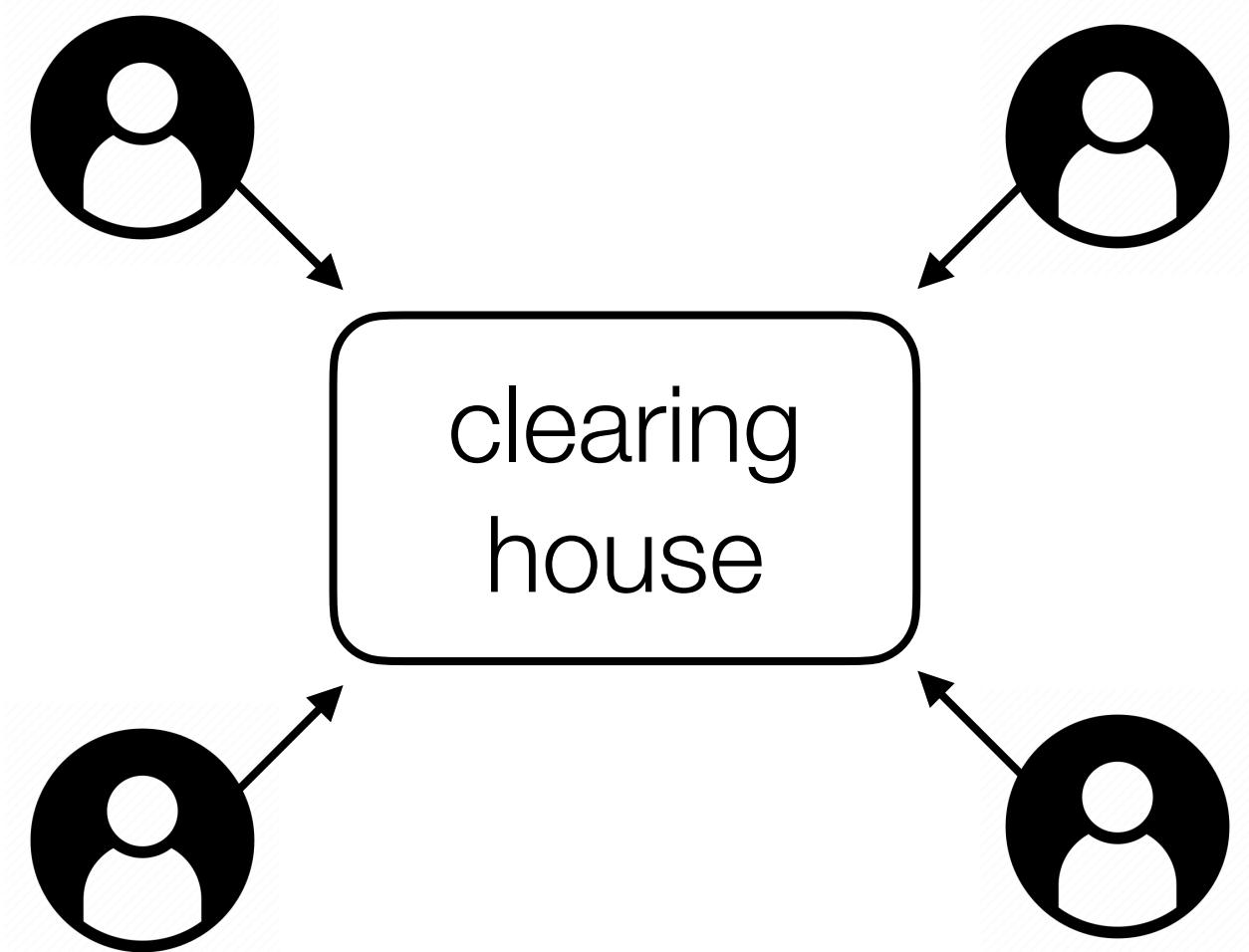
The problem with electronic cash: the Double Spending Problem



How can Bob and Carol be sure they are now the sole owner of Alice's coin?

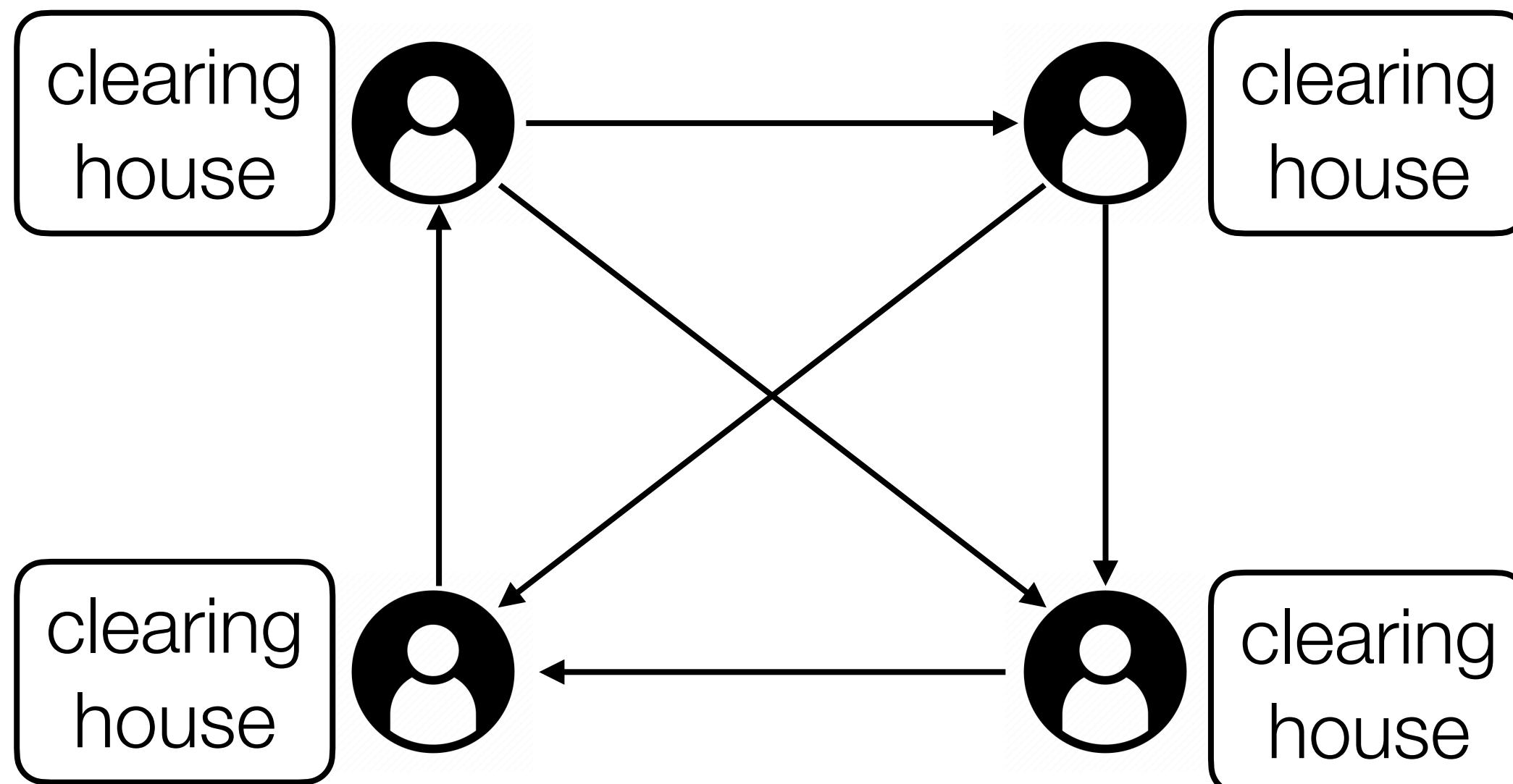
Straightforward solution: use a central clearing house

- The clearing house does the accounting of what tokens have already been spent. This **avoids “double spending”** the same token.
- The payments themselves can still be **anonymous**! We just need to record spent tokens. Privacy risks partially mitigated using blind signatures.
- Problem: everyone depends on the clearing house. **Risks:**
 - **Technical** risks: availability (what if the clearing house is unavailable?) and security (what if the clearing house gets attacked? This may include insider threats!)
 - **Economic** and **political** risks: what if the company running the clearing house goes bankrupt or is threatened in court? (E.g. Digicash actually went bankrupt in 1998)

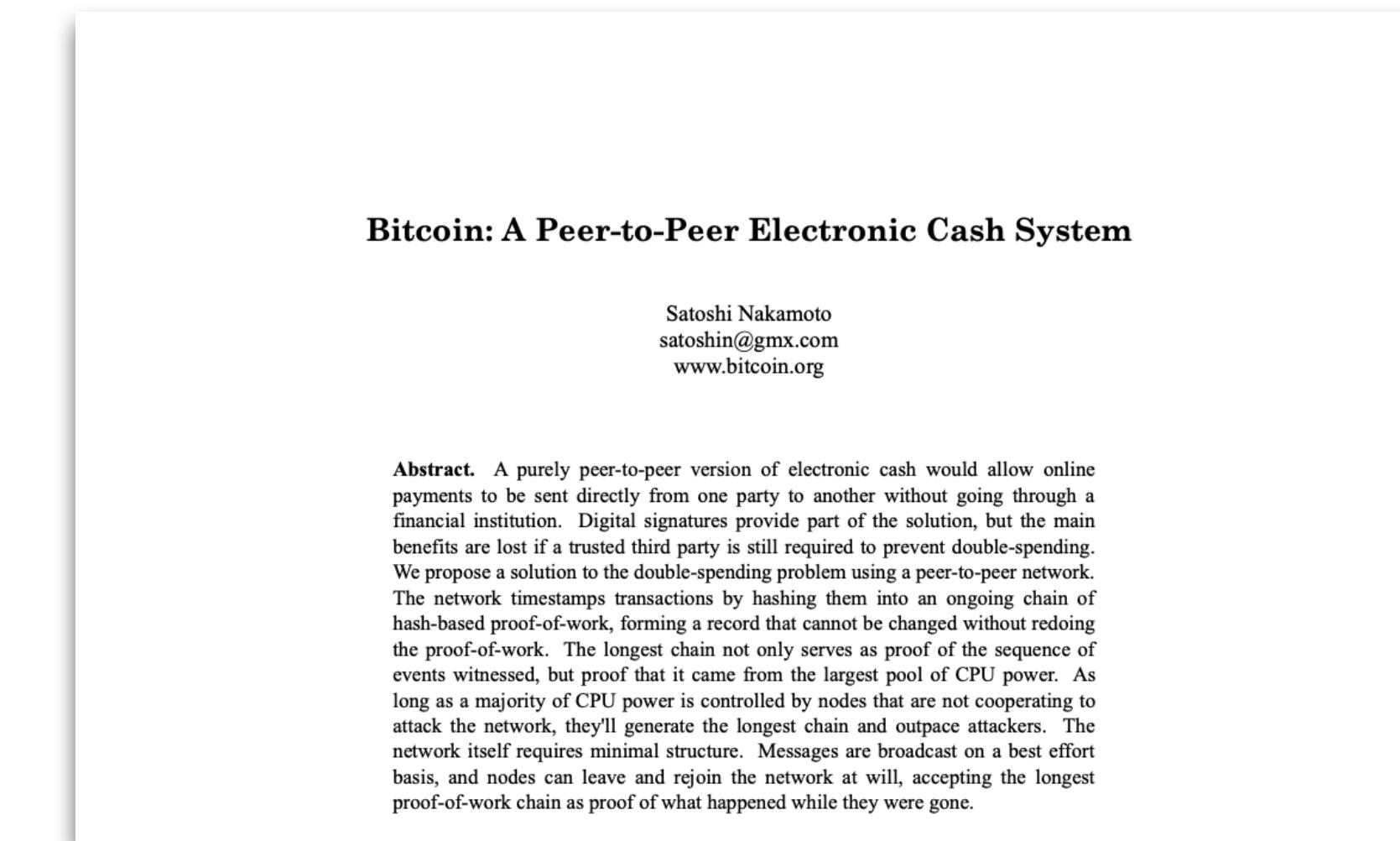


Blockchain networks

- Bitcoin's breakthrough idea: rather than having a single party record who owns what, let everyone collectively do the accounting of who owns what
- Store account balances in an append-only **replicated database** called a **blockchain**



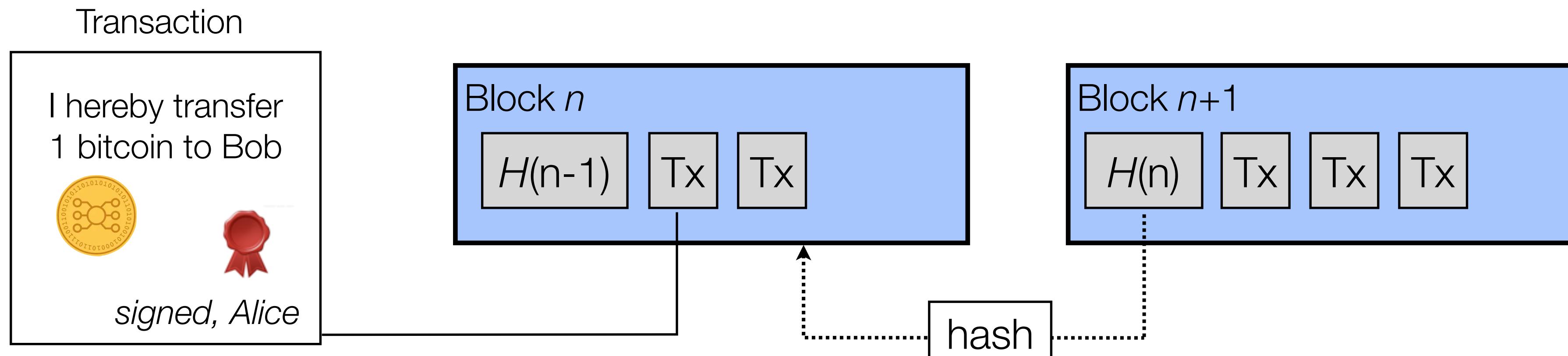
Fully decentralised
payment network



The “Bitcoin whitepaper”
by “Satoshi Nakamoto”, 2009

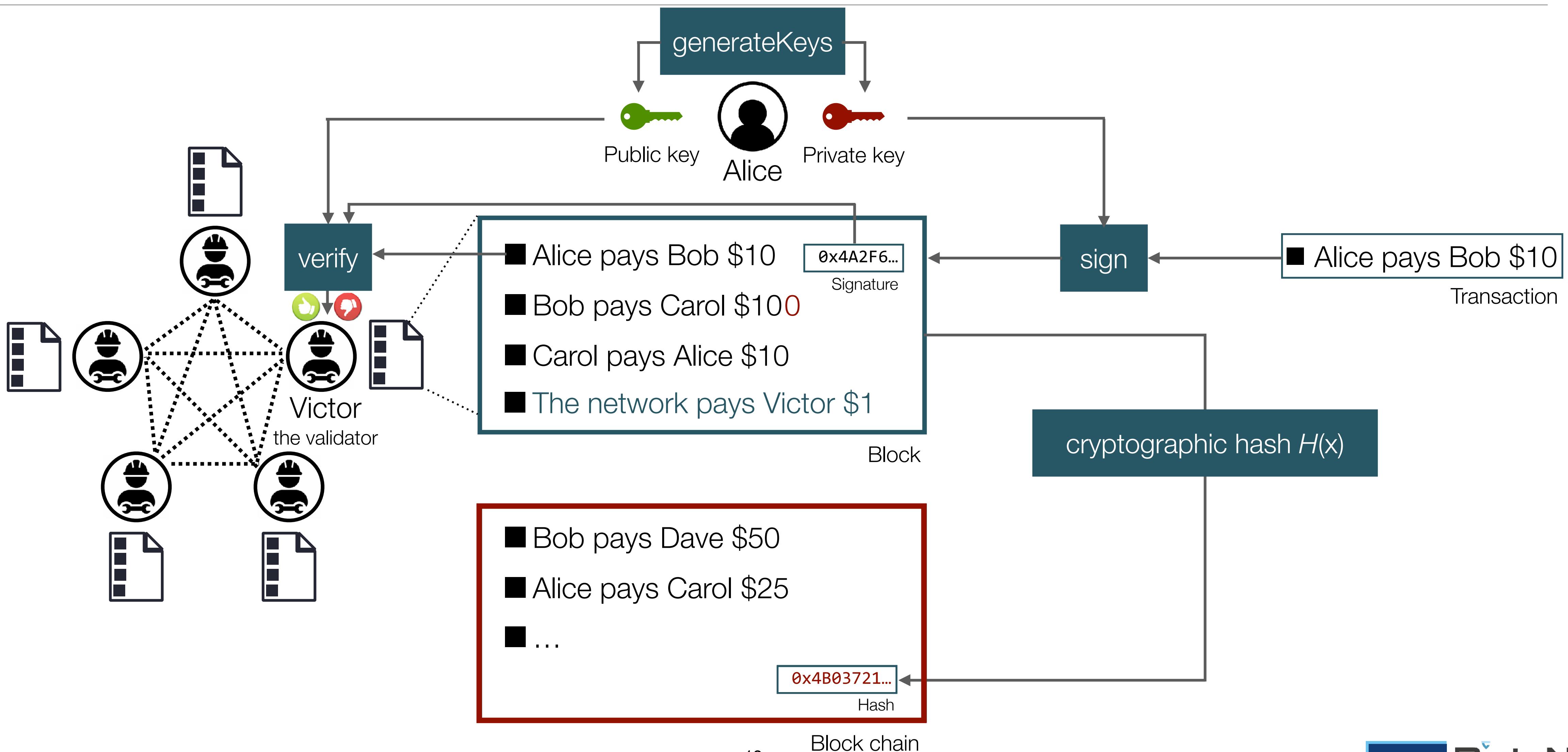
Bitcoin's blockchain

- Replace central clearing house by a **public, replicated, append-only, tamper-resistant ledger**
- Validator nodes group transactions in “blocks”, “chained” together into **a linear sequence** using cryptographic hashes, secured using “Proof of Work”



What are the cryptographic building blocks of a blockchain?

How cryptography is used to securely record transactions on a blockchain

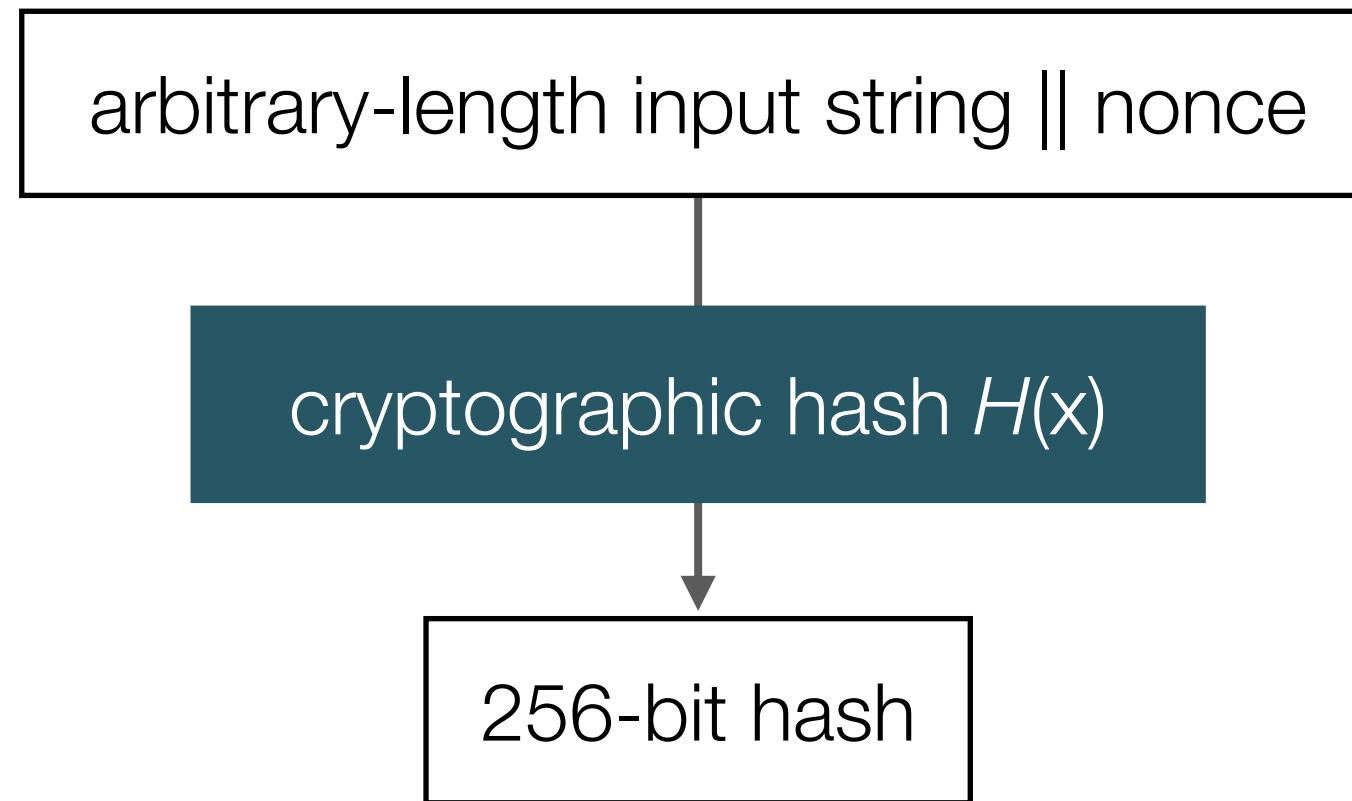


Common cryptographic algorithms used in blockchain systems

Cryptographic hashes

SHA-256 or KECCAK-256

Secure hash algorithm



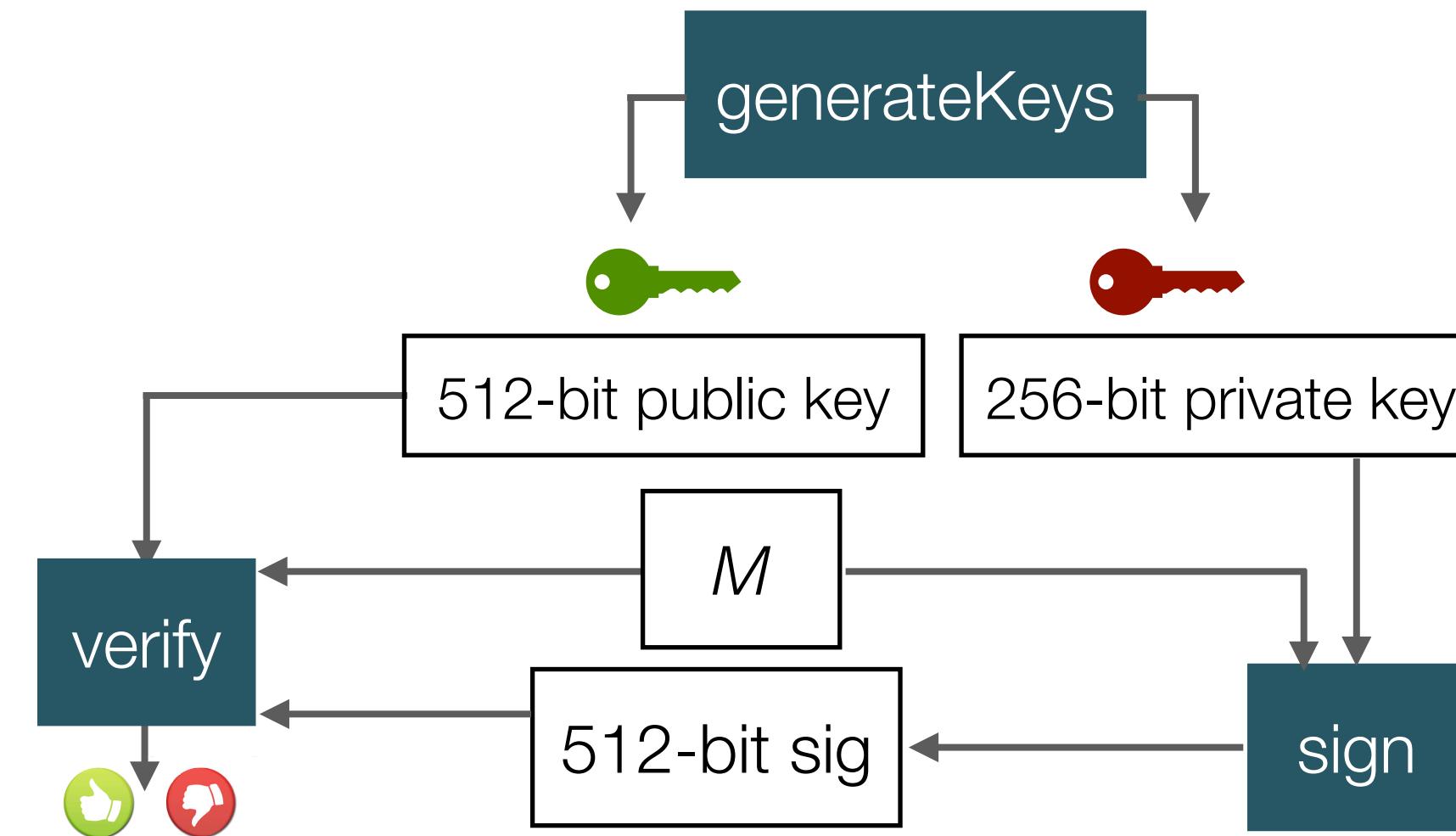
Desirable properties:

- H is collision-resistant
- H hides its input x
- H is “puzzle-friendly”

Digital signatures

ECDSA (secp256k1 curve)

Elliptic curve digital signature algorithm

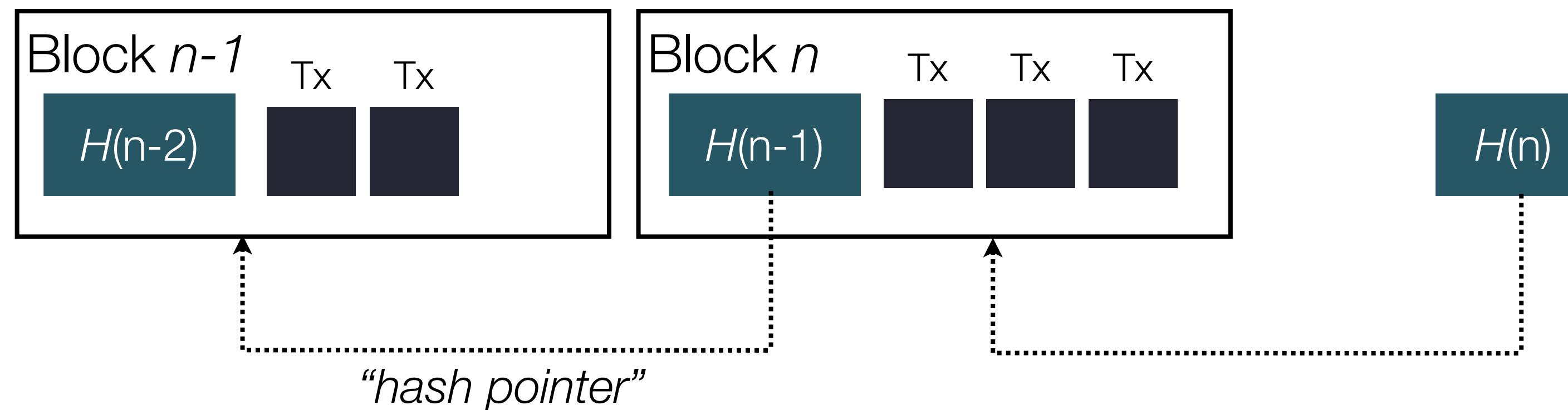


Desirable properties:

- Valid signatures must verify
- Signatures are unforgeable
- Signature is unique to M

Common cryptographic algorithms used in blockchain systems

Hash pointers



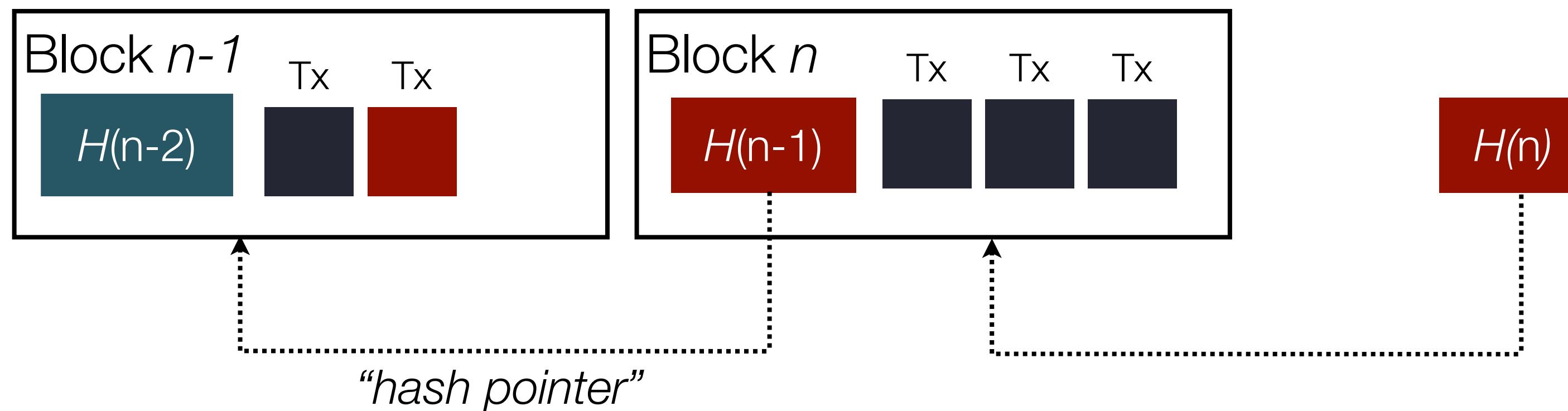
The hash is used both as:

- a unique identifier (to identify and lookup the data)
- a digest (to verify that the data has not been tampered with)

Any non-cyclical data structure can be built from hash pointers

Common cryptographic algorithms used in blockchain systems

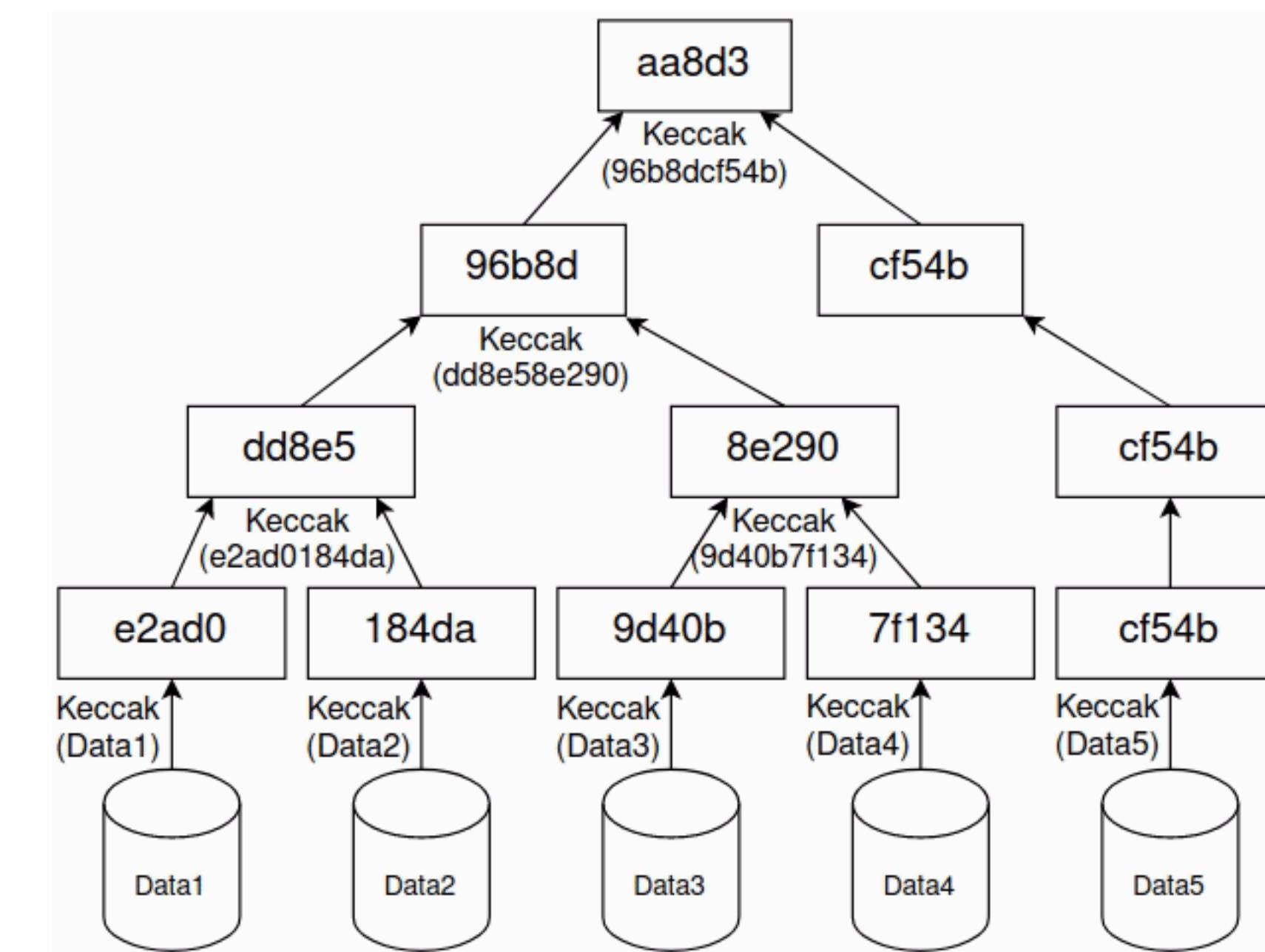
Why use hash pointers?



- We want the transaction log history to be immutable (i.e. only *append* new transaction, not *edit* past transactions).
- By using hash pointers, we ensure that modifying *any* data in *any* past block would invalidate the hash pointers of *all* the following blocks.
- This makes it immediately clear to anyone with a historical copy of the blockchain that data has been tampered with.
- This makes the transaction log “tamper-evident”.

Merkle Trees (a.k.a. Binary hash trees)

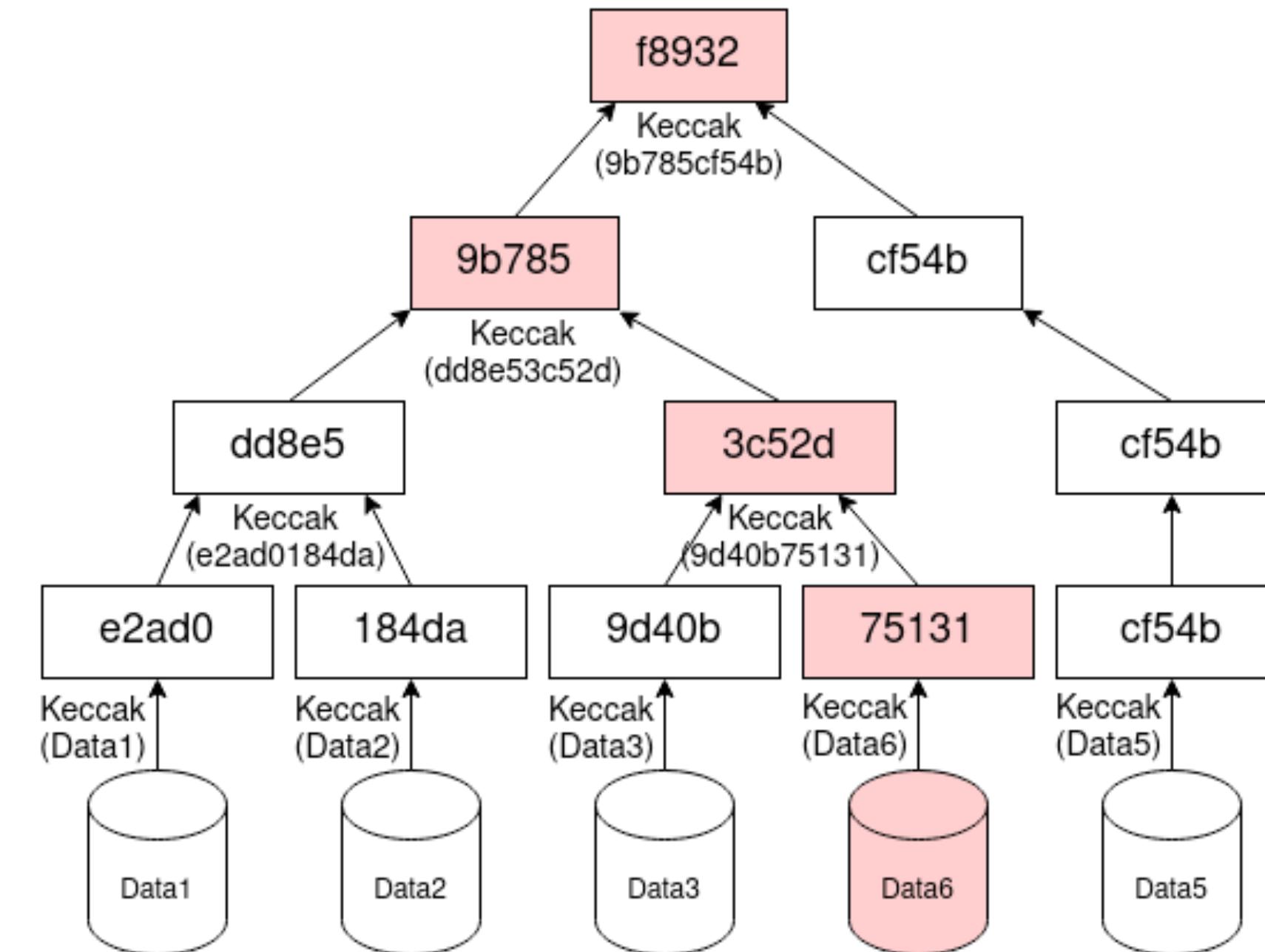
- Invented by cryptographer Ralph Merkle in 1979
- Goal: efficiently verify that a piece of data is included in a list of data blocks
- Leaf nodes are labelled with cryptographic hash of a single data element
- Branch nodes are labelled with cryptographic hash of the *concatenation* of the labels of its children



(Image credit: T. Kanstrén, Merkle Trees: Concepts and Use Cases, [medium.com](https://medium.com/@tomas_kansten/merkle-trees-concepts-and-use-cases-3a2a2a2a2a2a))

Merkle Trees: cryptographic commitment

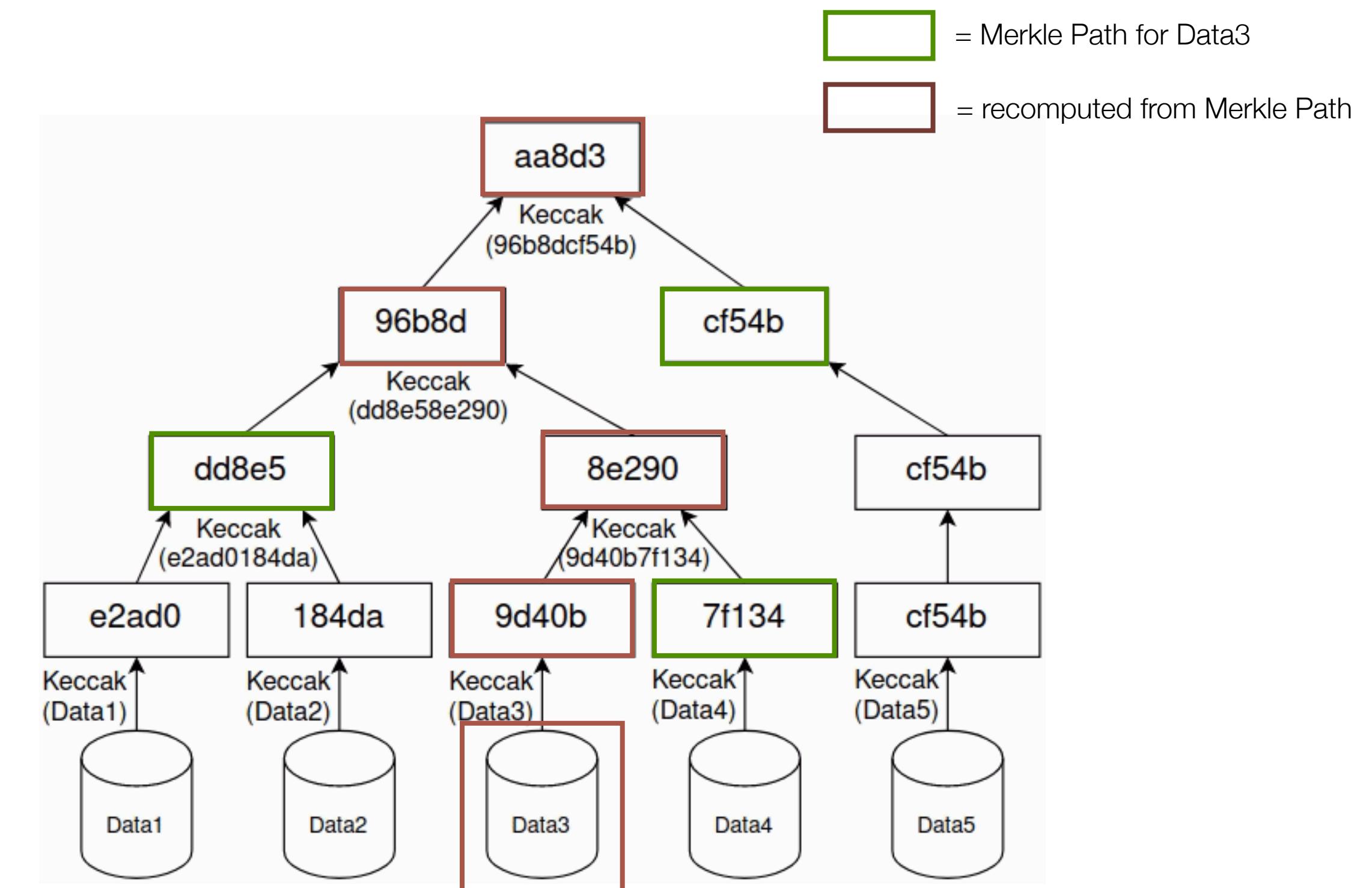
- Changing a single data item would change the leaf hash, and consequently all intermediate hash values up to the root hash
- The root node hash thus represents a *cryptographic commitment* to the entire list of data items



(Image credit: T. Kanstrén, Merkle Trees: Concepts and Use Cases, [medium.com](https://medium.com/@tomekkanstr%C3%A9n/merkle-trees-concepts-and-use-cases-1f3a2a2a0a))

Merkle Trees support efficient inclusion proofs

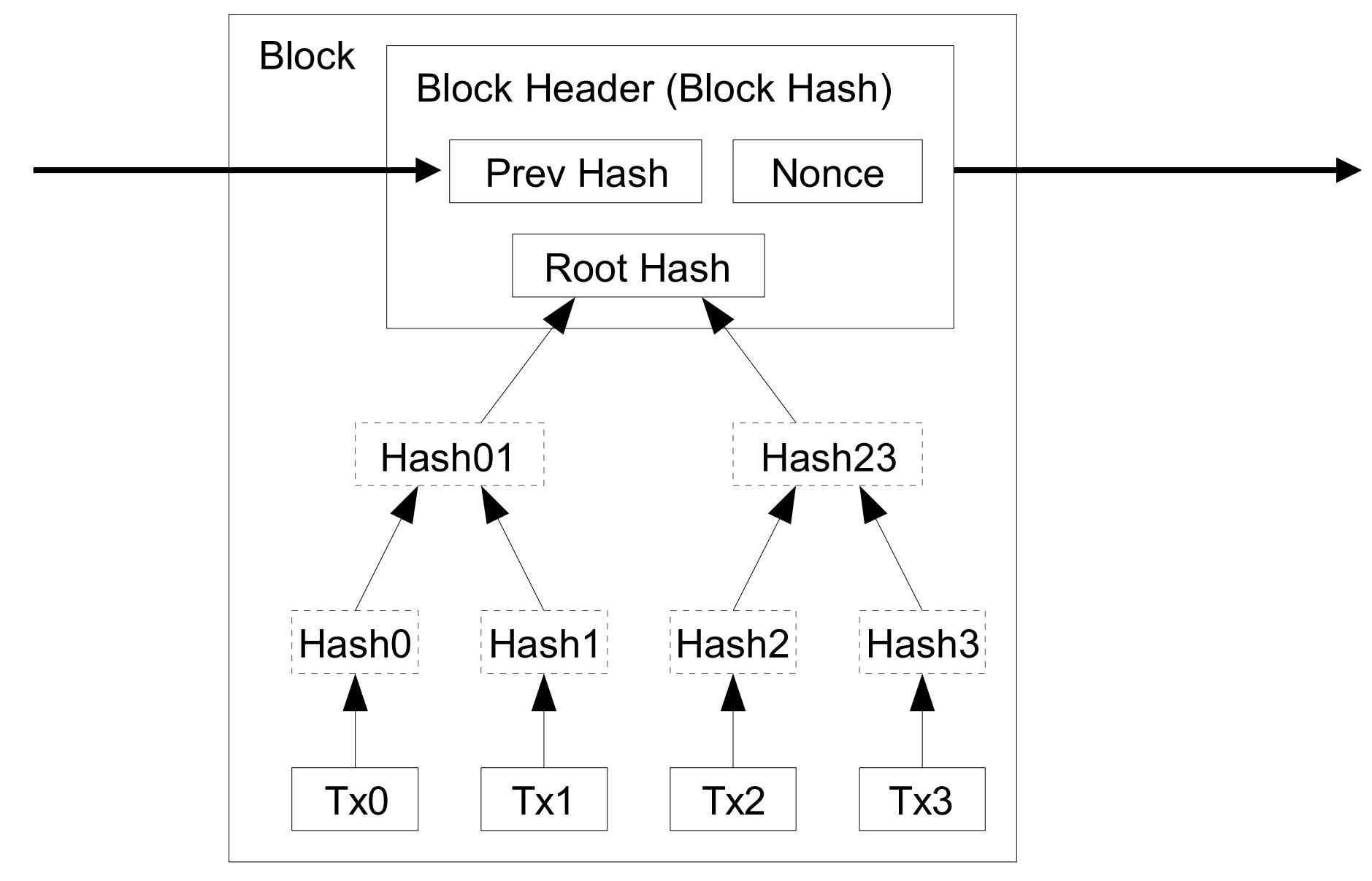
- Goal: prove that a data item is part of the original list (e.g. Data3)
- Only need the hash values of the branches along the data item's path
- $O(\log(n))$ steps, where n is the number of data items (leaves)
- How many steps would have been needed if we would have just stored the hash of the list of data items?



(Image credit: T. Kanstrén, Merkle Trees: Concepts and Use Cases, [medium.com](https://medium.com/@tomekkanstr%C3%A9n/merkle-trees-concepts-and-use-cases-3a2a2a0a2a))

Merkle trees in the Bitcoin blockchain

- An actual Bitcoin block consists of a Block Header and a transaction list stored separately as a Merkle Tree
- The block header contains the root hash of the Merkle Tree
- This enables clients to efficiently verify that a transaction was included in a block without downloading the full transaction information in each block (“**SPV**” or “Simplified Payment Verification”):
 - Assume client has information on a transaction to verify, including its associated Merkle Path
 - 1. Client queries the Bitcoin network for block headers included in the longest chain
 - 2. Client can recompute Merkle root hash from transaction information and Merkle Path
 - 3. Client can verify that its computed root hash is part of a block header in the longest chain



Transactions Hashed in a Merkle Tree

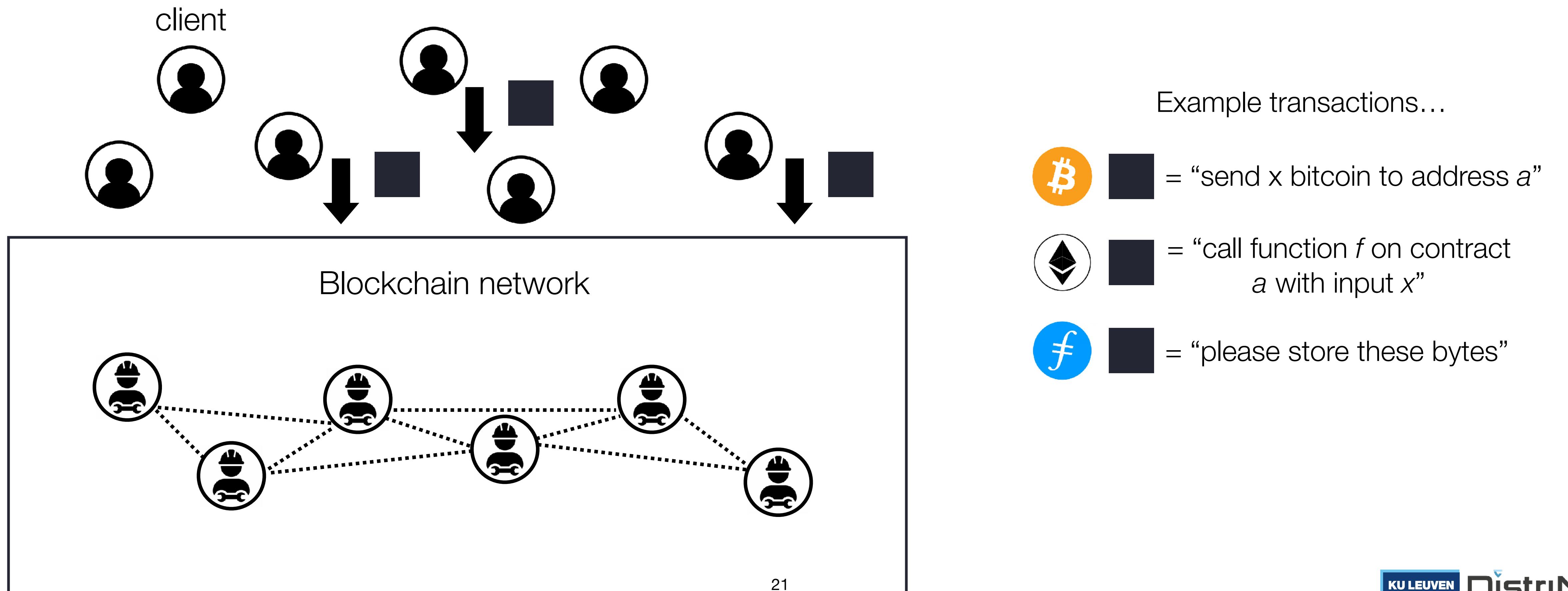
(Source: S. Nakamoto, 2008, “Bitcoin: A Peer-to-Peer Electronic Cash System”)

How does a blockchain network process transactions?

A.k.a. the “life of a blockchain transaction”

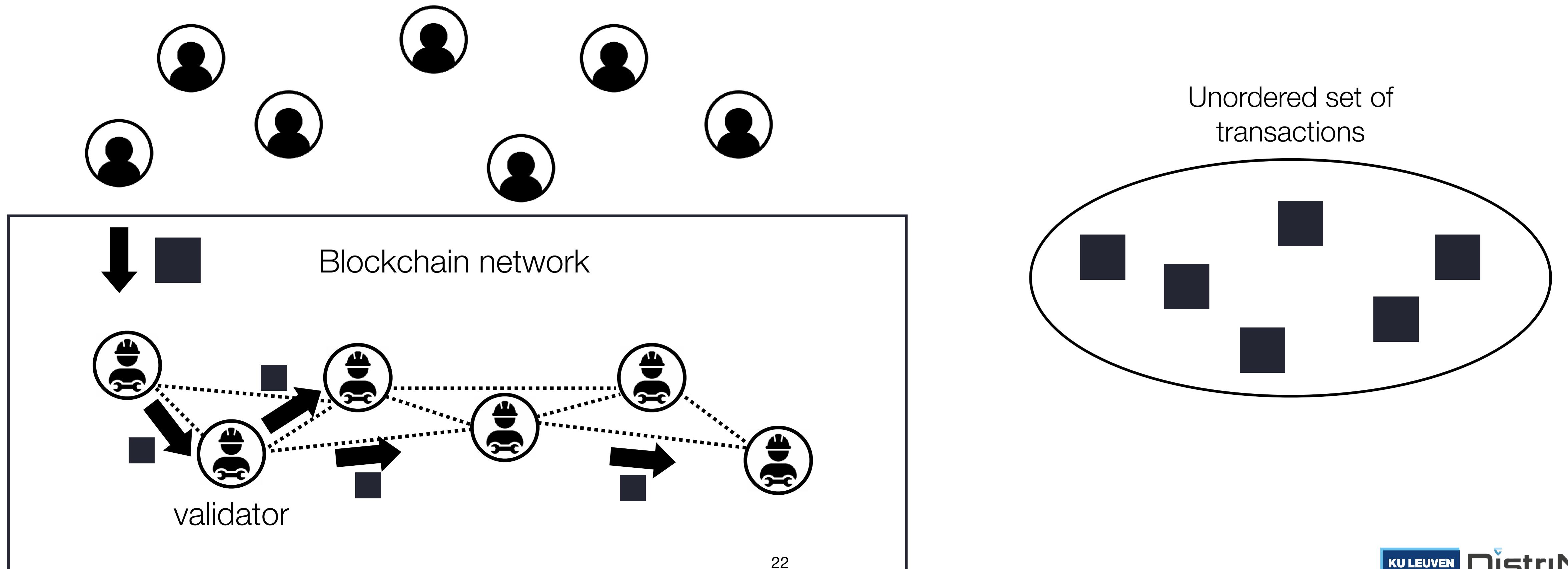
Step 1: clients submit signed transactions

- Clients **concurrently** submit signed transactions to one or more validators.



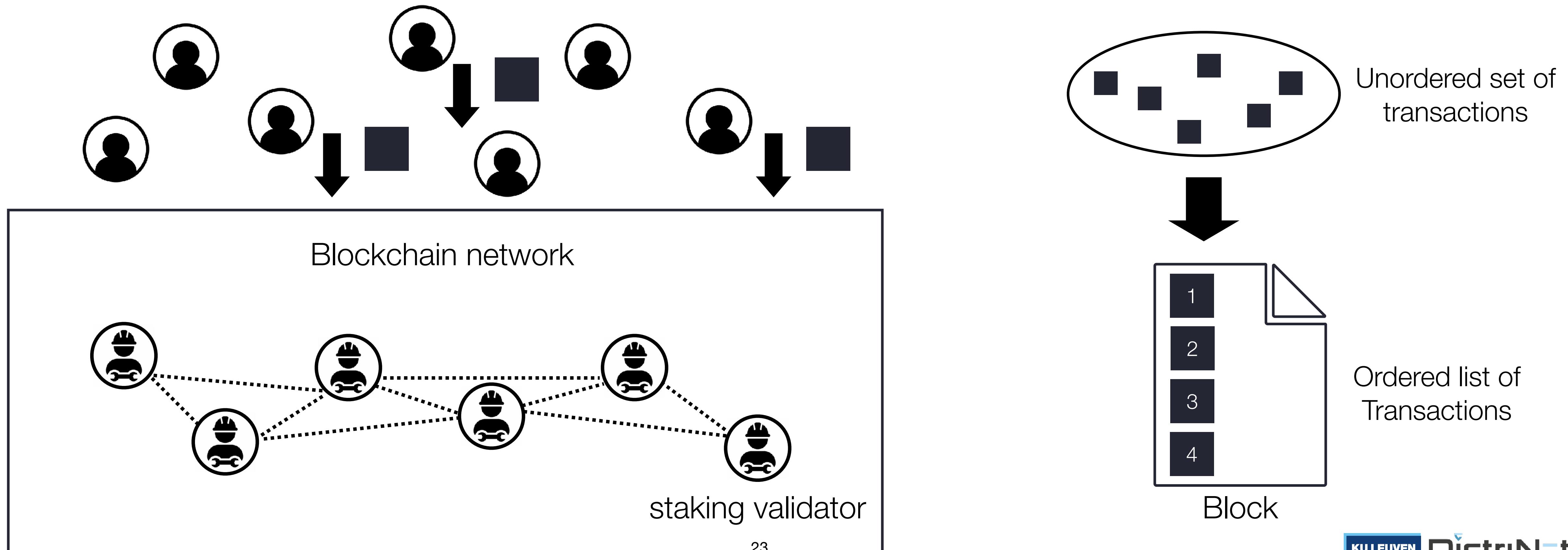
Step 2: validators validate and gossip transactions

- A **validator** is a network node that maintains an **unordered set** (“mempool”) of incoming transactions. It collects, validates and broadcasts transactions to other peers (using a **gossip** broadcast protocol)



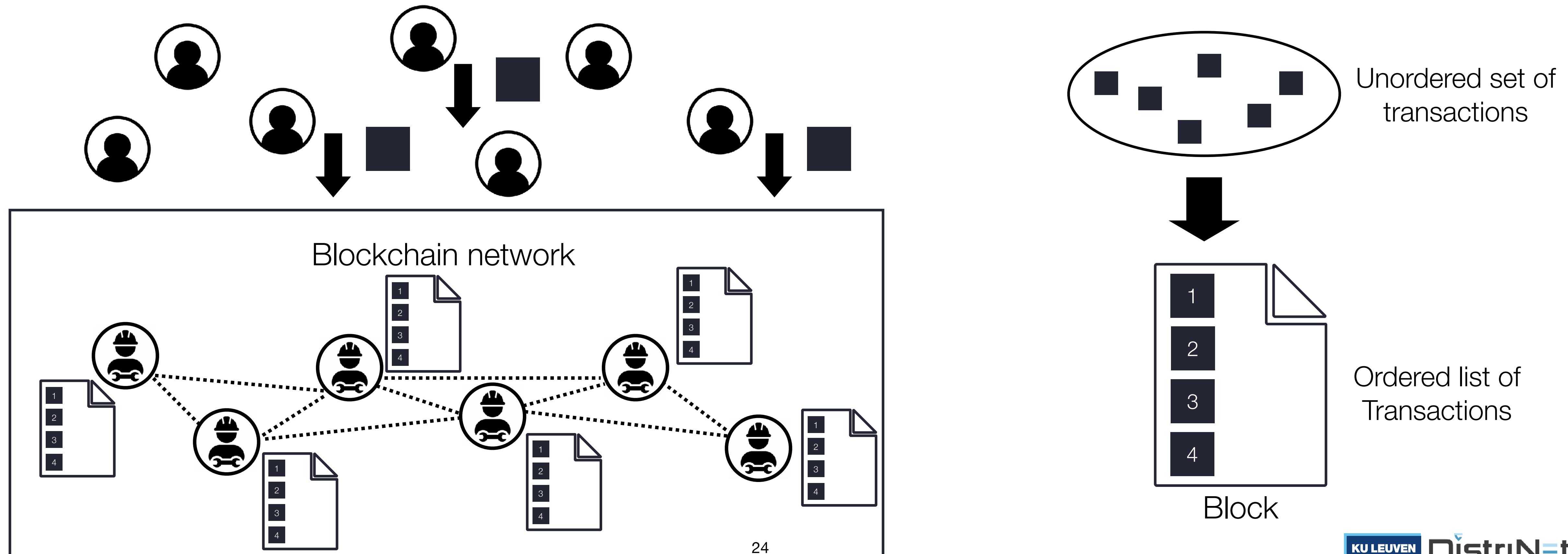
Step 3: a validator produces a block of transactions

- At regular intervals, a subset of validators pick a subset of transactions from the pool and sequence them, thus producing an *ordered* list of transactions. These validators are sometimes called “**miners**” or “**staking validators**”. The transaction list is called a “block”



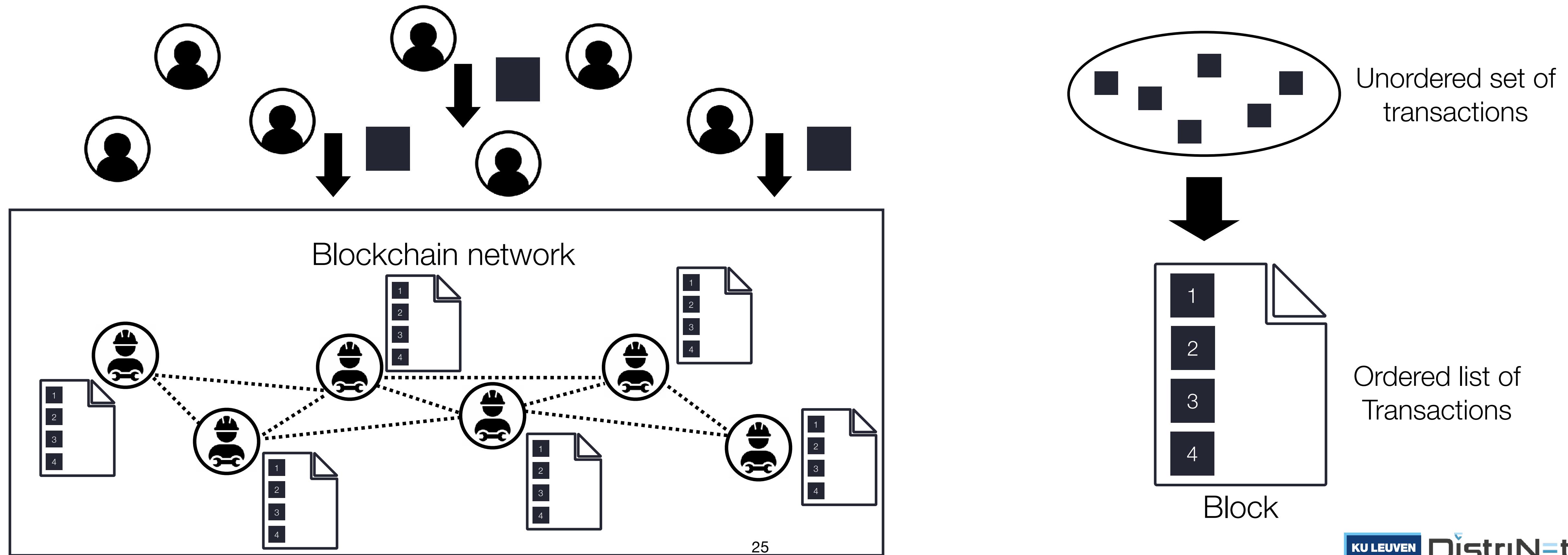
Step 4: validators gossip block and append to the blockchain

- The **block is broadcast** to all validators (again using gossip). Each validator **checks again** if all transactions in the block are valid. If yes, they **append** the block to their local transaction log (aka the blockchain).



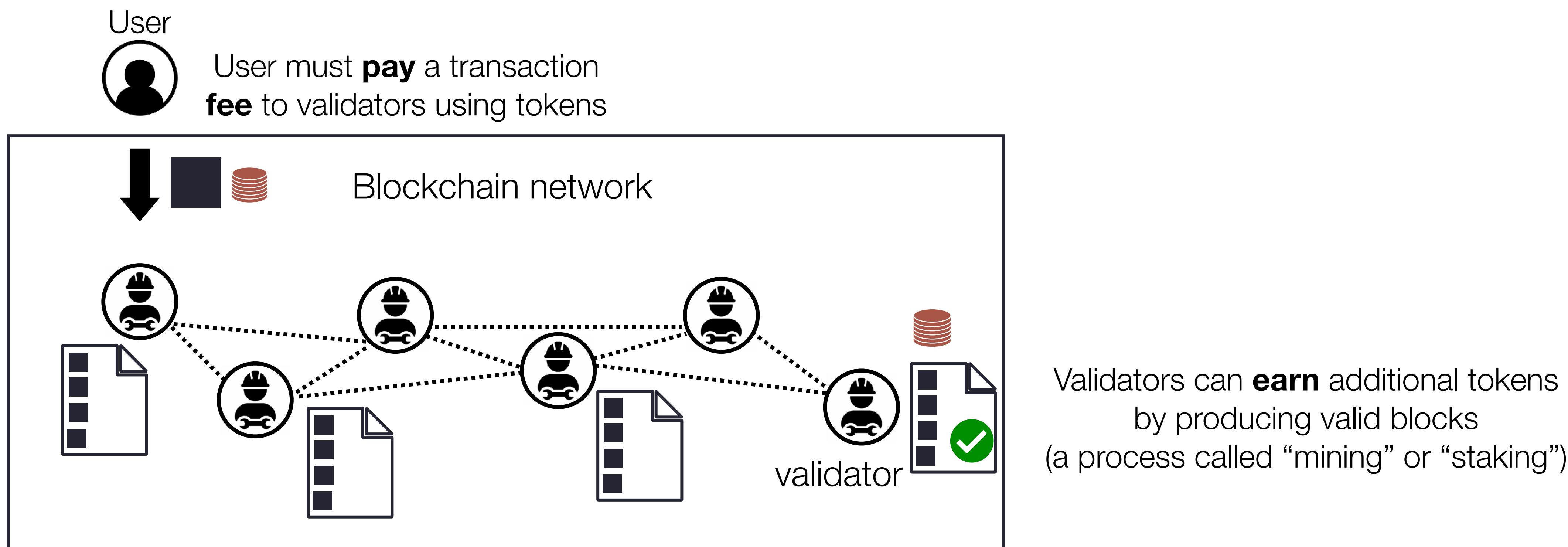
Consensus

- All validators must reach **consensus** on the exact same transaction history!
- Need to make sure that blocks get appended everywhere *in the same order*



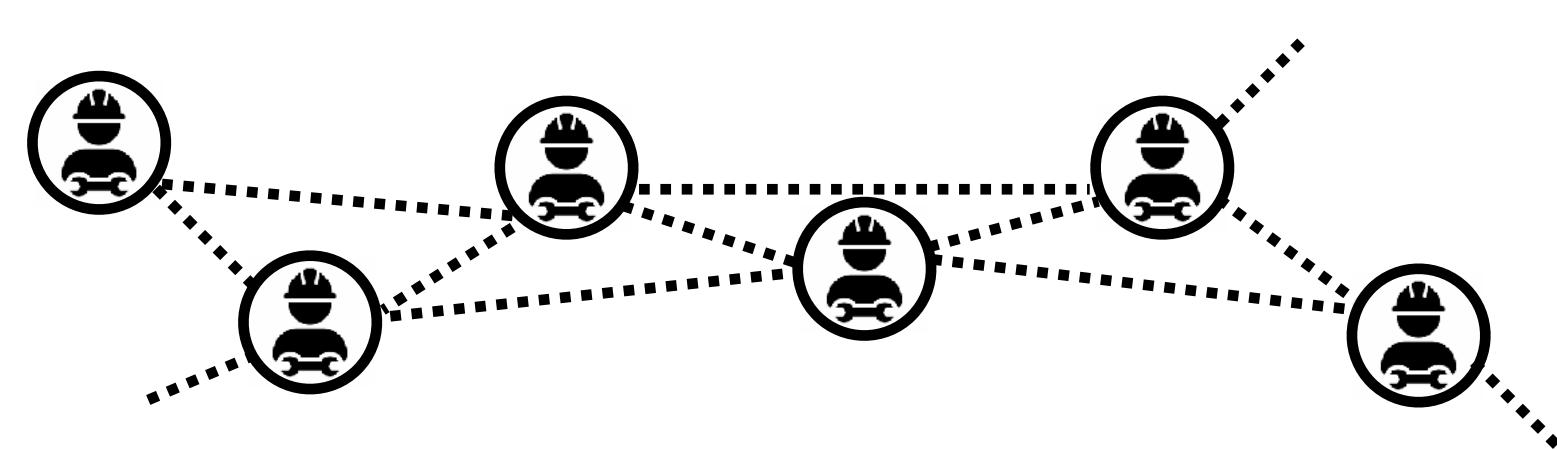
Blockchain networks: tokens, transaction fees and mining rewards

- **Tokens** are used to a) pay for transaction processing (transaction **fee**) and b) to **reward** validators for contributing hardware resources (compute, bandwidth, storage) to validate transactions. They act as an **incentive mechanism** to keep validators honest.



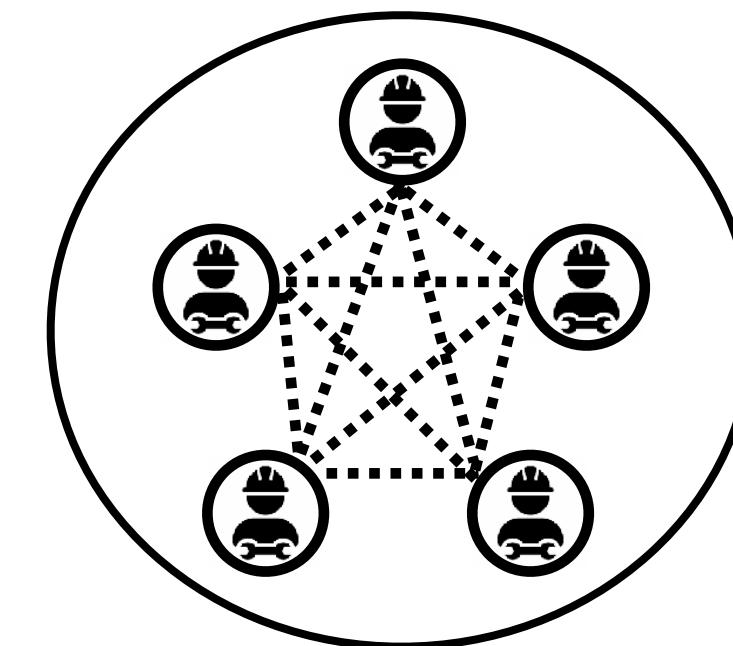
Who can be a validator?

- In **permissionless** blockchains: anyone can join the network to become a transaction validator. No need to ask for permission to anyone. Group membership is **open**.
- In **permissioned** blockchains: must receive *permission* from a coordinator or from existing validators in order to become a transaction validator. Group membership is **closed**.



Open

vs



Closed

Permissioned vs Permissionless networks: examples

- Examples of **permissionless** blockchain networks:

- Bitcoin (decentralized payments)
- Ethereum (decentralized computation)
- Filecoin (decentralized storage)
- Helium (decentralized wireless networks)



- Examples of **permissioned** blockchain networks:

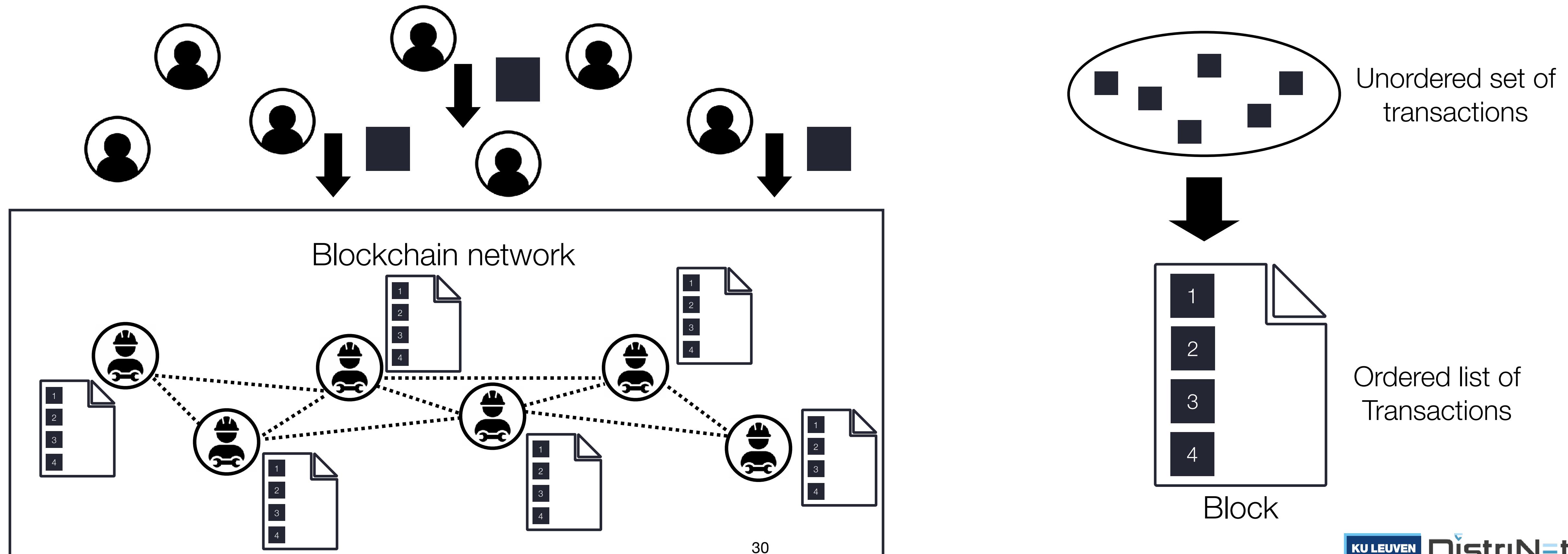
- Hyperledger Fabric
- Corda
- Private Ethereum networks (“Enterprise Ethereum”)
- Hyperledger Sawtooth



Consensus in Blockchain networks

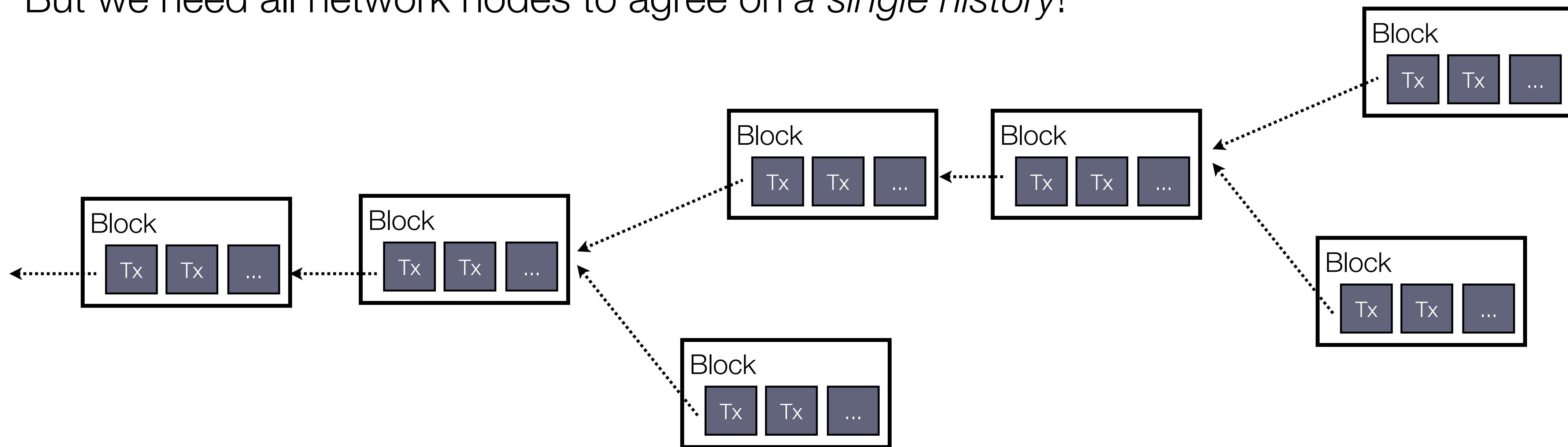
Consensus in Blockchain networks: recap

- All validators must reach **consensus** on the exact same transaction history!
- Need to make sure that blocks get appended everywhere *in the same order*



Problem: diverging histories

- In an open system, if *anyone* can easily produce a valid block and add it directly to the ledger, there is little hope that the network will end up agreeing on a *single* ledger
- More likely, we would end up with a quickly growing *tree* of blocks
- But we need all network nodes to agree on a *single history*!



How to get consensus: organize a vote?

- We can let the network **vote** to **elect a single validator node** to propose the next block
- Ideally the proposer node is chosen **randomly** to avoid any bias in the election process
- But how to organize a vote in an open and permissionless network?
 - 1. We don't even have a fixed list of nodes to organize a voting poll
 - 2. Even if we would have a list of nodes, how to assign **voting rights** to each one?
- One IP address = one vote? Problem: attacker may control multiple IP addresses
- This is known as a **sybil attack**. The same problem holds for any other type of “identity” that is cheap to create (e.g. public keys)

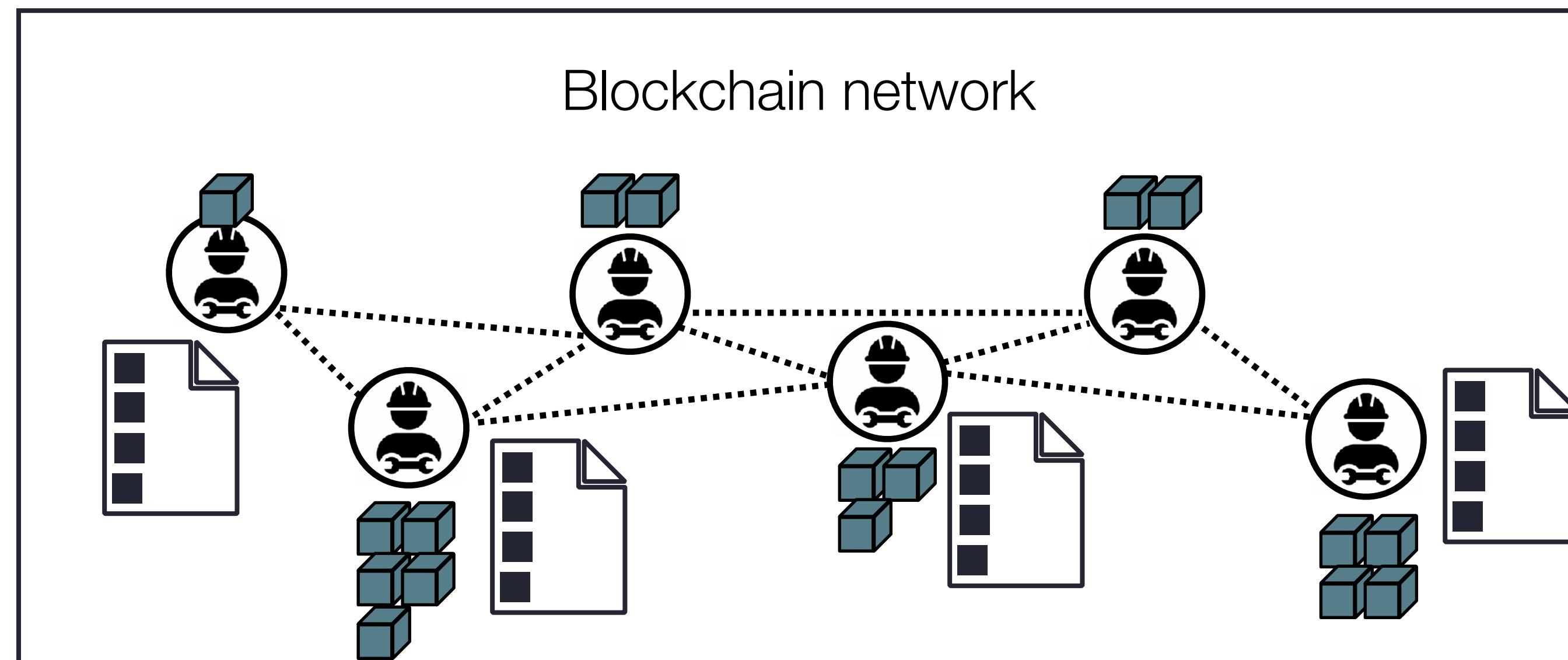
How to get consensus: organize a lottery!

- To elect a node from an open group of participants, organize a **lottery**: each node “buys” tickets, whoever can “prove” they have the lucky ticket is the winner (and so gets to propose the next block)
- The lottery should have the following properties:
 - **Fair** - node election should be distributed across the broadest possible population of participants (i.e. “everyone can buy a ticket”)
 - **Proportional** - The cost of controlling the election process should be proportional to the value gained from it (i.e. “the more tickets bought, the higher the chance of winning”)
 - **Verifiable** - It should be relatively simple for all participants to verify that the winning node was legitimately selected (i.e. “everyone can verify whether the winning ticket is indeed a valid ticket”)

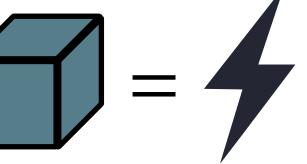
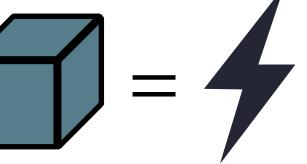
Lottery-based consensus in permissionless blockchains (“proof-of-X”)

- Validators enter the lottery by proving ownership of a digital or physically **scarce resource**
- Different blockchain networks may use different kinds of resources

Example lottery-based consensus protocols:



 “Proof-of-work”
(vote with compute power)

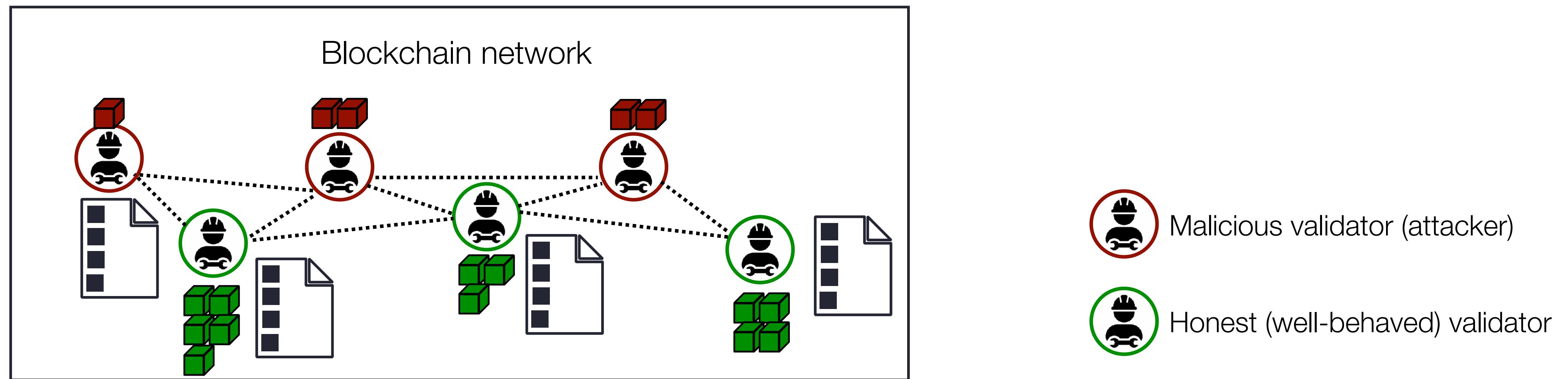
 = 

 “Proof-of-stake”
(vote with staked tokens)

 = 

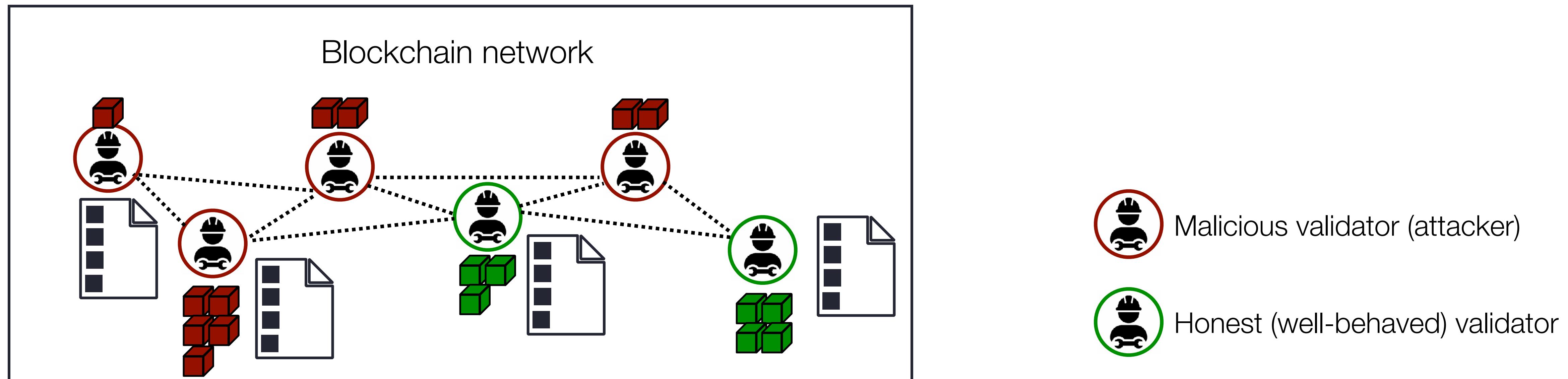
Lottery-based consensus in permissionless blockchains (“proof-of-X”)

- The integrity of the blockchain is guaranteed as long as a **majority** of the network, **weighted** by their resource ownership, is controlled by well-behaved validators



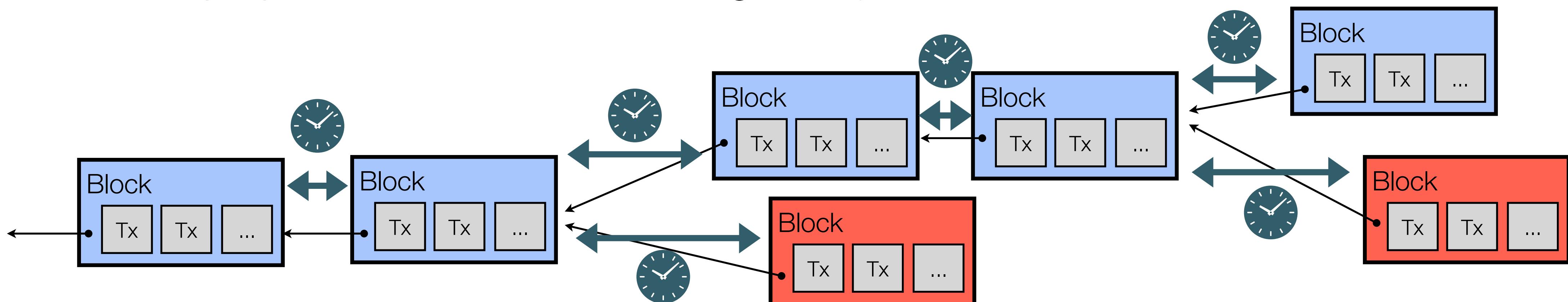
Attacking a permissionless blockchain network: “51% attack”

- If an attacker (or group of attackers) **controls >50% of the scarce resources**, they effectively control the production of new blocks.
- While such an attacker cannot create “fake” signed transactions (i.e. steal tokens), they can **reject (censor)** any number of transactions and can approve transactions that **double-spend** their own tokens by “forking” the blockchain and “rewriting” block history.



Proof-of-Work consensus

- Require blocks to contain a “proof-of-work”: a proof that significant (computational) work was done to find the solution to a puzzle, where the solution - once known - is easy to verify
- The purpose is to **slow down** block production
 - so that only **one node at a time** can propose a new block
 - so that there is time to **propagate the new block** across the entire P2P network to avoid disagreement on what is the latest valid block
- In Bitcoin: propose a new block on average every 10 minutes

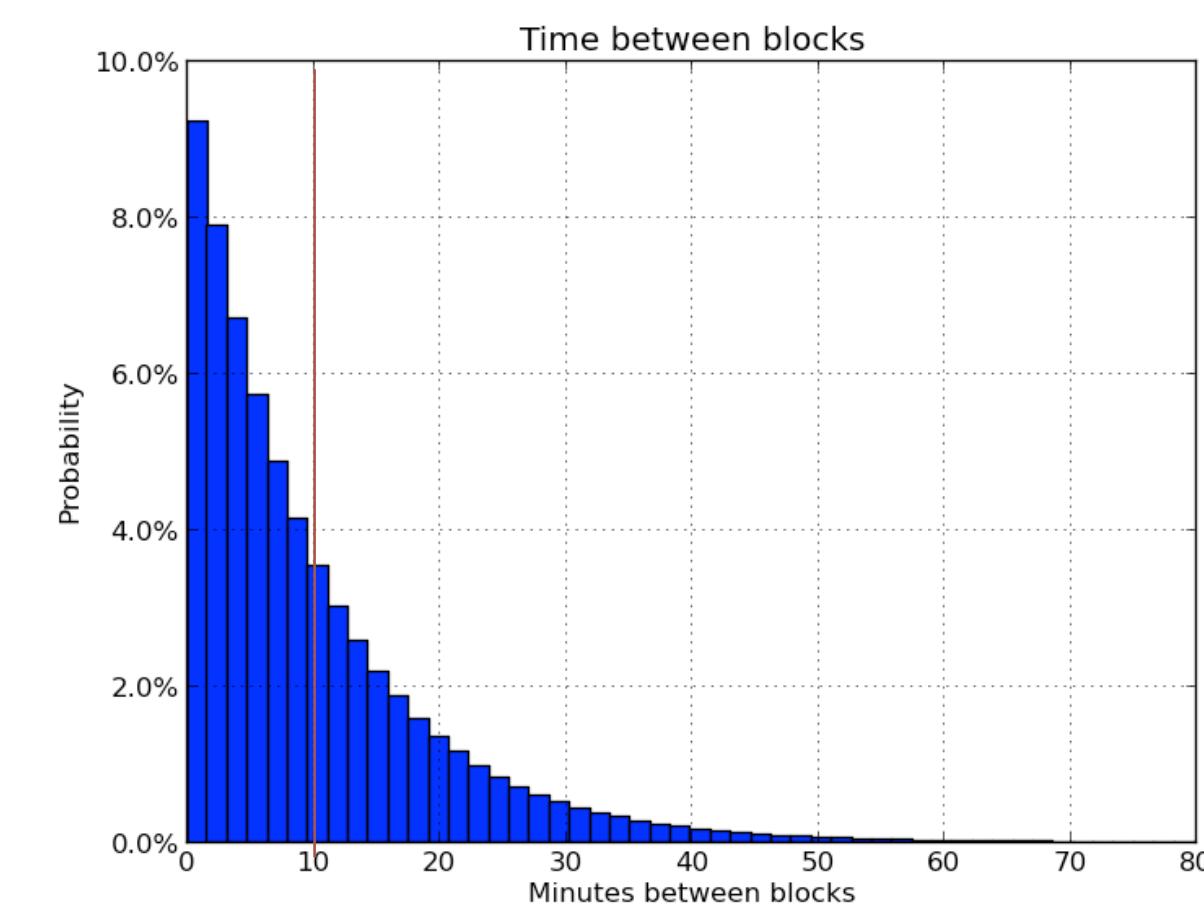
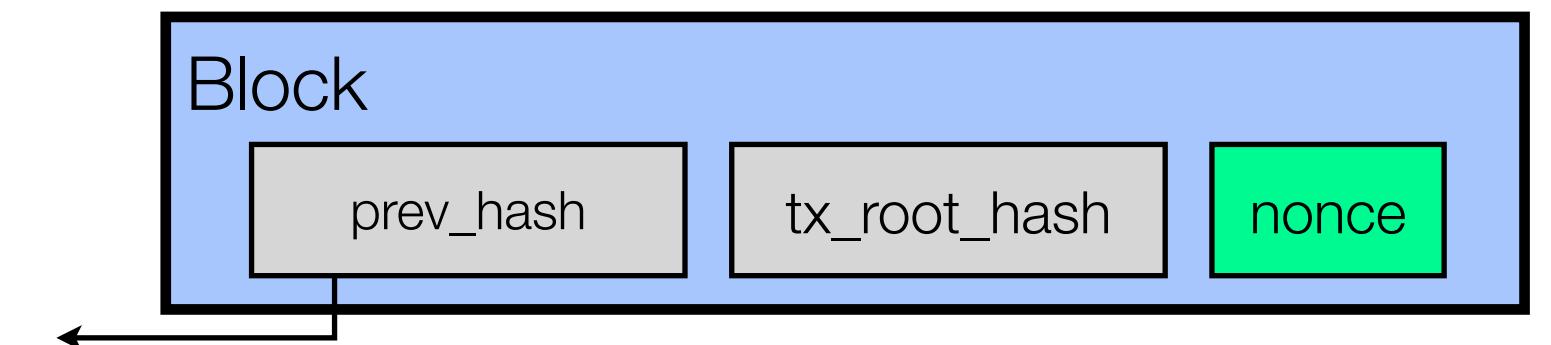


Proof-of-Work in Bitcoin

- The proof-of-work involves searching for a value v such that $\text{hash}(v)$ is smaller than a given target threshold value (known as the **difficulty** parameter)
- Because the output of a cryptographic hash cannot be predicted, there is no known strategy better than a **brute force** search
- The search is done by incrementing a number in the block (the **nonce**) until a value is found such that the block's hash satisfies the target difficulty
- The difficulty parameter is **adjusted** every 2016 blocks such that the **average time** between blocks remains 10 minutes.

Find a nonce (a number) such that:

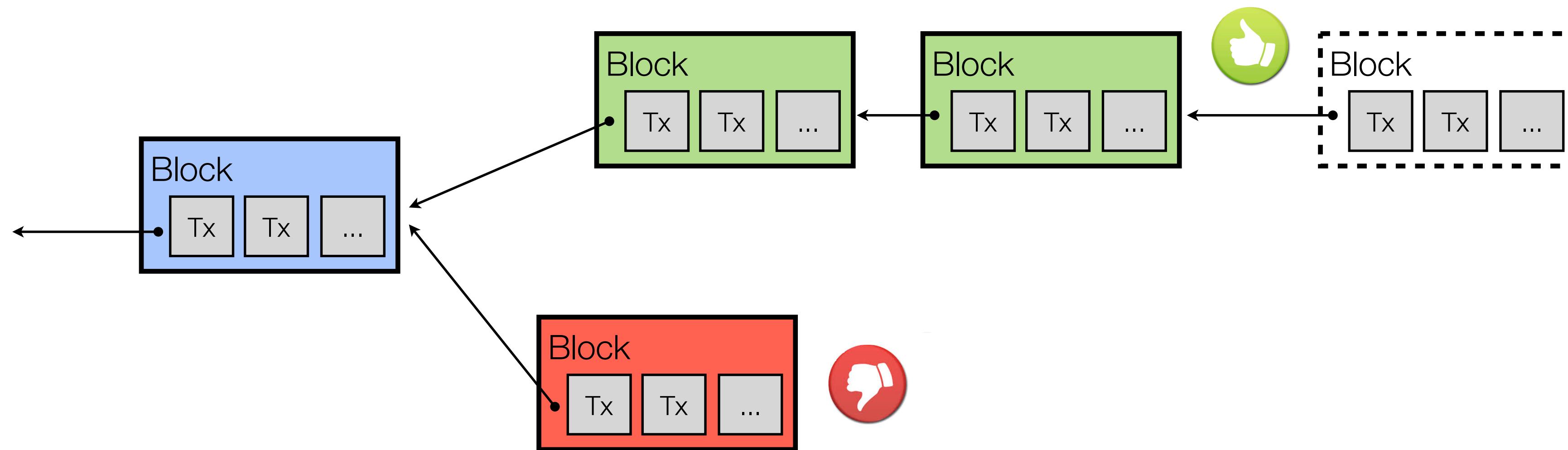
$$H(\text{nonce} \parallel \text{prev_hash} \parallel \text{tx_root_hash}) < \text{target}$$



(source: [Bitcoin wiki](#), retrieved November 2022)

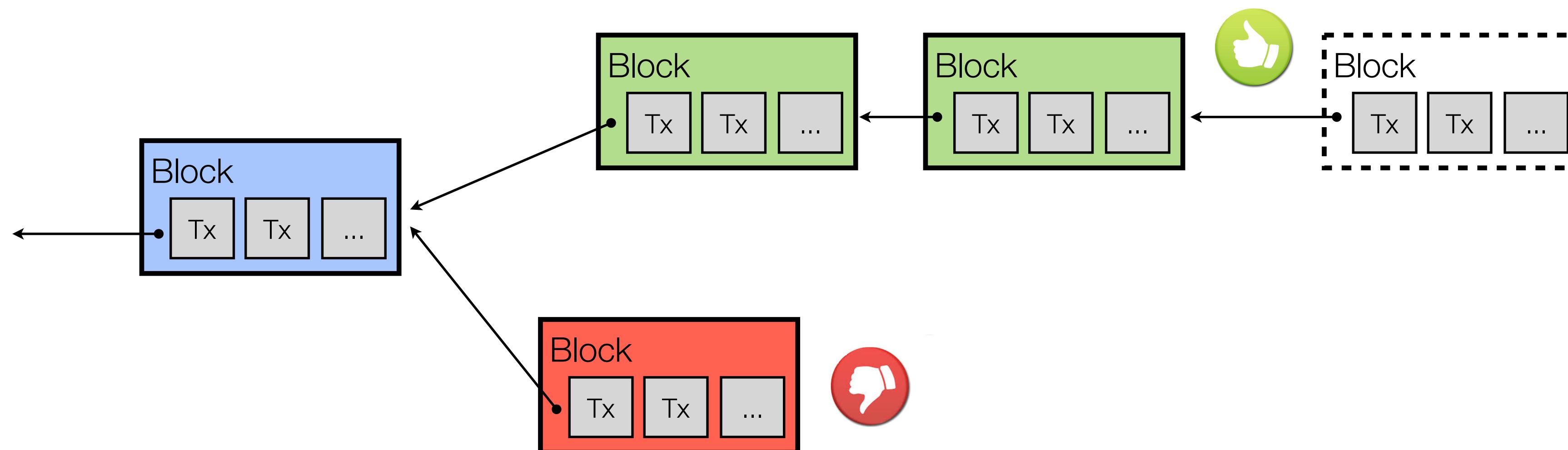
How Proof-of-Work solves the consensus problem

- Nodes implicitly “vote” with their computational power
- Nodes silently **accept** a block by working on extending the block (= mining)
- Nodes silently **reject** a block by refusing to work on it
- The majority decision is represented by **the longest chain**, which has the greatest proof-of-work effort invested in it.



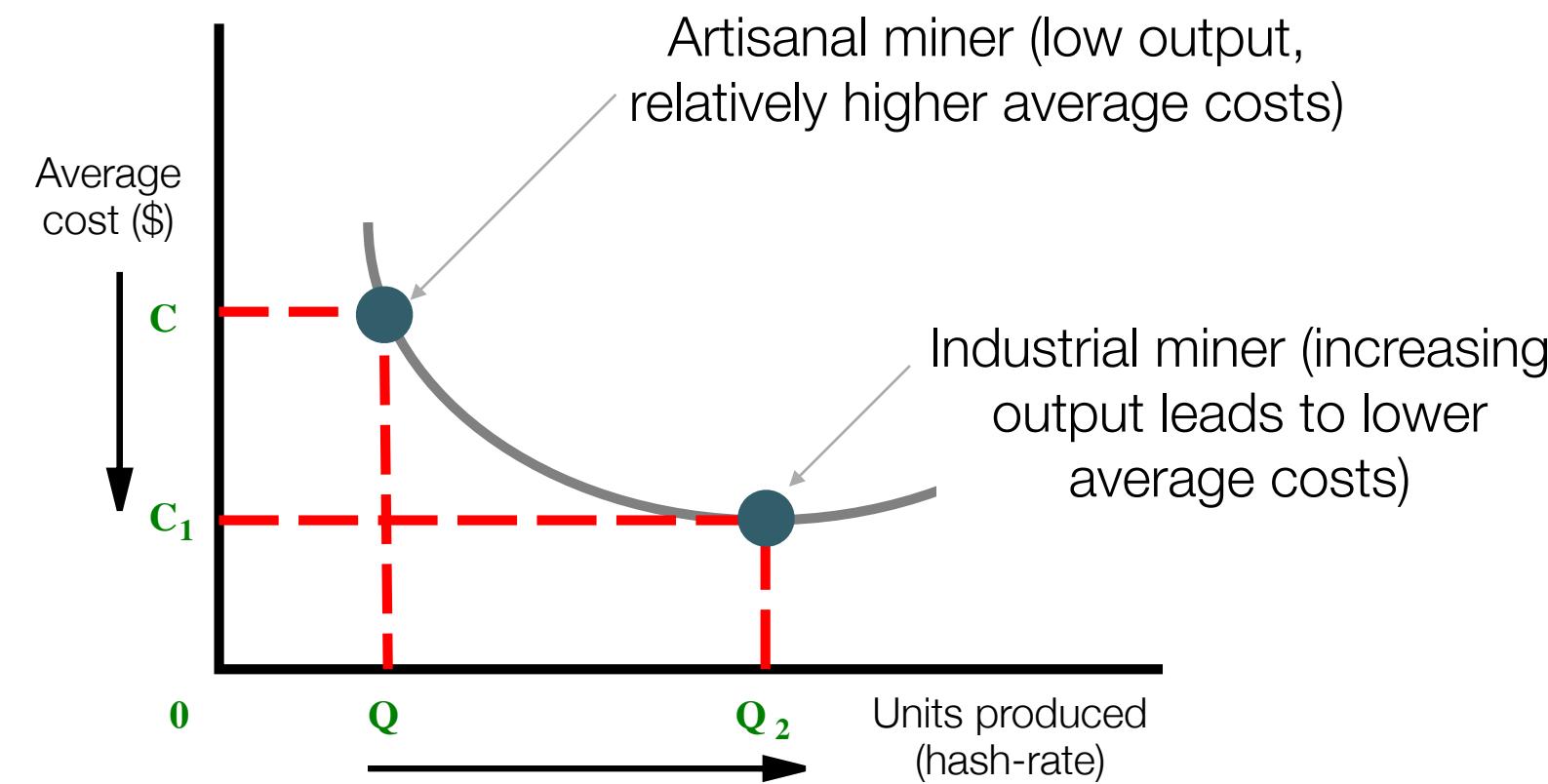
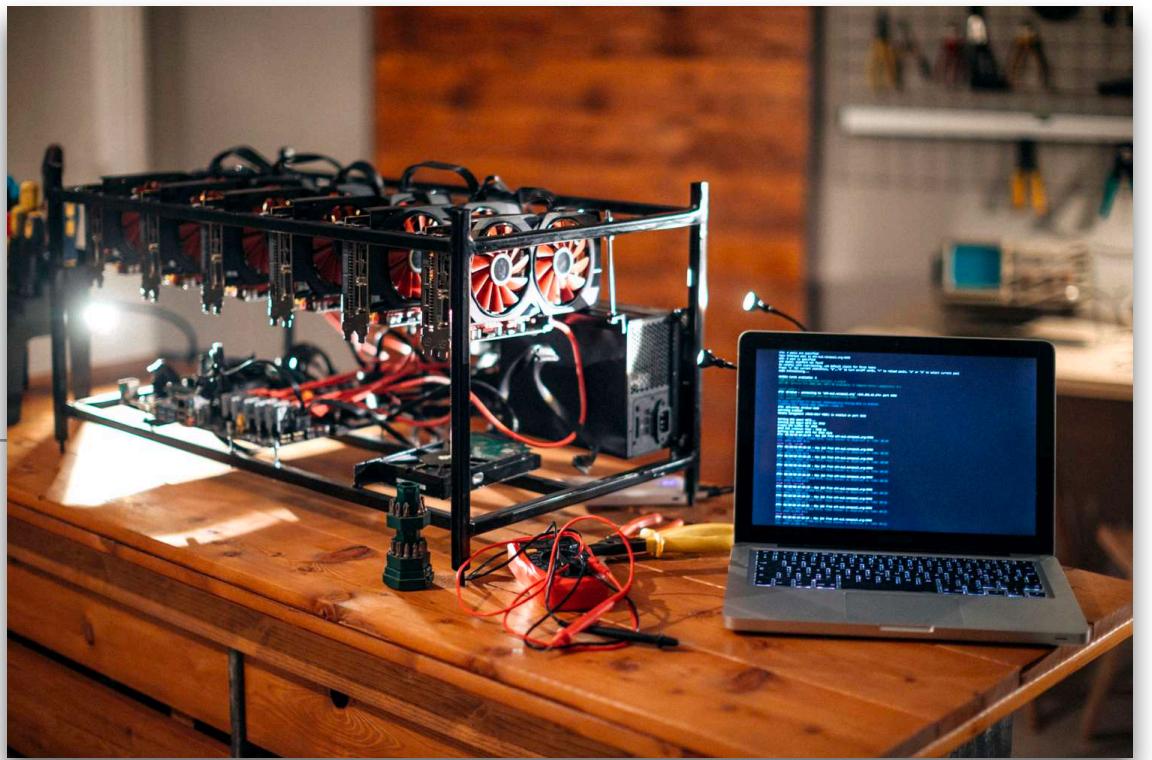
How Proof-of-Work solves the consensus problem

- If a majority of compute power is controlled by honest nodes, the honest chain will grow the fastest and outpace any competing chains.
- Put differently: an attacker must control more compute power than **all the honest nodes combined** in order to outpace the “honest chain”



Proof-of-Work

- Miners “race” each other to find the next block. The more computational power a miner has, the higher the chance of winning the race.
- But Proof-of-Work is:
 - Slow (by design)
 - Energy-inefficient (by design)
 - Subject to centralizing economies of scale (mining pools, large-scale mining facilities)



A large-scale ASIC-based Bitcoin “mining farm”
(Image credit: [stockhouse.com](#))

Proof-of-Stake

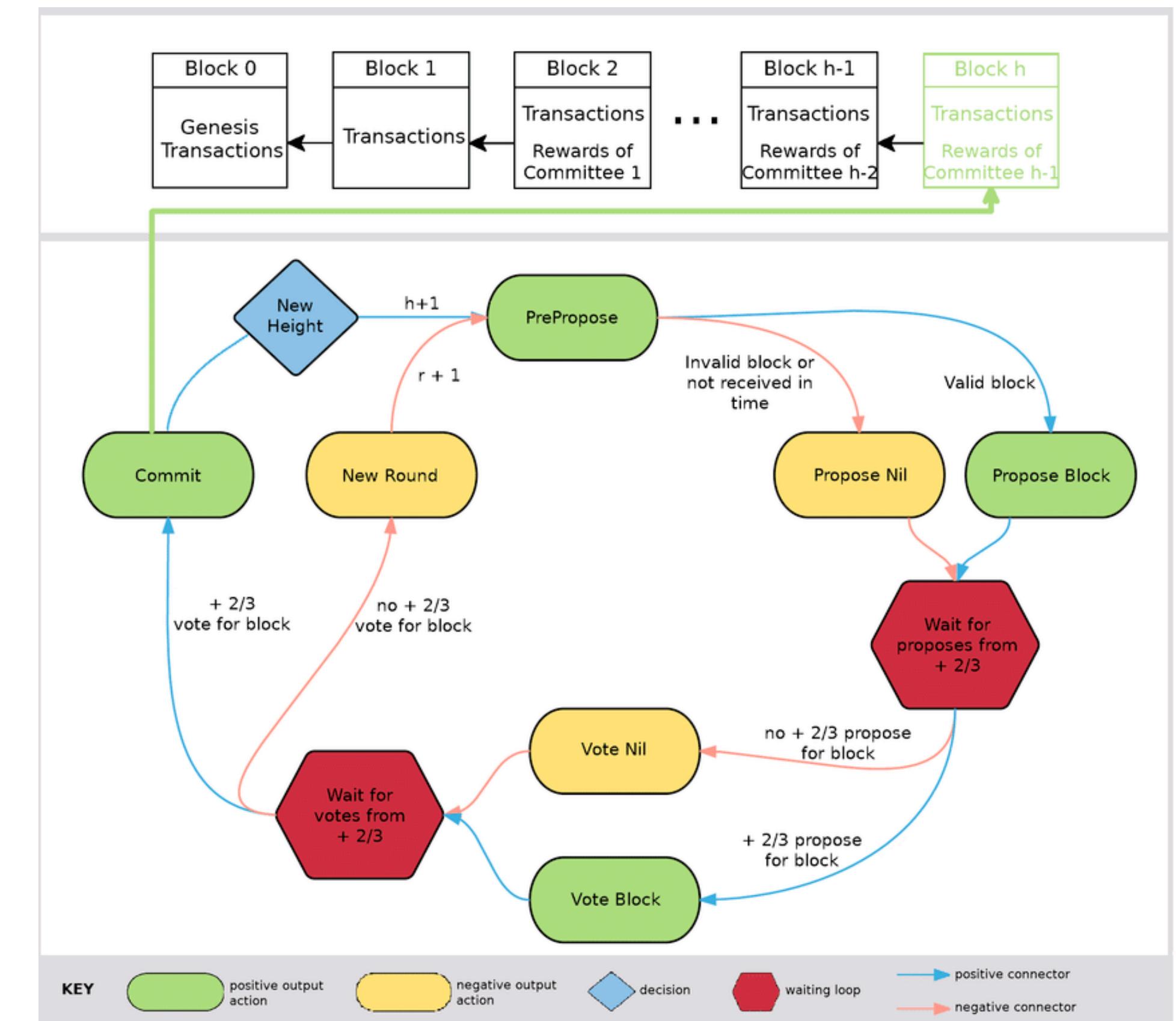
- Proof-of-Stake (PoS): the chance of proposing the next block is **proportional to the economic stake** in the system.
 - The more tokens “staked” (= locked in escrow), the higher the chance of becoming the next block proposer.
- Many **variations** of PoS **exist**. Two large families include:
 - **Lottery-based** Proof-of-Stake. Similar to Proof-of-Work. Also called **chain-based** Proof-of-Stake.
 - **Voting-based** Proof-of-Stake. Uses a BFT algorithm like PBFT or similar. Also called **BFT-based** Proof-of-Stake.

Two families of voting-based consensus algorithms

- **Crash fault-tolerant (CFT) consensus:** assume participants may fail due to crashes or network failures, but also assume all participants execute the consensus algorithm correctly and strictly follow the same protocol.
 - Tolerate up to (but not including) 1/2 participants failing by crashing (“fail-stop”)
 - Example: Paxos (Lamport, 1989)
- **Byzantine fault-tolerant (BFT) consensus:** assume participants may fail due to crashes or network failures, but make no additional assumptions. In particular, processes may incorrectly execute the consensus algorithm and may deviate from the protocol in arbitrary ways.
 - Tolerate up to (but not including) 1/3 processes failing in arbitrary ways
 - Example: PBFT (Castro and Liskov, 1999)

PBFT in Permissionless blockchains: Tendermint

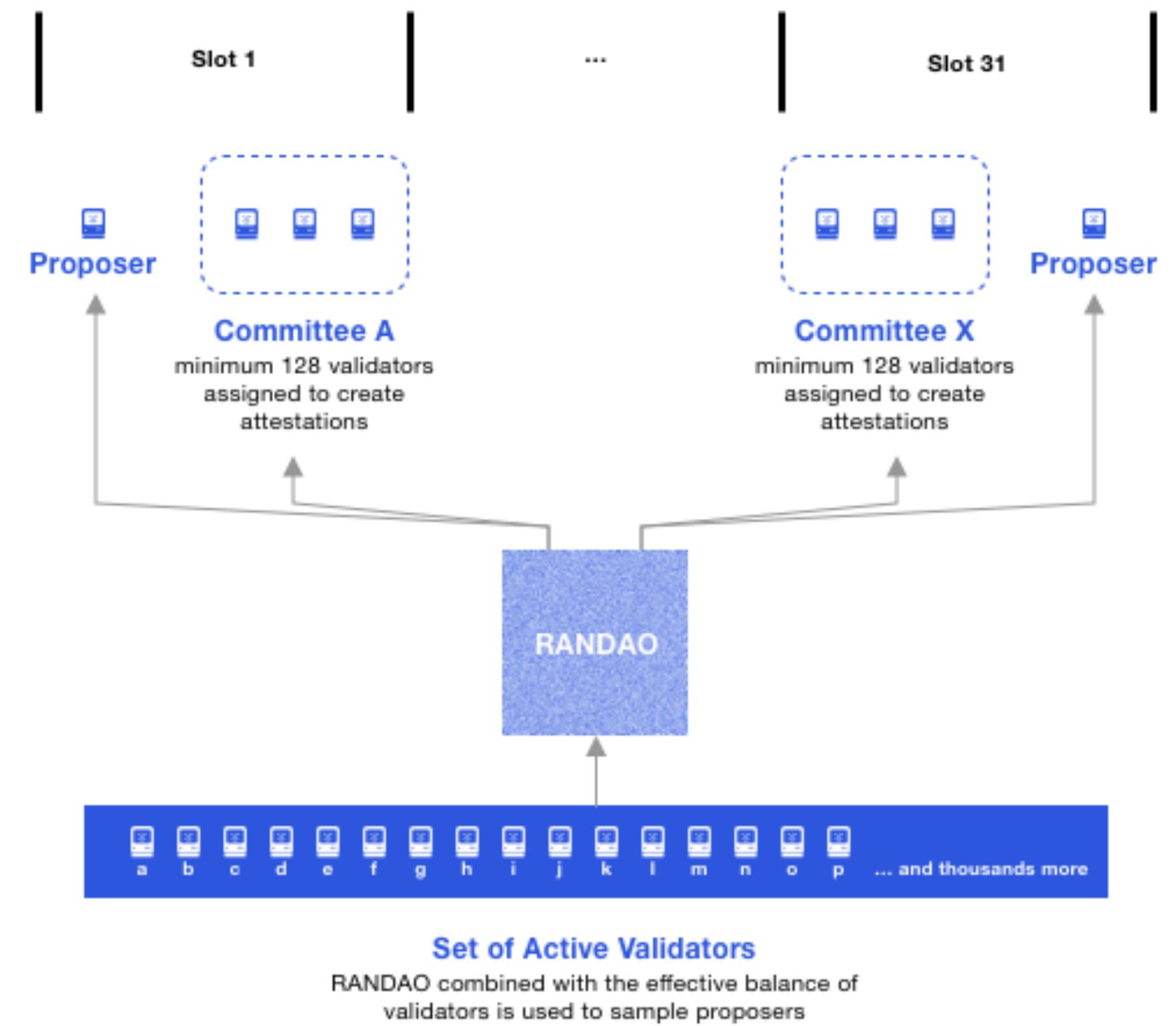
- Tendermint is an **adaptation of PBFT** to function as a consensus algorithm for a **permissionless** blockchain *without requiring Proof-of-Work mining*
- It was one of the first attempts (~2014) to adapt classical (pre-blockchain) BFT algorithms such as PBFT to support consensus in the context of a blockchain:
 - Tendermint uses **“Proof-of-Stake”** to limit participation in the committee and to introduce token incentives (rewards and penalties).
 - Rather than seeking agreement on individual *operations*, peers take turns **proposing the next block** in the chain. If a $+2/3$ quorum agrees on the block, it is added.
 - Tendermint assumes a large, slow, wide-area network rather than a small, fast, local-area network. Therefore, as in Bitcoin and Ethereum, peers use **gossip** communication.
 - Tendermint supports **dynamic group membership** safely by requiring a $+2/3$ quorum of validators to approve of membership changes. It is commonly used along with Proof-of-Stake so that only peers that can prove ownership of staked tokens can participate.
 - Tendermint supports **slashing** of staked tokens when validators are observed to deviate from the protocol.
- Tendermint is used as the consensus algorithm in the **Cosmos** project and the Cosmos Hub permissionless blockchain. The latest version is now known as “CometBFT”.



(Source: Lagaille, N.; Djari, M.A.; Gürcan, Ö. A Computational Study on Fairness of the Tendermint Blockchain Protocol. *Information* 2019, 10, p. 378)

Proof-of-Stake consensus in Ethereum: Beacon Chain protocol

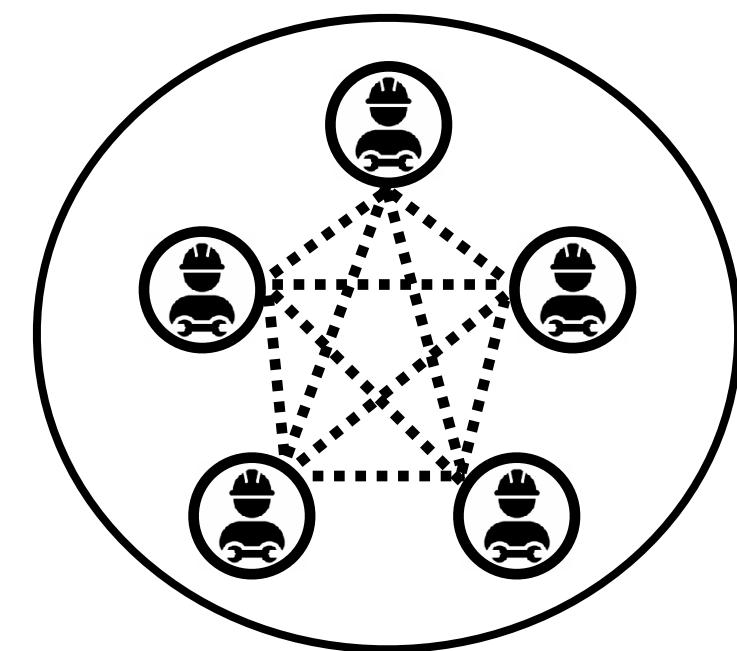
- Nodes have to **stake minimum 32 ether** into a deposit contract as collateral to become a **validator**. Some or all of a validator's stake can be destroyed if it is found to be dishonest. Nodes thus have strong **economic incentives** to remain honest.
- Ethereum works with fixed time slots. In every time slot (spaced 12 seconds apart) a validator is **pseudorandomly selected** to be the block **proposer** and another group of nodes is pseudorandomly selected to form a **committee** (with a minimum size of 128).
- The chance to get elected as the block proposer is **proportional to a validator's staked funds**.
- The **proposer** bundles transactions, executes them and determines the new system state. They wrap this information into a block and broadcast it to the committee.
- When validators in the **committee** receive the block, they re-execute the transactions to ensure they reach the identical new system state. If they agree, they **attest** to the validity of the block by signing it. **A 2/3 majority weighted by stake is needed** to finalize the block.
- Validators sign blocks using **BLS** signatures (for compact **signature aggregation**: only 96 bytes per aggregate signature)
- If a validator sees two conflicting blocks for the same slot they pick the one with the **greatest economic weight** of block attestations (LMD-GHOST fork-choice rule).



(Image credit: ConsenSys. Source: consensys.net, February 2020)

Consensus in Permissioned Blockchains

- Avoid the privacy and scalability challenges of permissionless blockchains by **limiting** readers and/or writers **to** a set of **authorised parties only**
- This **avoids** the **sybil attack** problem and the need to use “**lottery**”-based consensus (Proof-of-Work, Proof-of-Stake, ...)
- Instead, use standard “**voting**”-based consensus algorithms such as PBFT



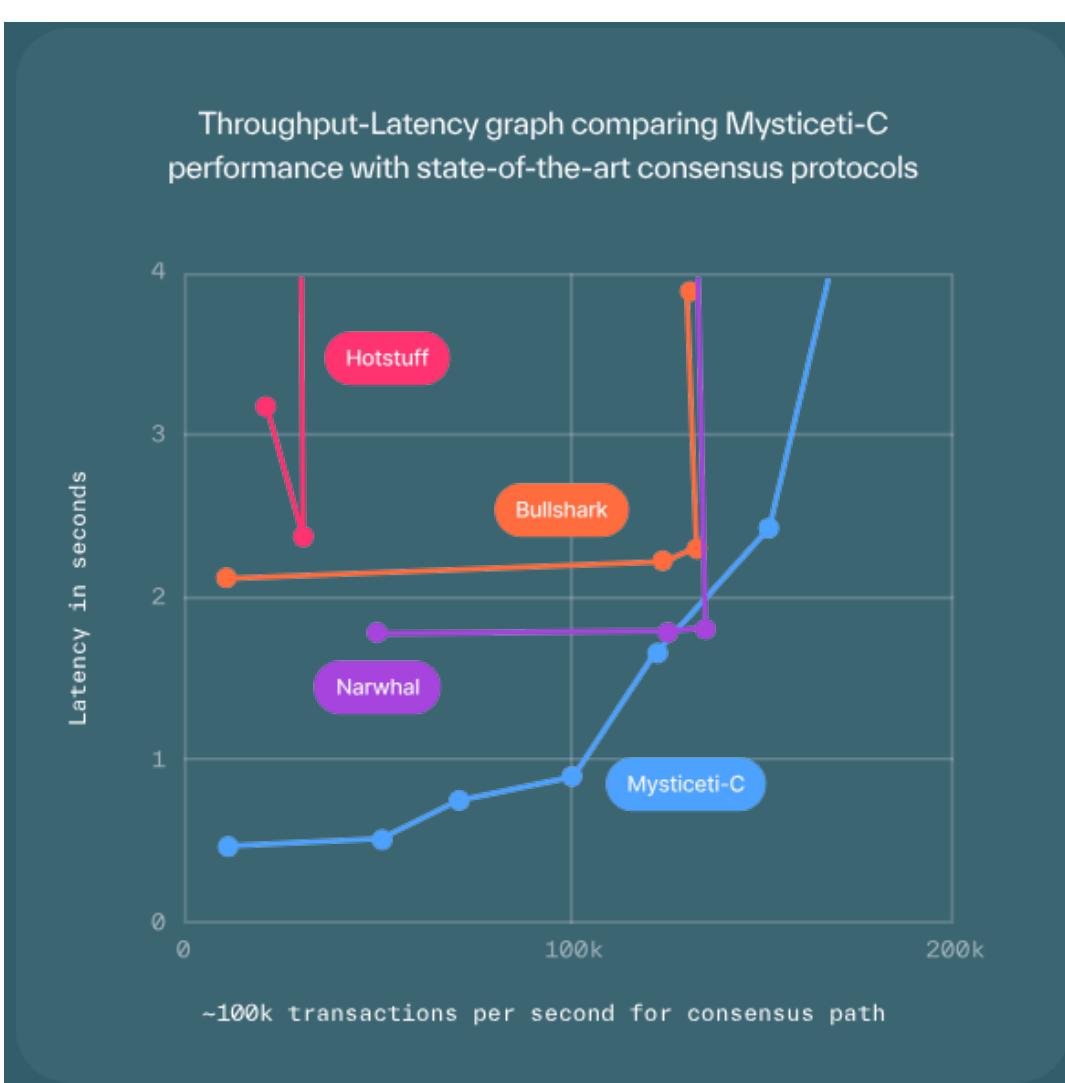
Permissioned vs Permissionless Blockchains: summary

	Permissionless	Permissioned
Network peers	Validator nodes are pseudonymous .	Validator node identity is usually revealed .
Peer membership	Open (anyone can join, no need to ask “permission” to join)	Closed (an administrator authorizes membership, or pre-existing members vote to update the membership list)
Network size	Scales to large number of peers (>1000 nodes)	Usually small (< 100 nodes)
Network connectivity	Low (not all peers may be able to connect to all other peers)	High (often fully connected - all nodes can reach all other nodes)
Consensus achieved via	Lottery -based algorithms, based on proof of owning some scarce resource (e.g. Proof-of-Work, Proof-of-Stake)	Voting -based algorithms, such as Byzantine Fault-tolerant (BFT) consensus algorithms (e.g. PBFT)
Transaction throughput	Low (~10 TPS for Bitcoin, Ethereum). Generally: the larger the network, the lower the TPS.	High (10,000 or more TPS) (TPS = transactions per second)
Transaction & Block finality	Probabilistic & slow (blocks are considered final only after being extended by enough newer blocks, which can take 10s of minutes)	Deterministic & fast (blocks are considered final as soon as 2/3 of validators accepted it, which may take < 1 second)
Safety threshold	At least 50% of a scarce resource (compute power, staked tokens) under the control of honest (correct) peers.	At least $2f + 1$ honest (correct) peers for every f byzantine peers ($N - f = 2f+1$). In other words, >2/3 or 67% honest.
Energy-efficiency	Very low for Proof-of-Work. High for Proof-of-Stake.	High (similar to standard replicated databases)

Final words about consensus algorithms

- Consensus protocols, like cryptographic protocols, are rife with implementation subtleties. Just like it is not wise to invent your own cryptography protocol, it is usually not wise to invent your own consensus algorithm.
- Before Blockchain (pre-2009) the focus of the academic community was almost exclusively on crash fault-tolerant (CFT) consensus among a *closed* group of processes.
- The PBFT algorithm (1999) was a milestone in achieving byzantine fault-tolerant (BFT) consensus in real-world networks, but also still assumed a *closed* group of processes.
- With the advent of Blockchain (post-2009), the focus has shifted to study BFT consensus in an *open* and *adversarial* environment (there is no a-priori closed group of processes).
- Today the **state-of-the-art** are **DAG-based consensus** algorithms
 - **DAG-Rider**: All You Need Is DAG (PODC 2021). [I. Keidar, E. Kokoris-Kogias, O. Naor, A. Spiegelman]
 - **Narwhal & Tusk** (EuroSys 2022) [G. Danezis, E. Kokoris-Kogias, A. Sonnino, A. Spiegelman]
 - **Bullshark** (CCS 2022) [A. Spiegelman, N. Giridharan, A. Sonnino, E. Kokoris-Kogias]

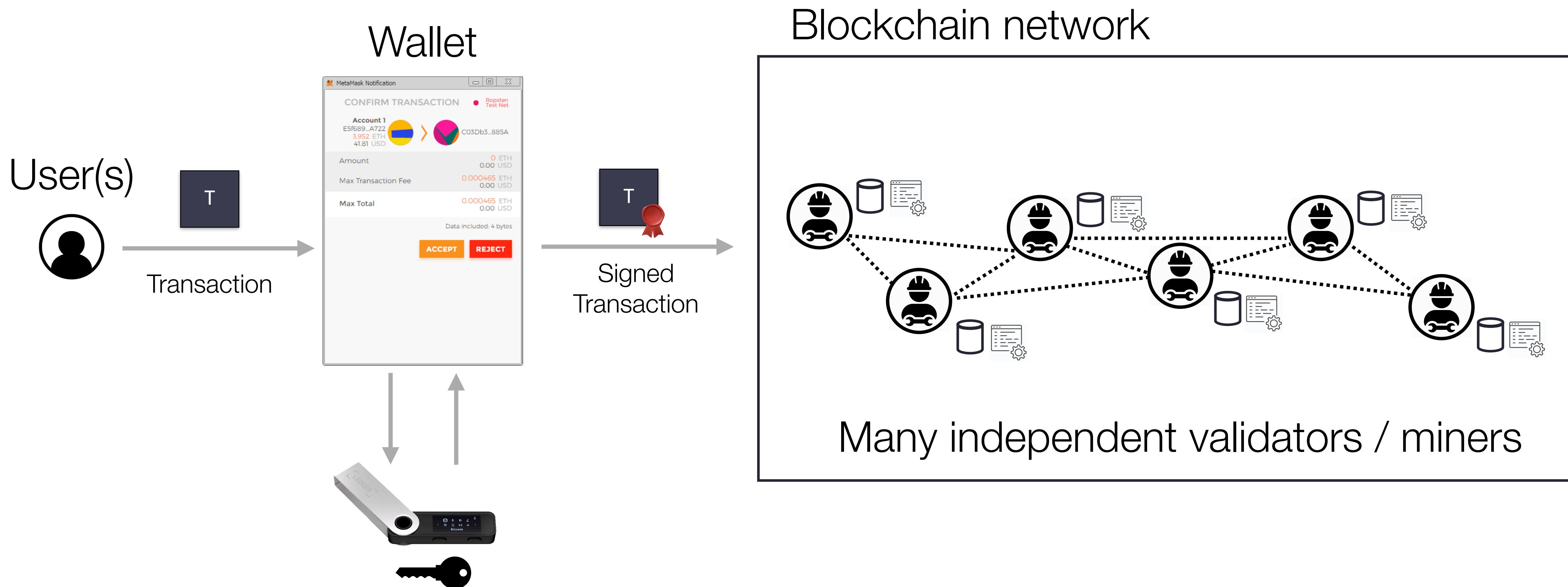
Sui Mysticeti: 100.000 tps at
<1sec finality ([paper](#))



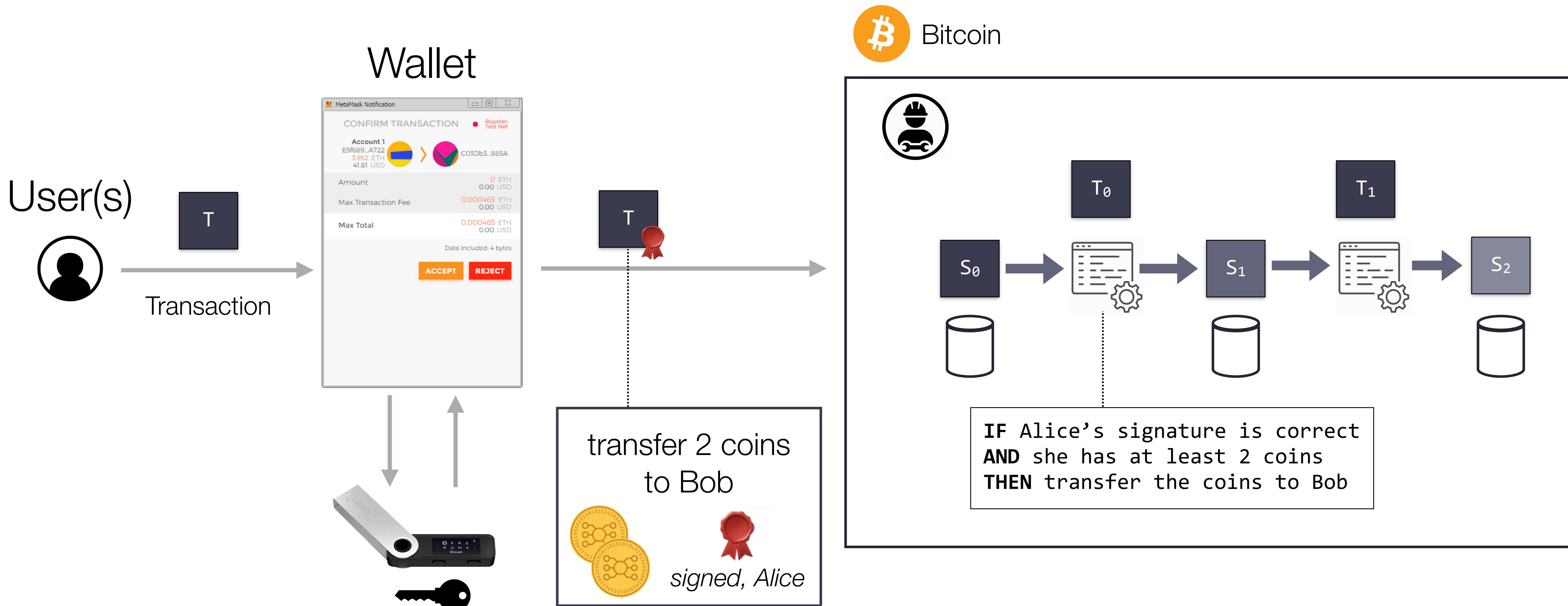
(Source: Sui / Myster Labs, 2024)

Blockchains as trusted computers: **smart contracts** and **Ethereum**

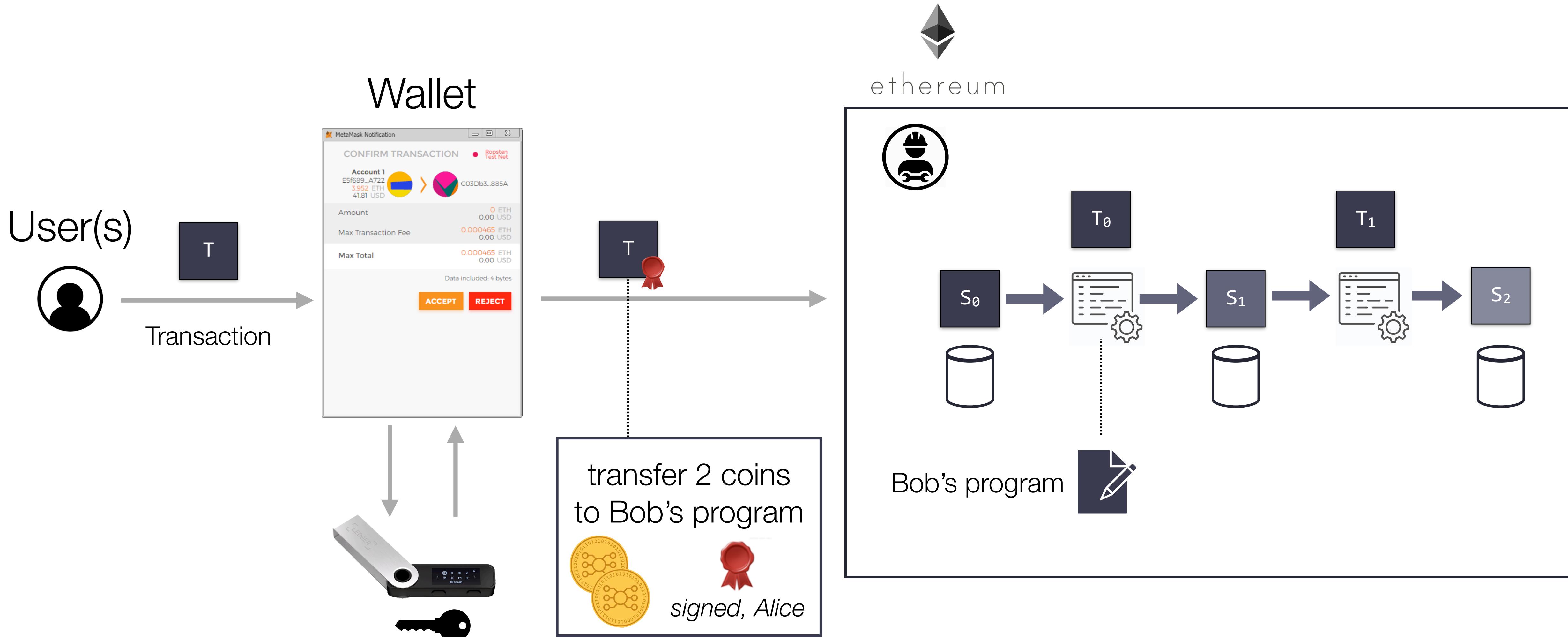
Physical view: a blockchain is a peer-to-peer network of computers



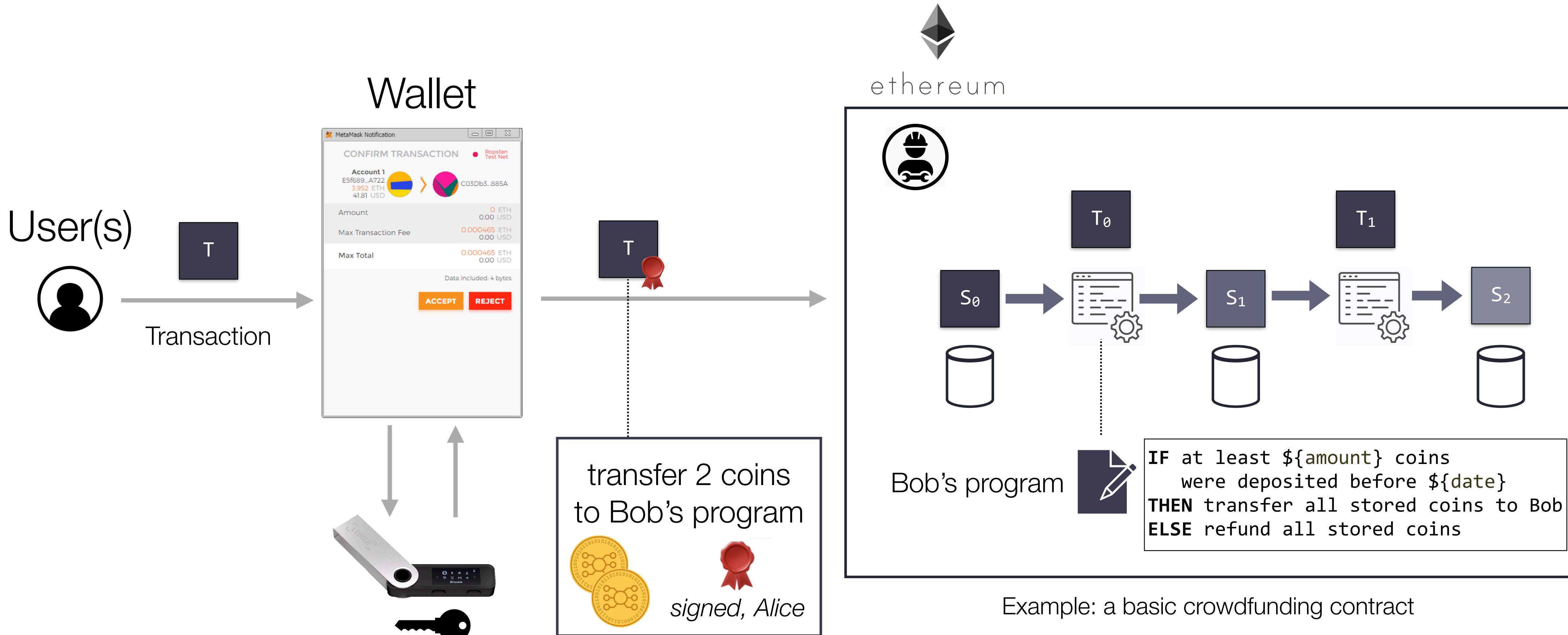
Logical view: a blockchain is a transaction processing machine



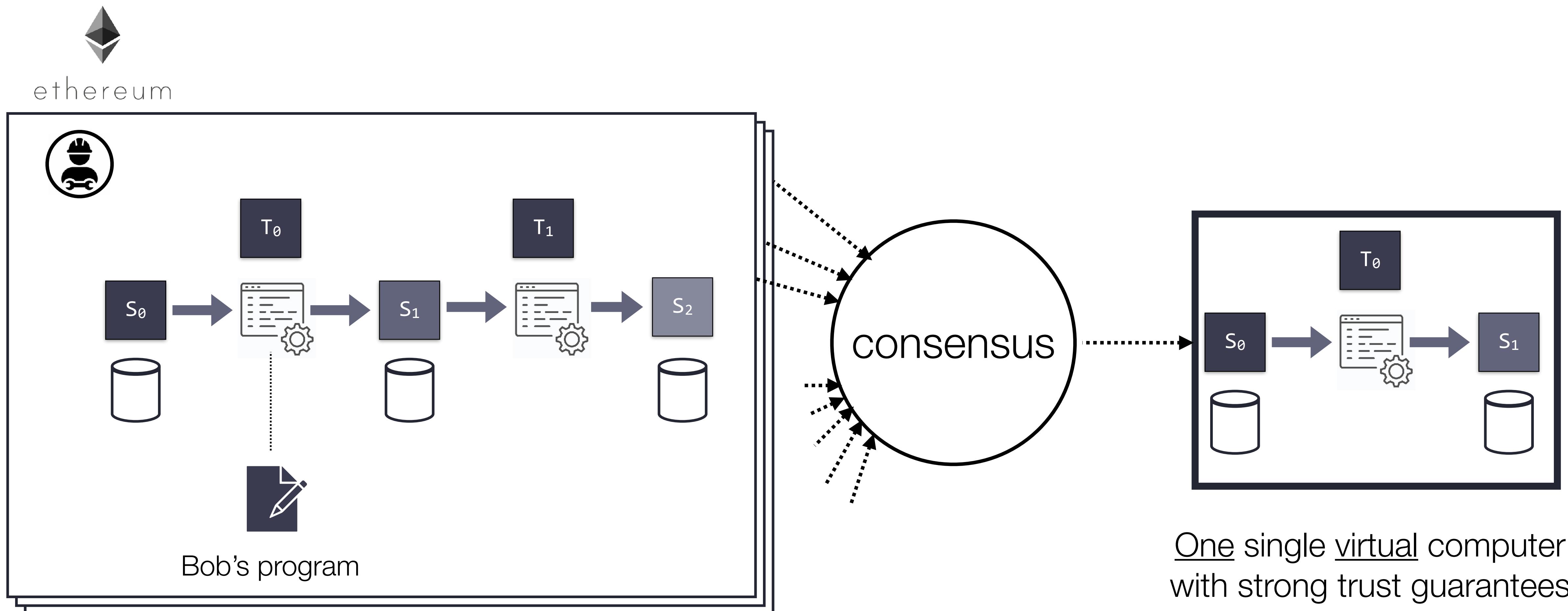
Ethereum's innovation: make the transactions programmable!



Ethereum's innovation: make the transactions programmable!



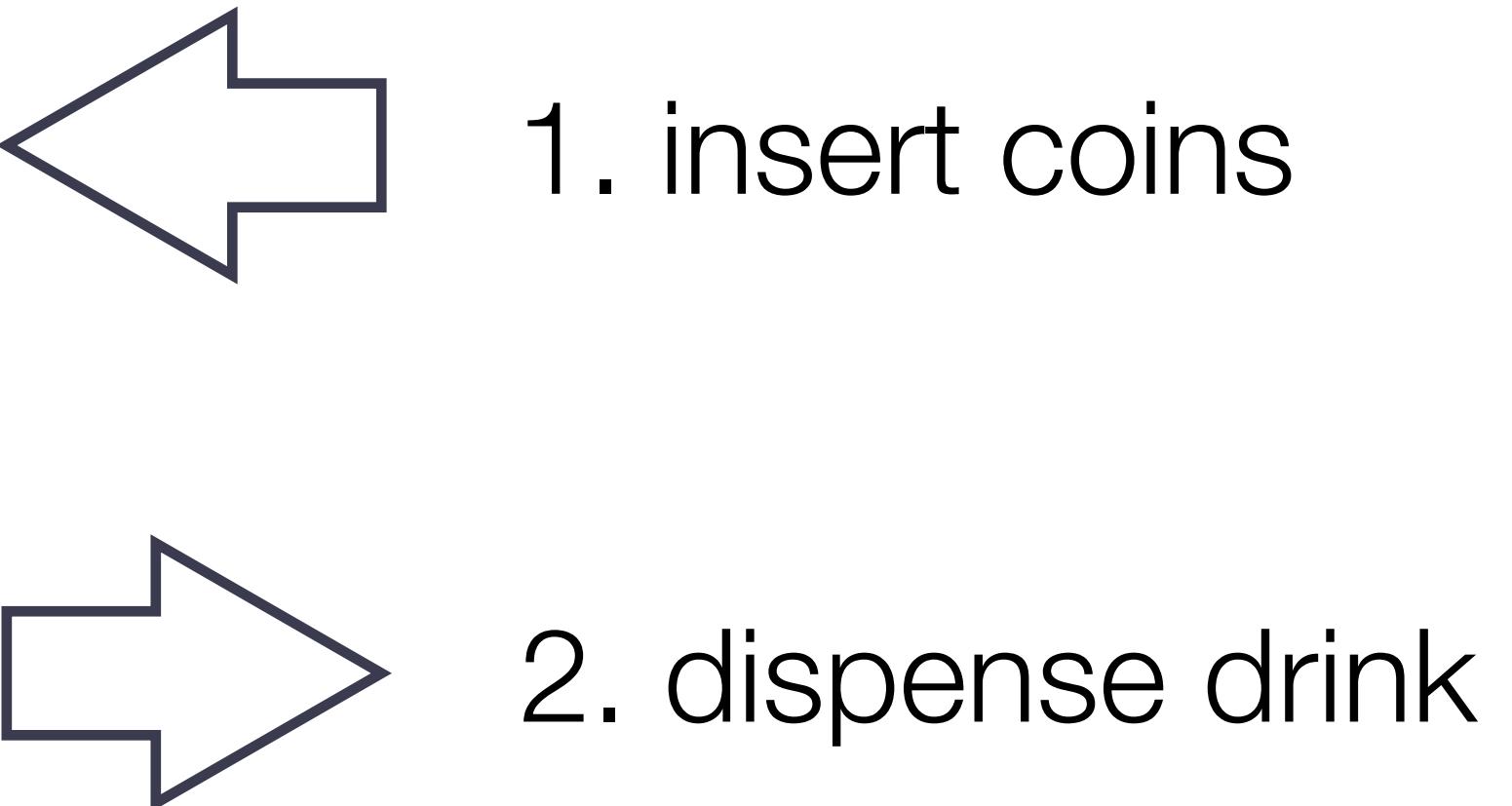
Blockchains as *trusted* virtual computers



Many (1000s) untrustworthy physical computers

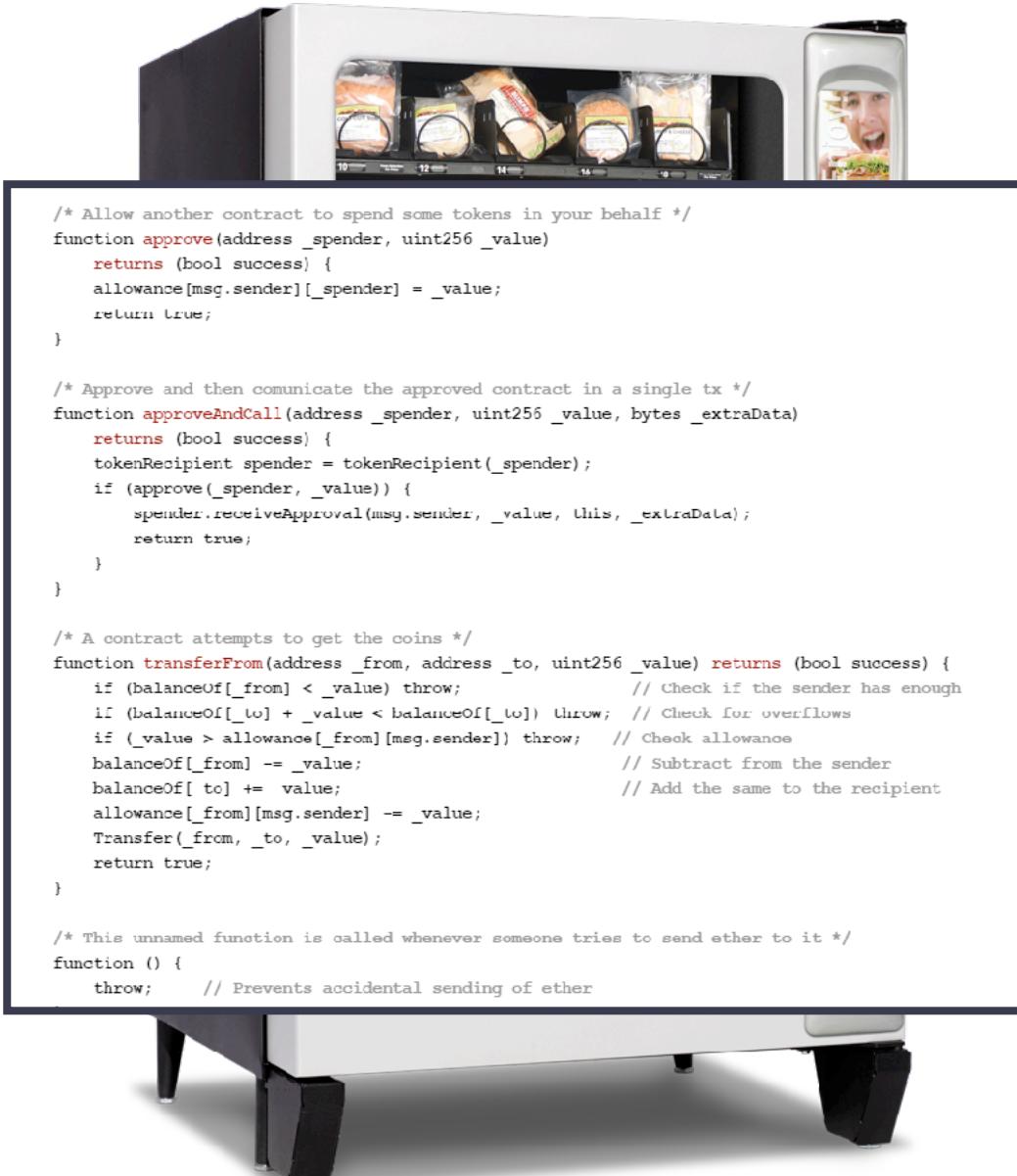
Smart contracts: basic principle

- A vending machine is an **automaton** that can trade **physical** assets

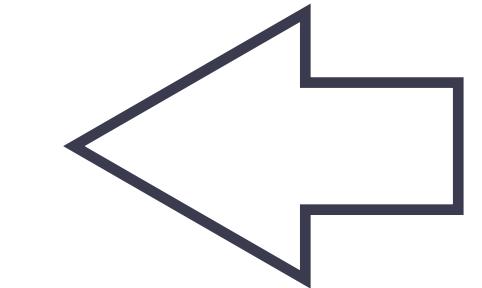


Smart contracts: basic principle

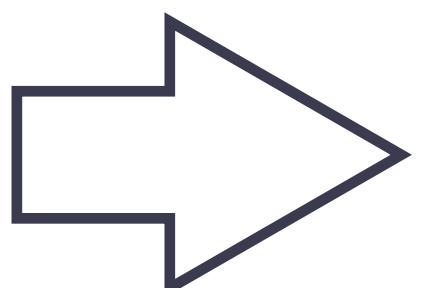
- A smart contract is an **automaton** that can trade **digital assets**



code



1. insert digital coins (tokens)



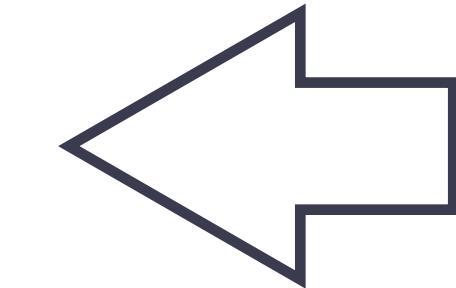
2. dispense other digital assets
or electronic rights

But who should we trust to faithfully execute the automaton's code?

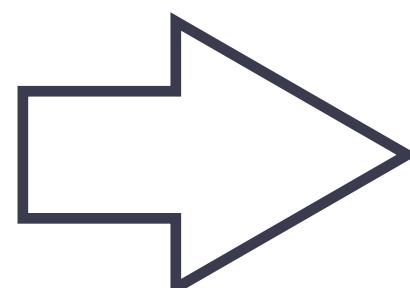
- A smart contract is an **automaton** that can trade **digital** assets



code



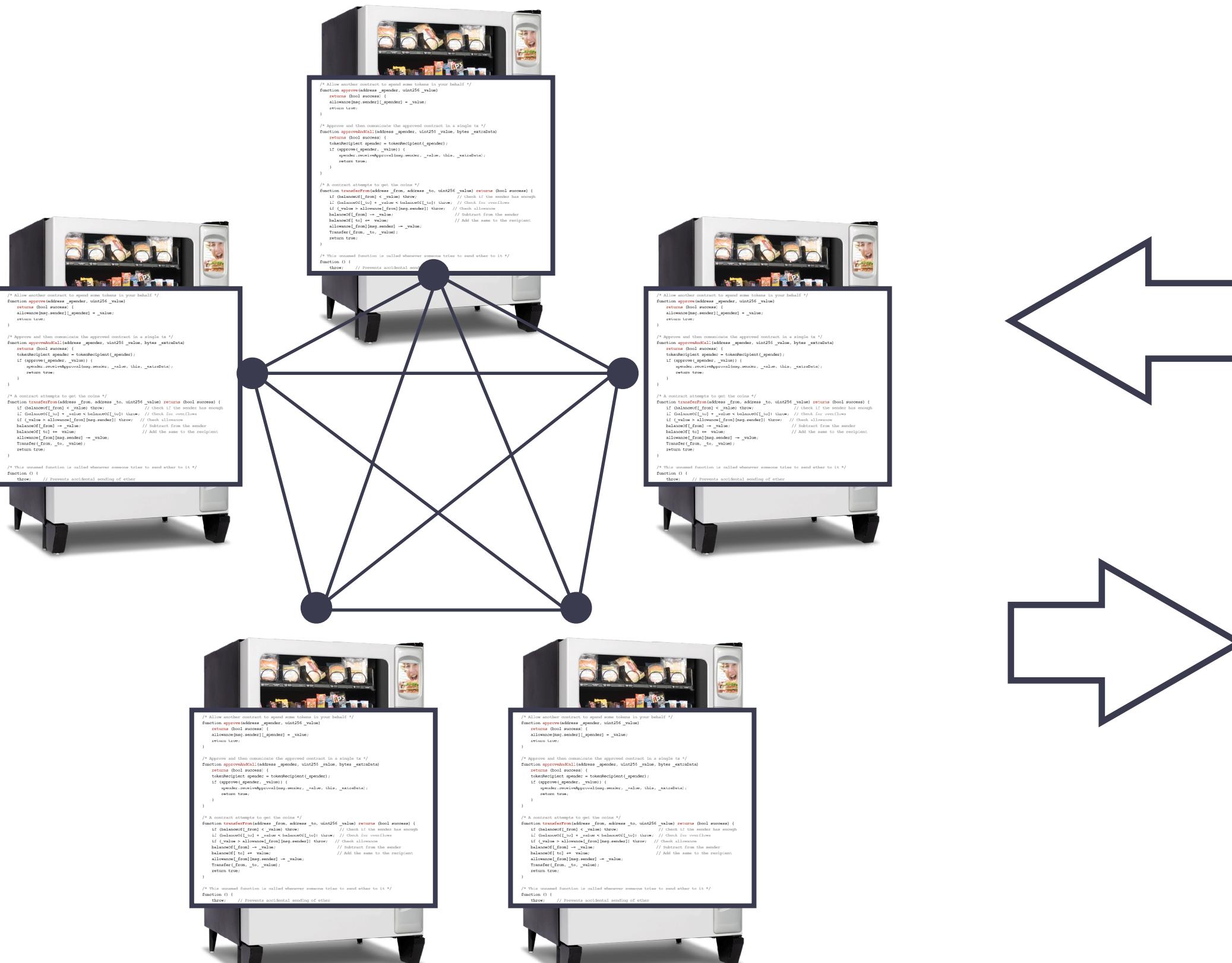
1. insert digital coins (tokens)



2. dispense other digital assets
or electronic rights

Delegate trust to a decentralised network (= blockchain!)

- A smart contract is a **replicated automaton** that can trade **digital assets**

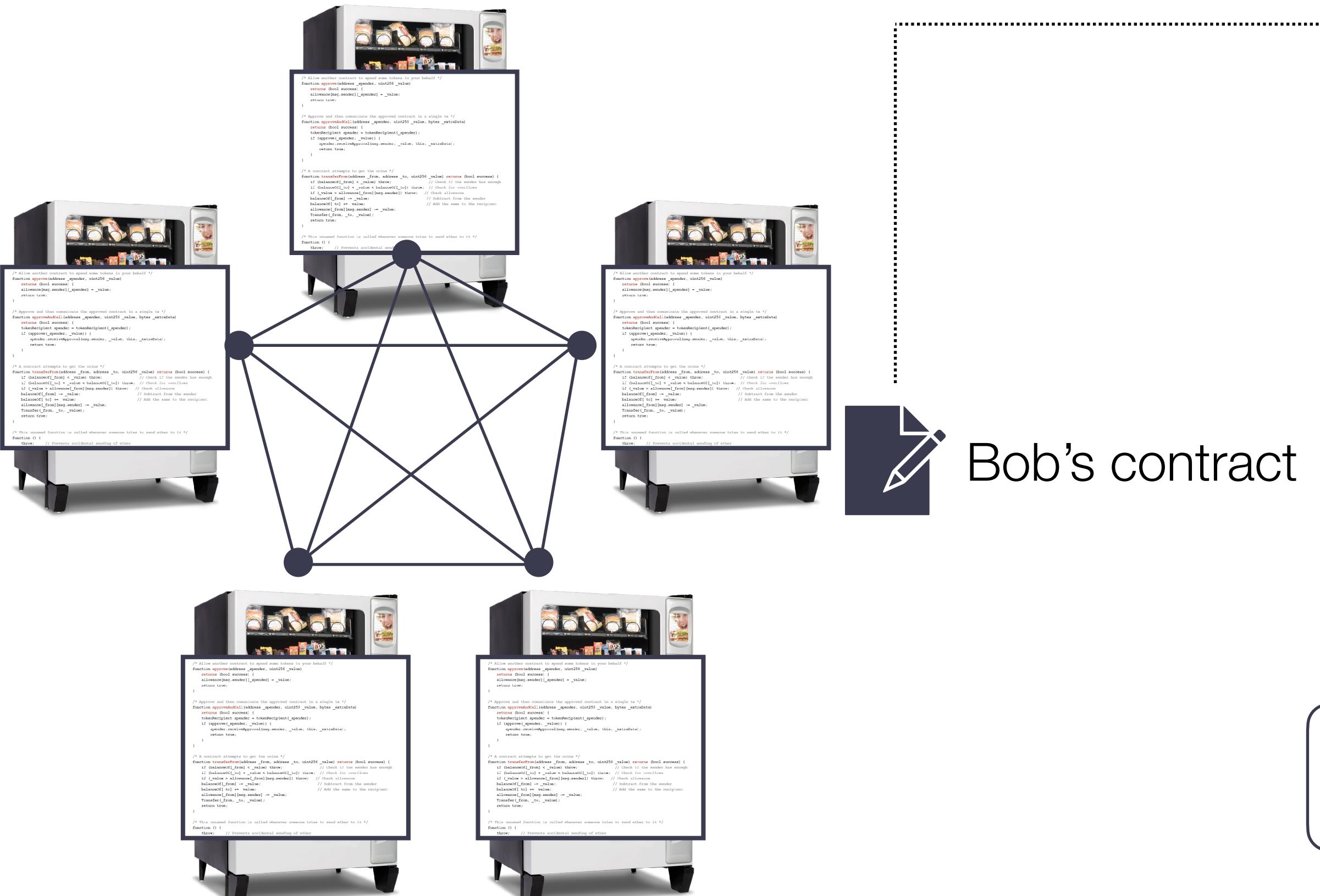


replicated code

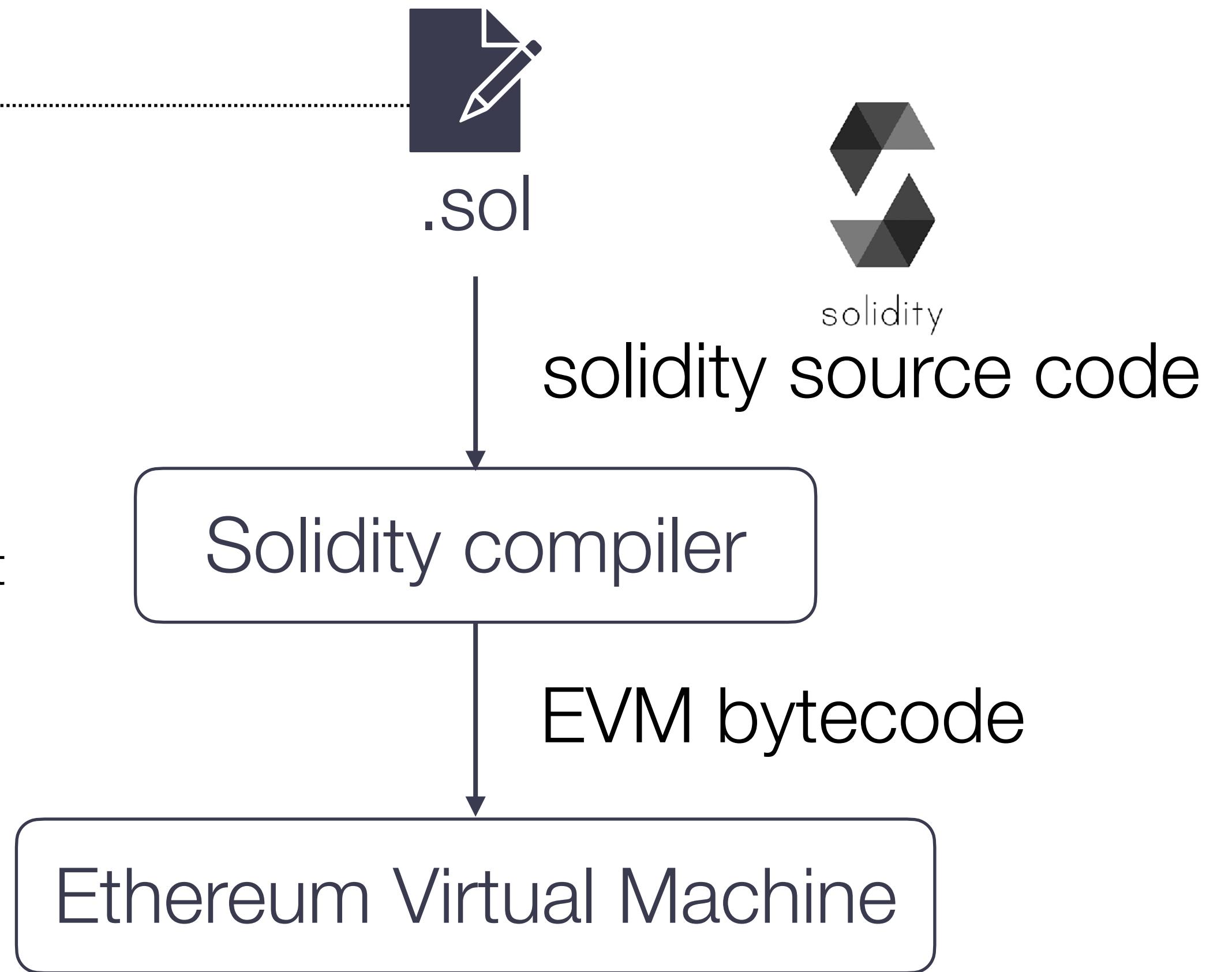
1. insert digital coins (tokens)

2. dispense other digital assets
or electronic rights

Contracts are compiled into bytecode for a simple stack machine



network of validator nodes

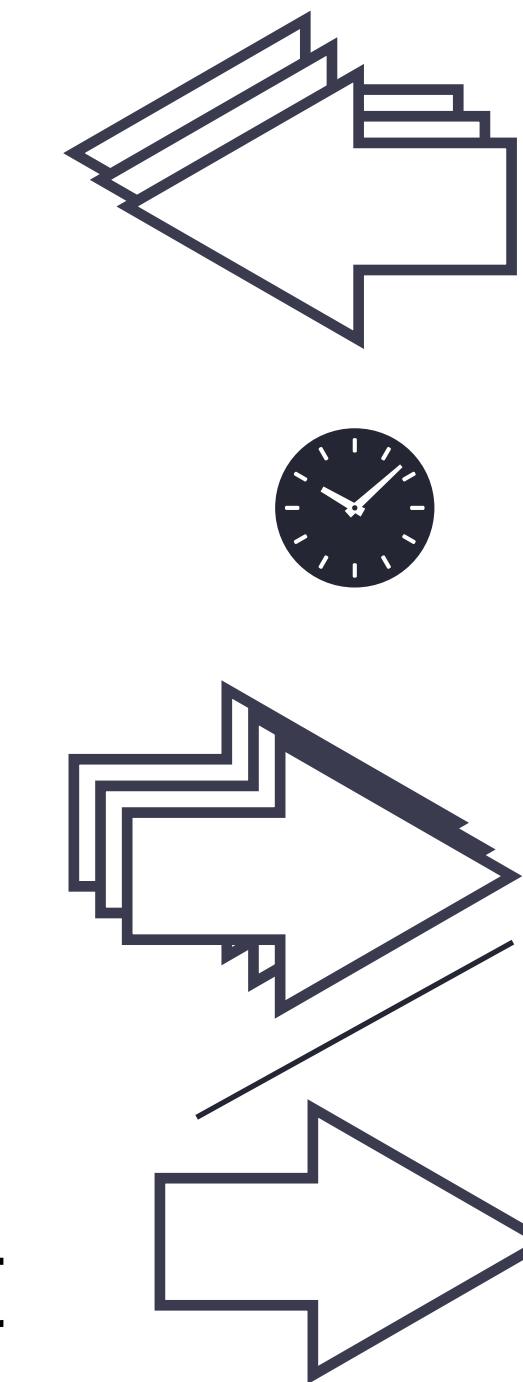


Example: crowdfunding as a smart contract

- Can we model a crowdfunding campaign as an automaton?

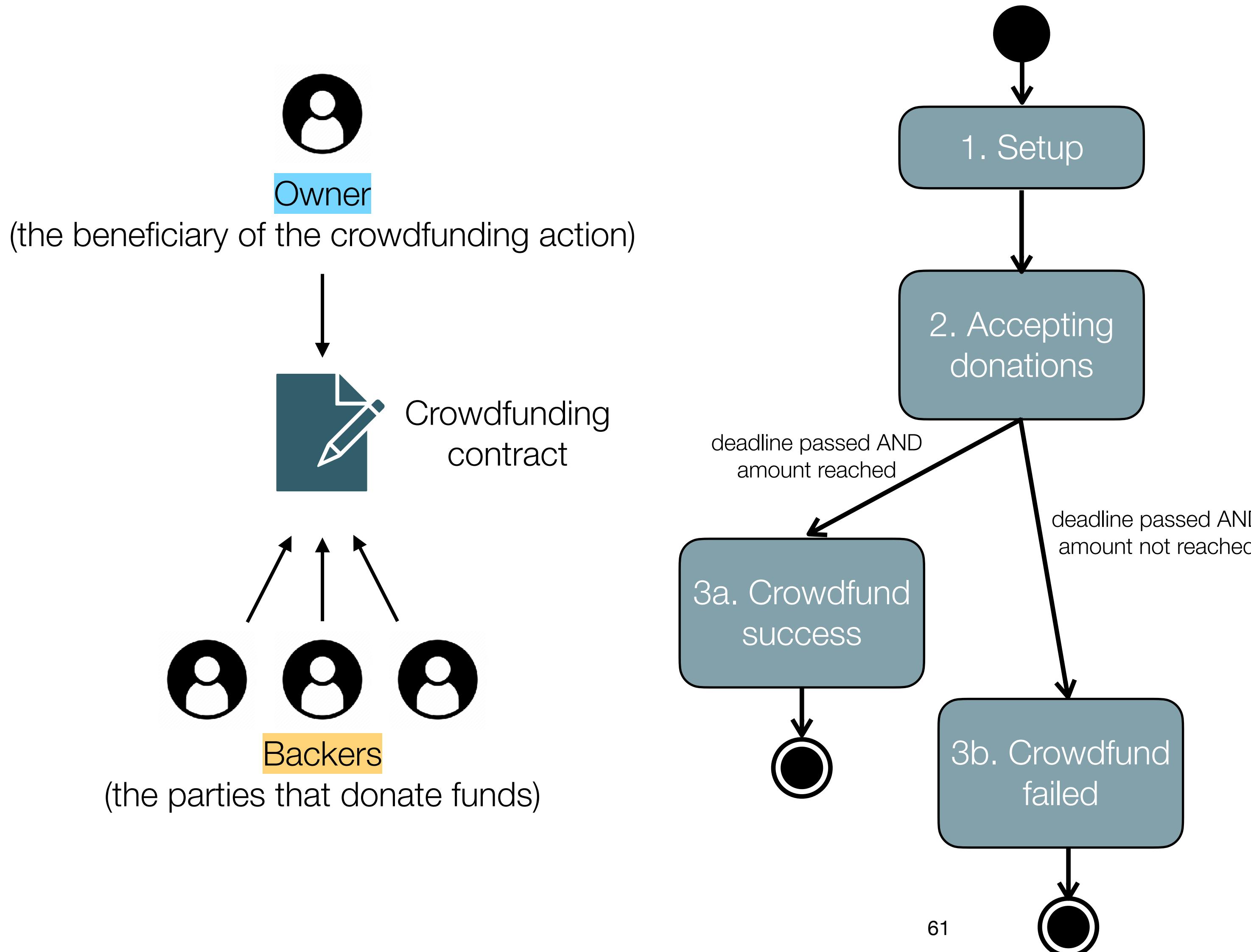


crowdfunding contract



1. Backers deposit tokens (pledge support)
2. Wait until deadline to see if the goal was met
- 3a. Either the backers withdraw their share...
- 3b. or the beneficiary withdraws the full deposit

Example: crowdfunding as a smart contract



Step 1: the **owner** creates the contract, stating target amount + funding deadline (which **cannot be changed** afterwards)

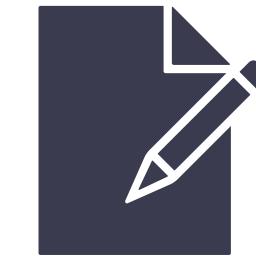
Step 2: **backers** can donate money **(deposit** funds into the contract)
IF the funding deadline has not yet passed

Step 3a (crowdfunding successful):
the **owner** can claim the funds
(withdraw funds from the contract)
IF the funding deadline has passed AND the minimum target amount has been met

Step 3b (crowdfunding failed):
backers can reclaim their donations
(withdraw funds from the contract)
IF the funding deadline has passed AND the minimum target amount has **not** been met

Crowdfunding contract: Solidity source code

```
contract Crowdfunding {  
    address public owner;      // the beneficiary address  
    uint256 public deadline;  // campaign deadline in number of days  
    uint256 public goal;      // funding goal in ether  
    mapping (address => uint256) public backers; // the share of each backer  
  
    constructor(uint256 numberOfDay, uint256 _goal) {  
        owner = msg.sender;  
        deadline = block.timestamp + (numberOfDay * 1 days);  
        goal = _goal;  
    }  
    function donate() public payable {  
        require(block.timestamp < deadline); // before the fundraising deadline  
        backers[msg.sender] += msg.value;  
    }  
    function claimFunds() public {  
        require(address(this).balance >= goal); // funding goal met  
        require(block.timestamp >= deadline); // after the withdrawal period  
        require(msg.sender == owner);  
        payable(msg.sender).transfer(address(this).balance);  
    }  
    function getRefund() public {  
        require(address(this).balance < goal); // campaign failed: goal not met  
        require(block.timestamp >= deadline); // in the withdrawal period  
        uint256 donation = backers[msg.sender];  
        backers[msg.sender] = 0;  
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```



.sol

(Based on: Ilya Sergey, “The next 700 smart contract languages”, Principles of Blockchain Systems 2021)

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```

Declare a contract.

Similar to a class in OOP, a contract can have **state** (variables) and **behaviour** (functions)

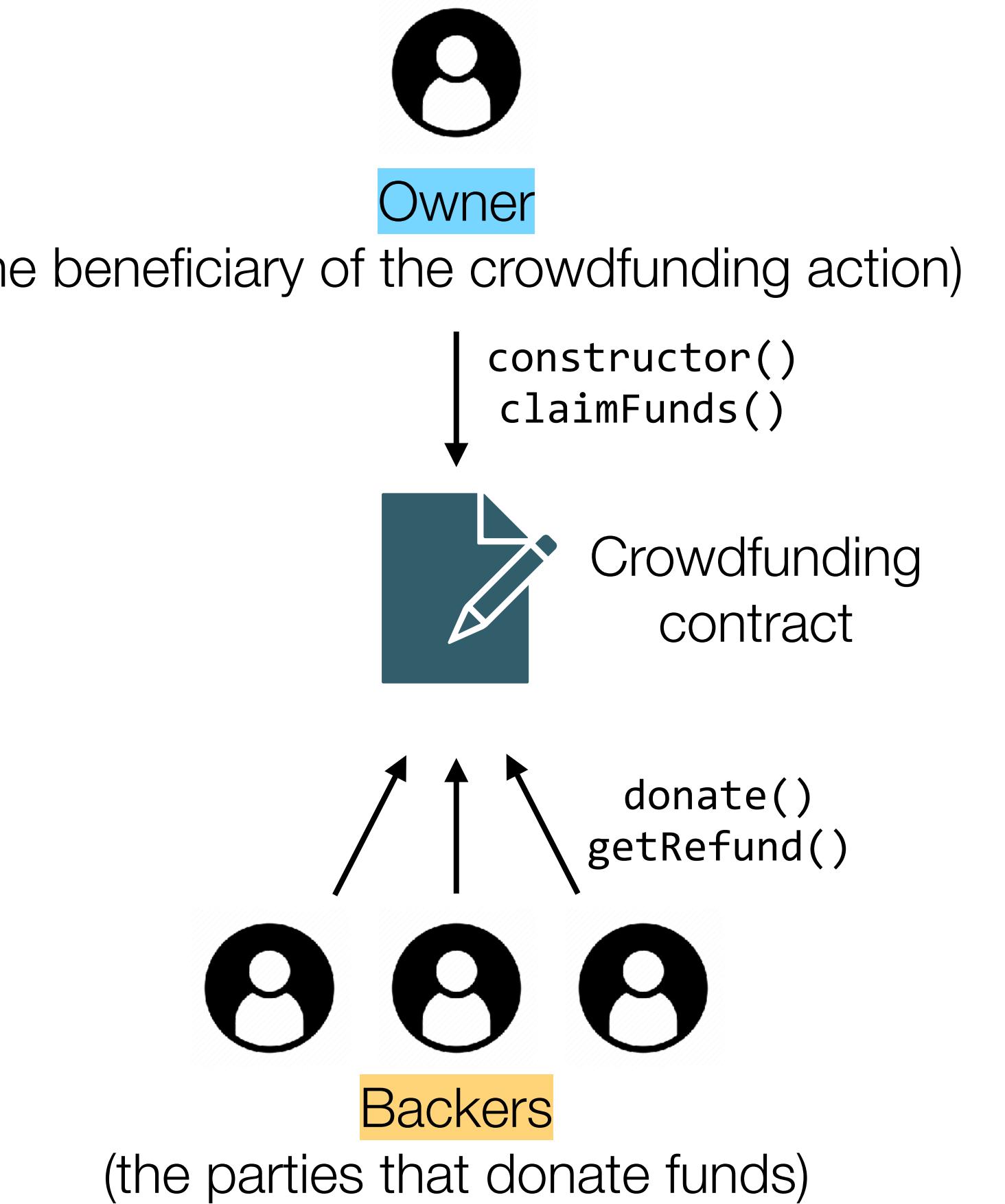
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    }  
}
```

All contract state is **replicated** and publicly **persisted** on the blockchain.

Crowdfunding contract: Solidity source code

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    }  
}
```

Instructions to deposit and withdraw money (ether)

Decentralized Applications (Dapps)

Decentralized applications: what and why?

- **Decentralized applications (dapps)** are web applications backed by smart contracts
 - To achieve **transparency** (publish the core application logic on a blockchain, immutable and verifiable by anyone)
 - To resist **censorship** (avoid a single point of control)
 - To improve **reliability** (avoid a single point of failure)

Decentralized applications: examples



Decentralized autonomous organizations (DAOs)



Decentralized prediction markets & betting platforms



Decentralized lending and borrowing protocol



“Play-to-earn” games



Decentralized exchanges
Atomic token swaps

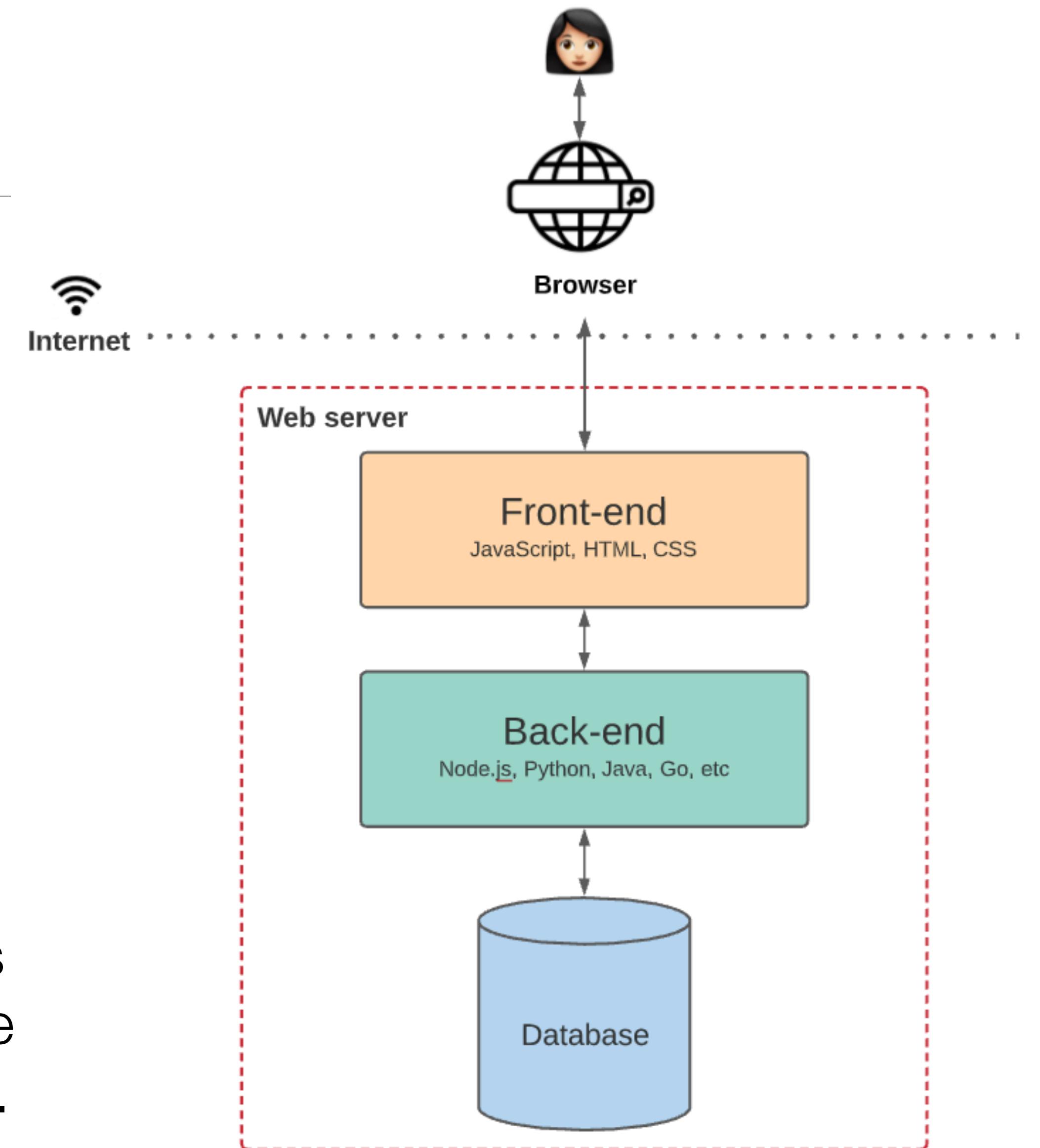


WEIFUND IS
DECENTRALIZED
CROWD-FUNDING

Decentralized crowd-funding

Traditional Web application architecture

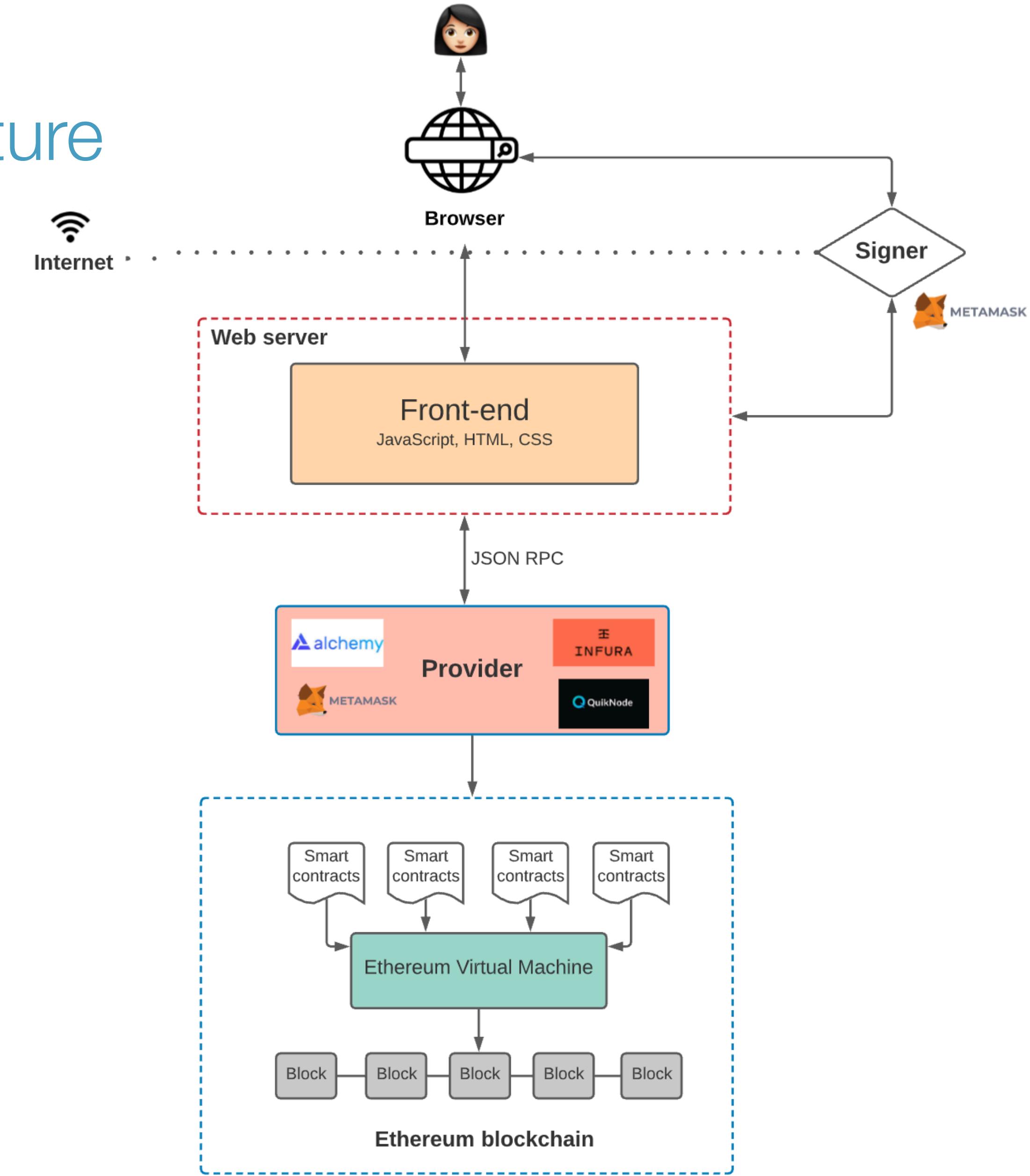
- Following a standard “3-tier” architecture:
- **Front-end**: code that runs in the browser (or on a mobile app), mostly UI logic
- **Back-end**: code that runs on a web server, focus on business logic
- **Database**: persists the application state
- It is common for the application to define the user’s identity and to store username and password in the database. The user **does not control** their identity.



(Source: P. Kasireddy, “The Architecture of a Web 3.0 application”, Medium.com:
<https://www.preethikasireddy.com/post/the-architecture-of-a-web-3-0-application>)

Decentralized Web application architecture

- **Front-end:** largely unchanged (mostly UI logic)
- **Back-end:** (part of) the application logic is implemented as a smart contract and published on the blockchain
- **Database?** The state of the smart contract is persisted on the blockchain (replicated across all validator nodes)
- **Node-as-a-Service Provider:** offers a REST API to relay requests from browsers or mobile apps to peers in the blockchain network.
- **Signer:** for any user action that results in an update to the smart contract, a **signature** is needed from the user. This task typically delegated to a wallet that securely stores the user's keys. The **user retains control** over their keys (they are *not* stored or controlled by the application).



Common Dapp “dev stack” options

- **Front-end** libraries



web3.js



ethers.js

- **Frameworks**



Hardhat



TRUFFLE

- **Node Providers**



alchemy



INFURA

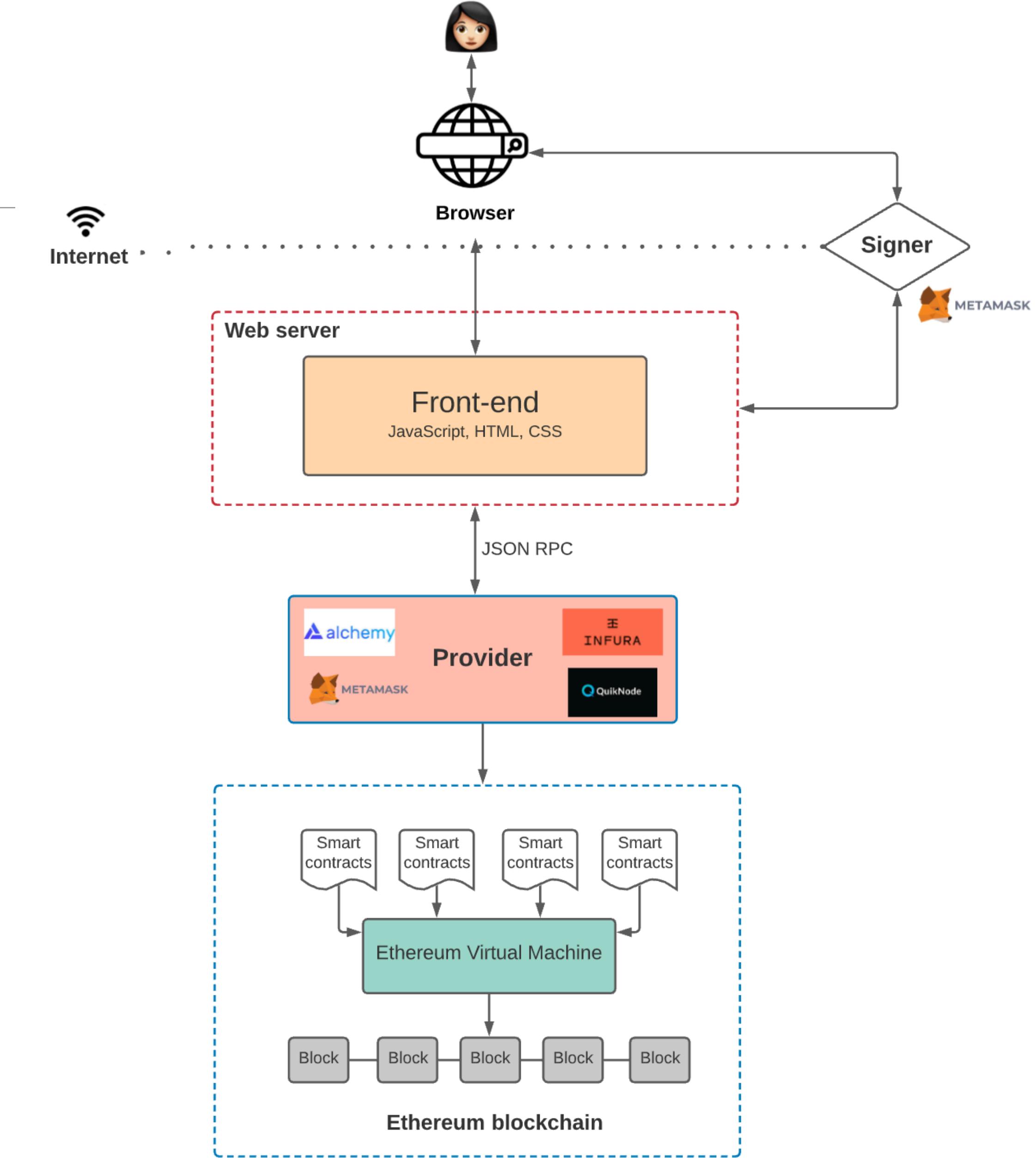
- **Signers**



METAMASK



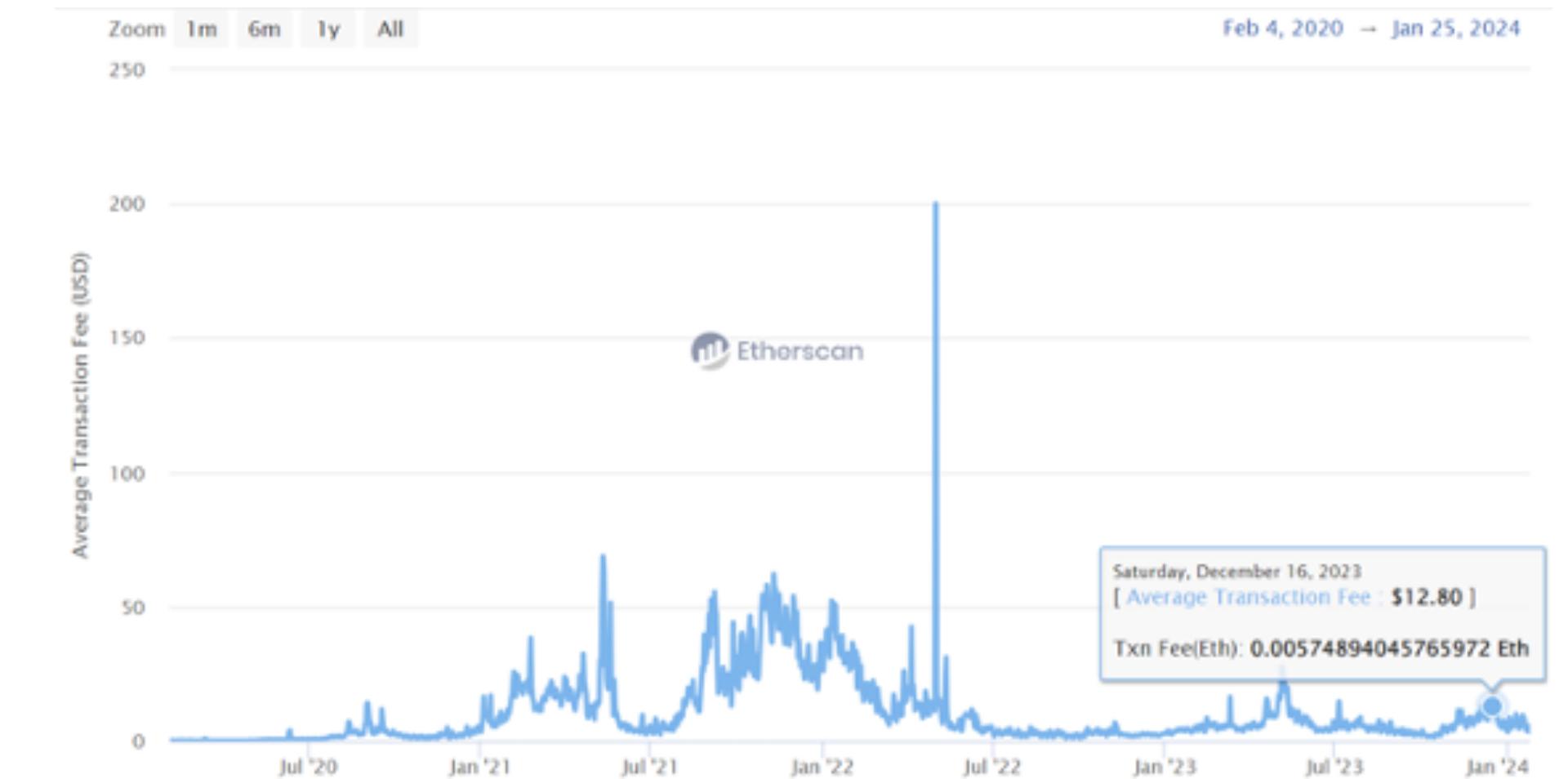
web3auth



Ethereum has challenges

- Can be expensive to use (> \$10 in transaction fees is not uncommon)
- Slow (~10-14 transactions per second)
- Bugs in contracts can be fatal

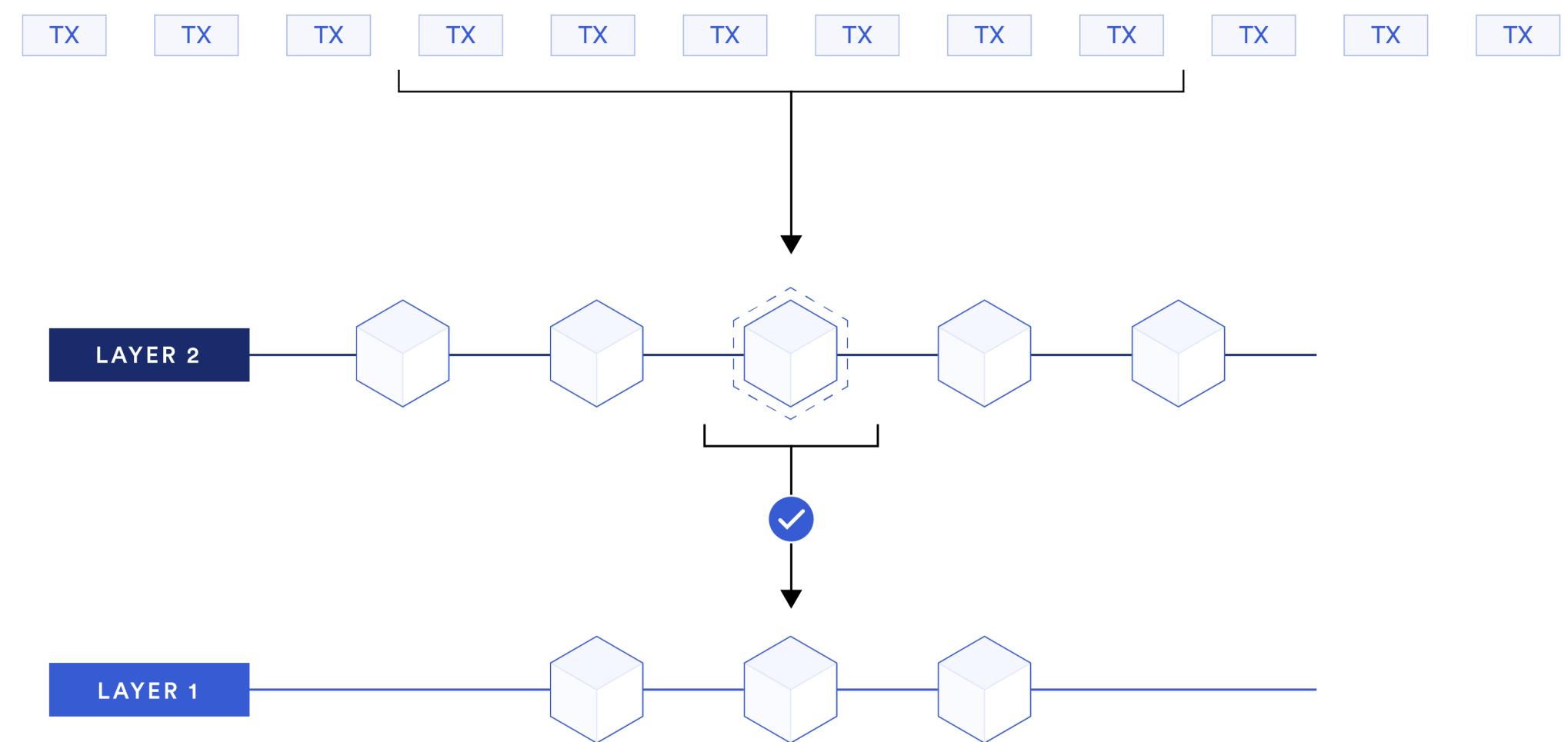
"On the layer 1 Ethereum blockchain, high demand leads to slower transactions and nonviable gas prices."¹



1 <https://ethereum.org/en/developers/docs/scaling>

“Layer 2” scaling solutions (a.k.a. “rollups”)

- Key idea: batch many “Layer 2” (L2) transactions into a single combined transaction stored on “Layer 1” (L1)
- Offer a way for anyone to verify that the batch of L2 transactions was correctly executed
 - “fraud proofs” => optimistic rollups
 - “zero-knowledge proofs” => zk-rollups



(Source: Chainlink)

“Layer 2” scaling solutions: landscape



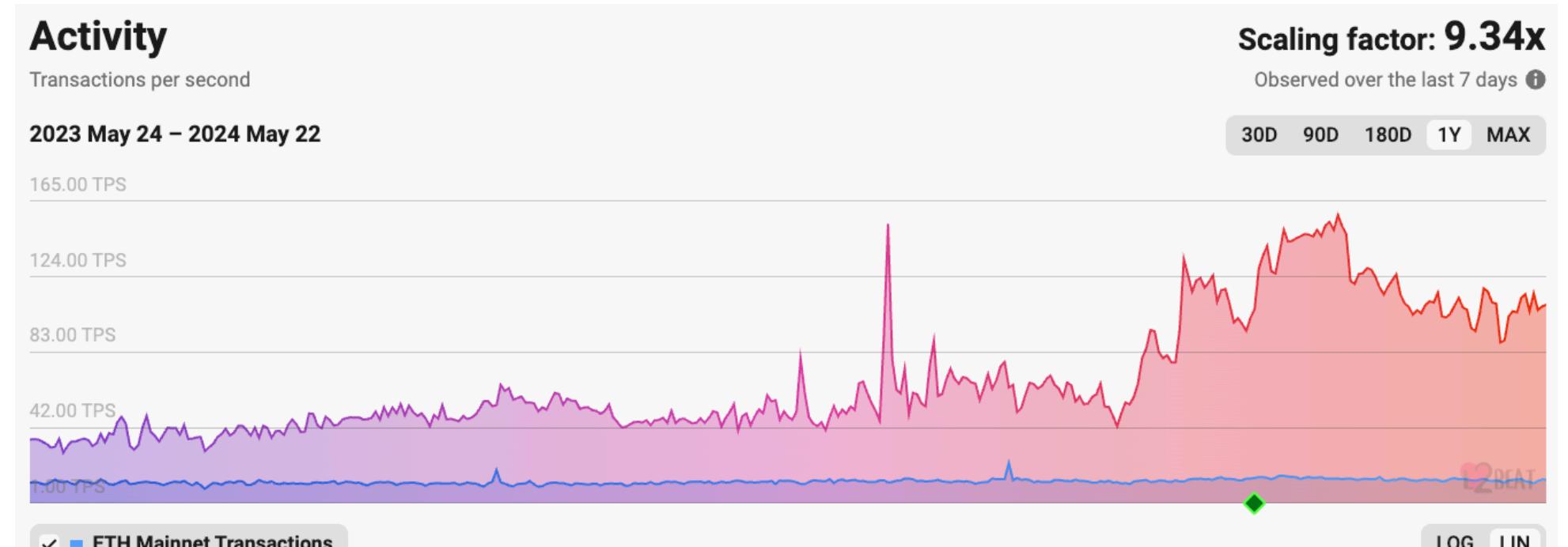
“Layer 2” scaling solutions: benefits

- **Lower** transaction **fees** (< \$0.01 / tx)

Name	Send ETH	Swap tokens
StarkNet	< \$0.01	< \$0.01 ▾
Arbitrum One	< \$0.01	\$0.01 ▾
Optimism	< \$0.01	\$0.02 ▾
Polygon zkEVM	\$0.02	\$0.32 ▾
Metis Network ⚠	\$0.03	\$0.14 ▾
Loopring	\$0.05	- ▾
zkSync Lite	\$0.06	\$0.14 ▾
DeGate	\$0.17	- ▾

(Source: [l2fees.info](#))

- **Higher** transaction **throughput**
(100-1000 tps at ~13min finality)



(Source: L2Beat)

Conclusion

Blockchain: hot topics & open challenges

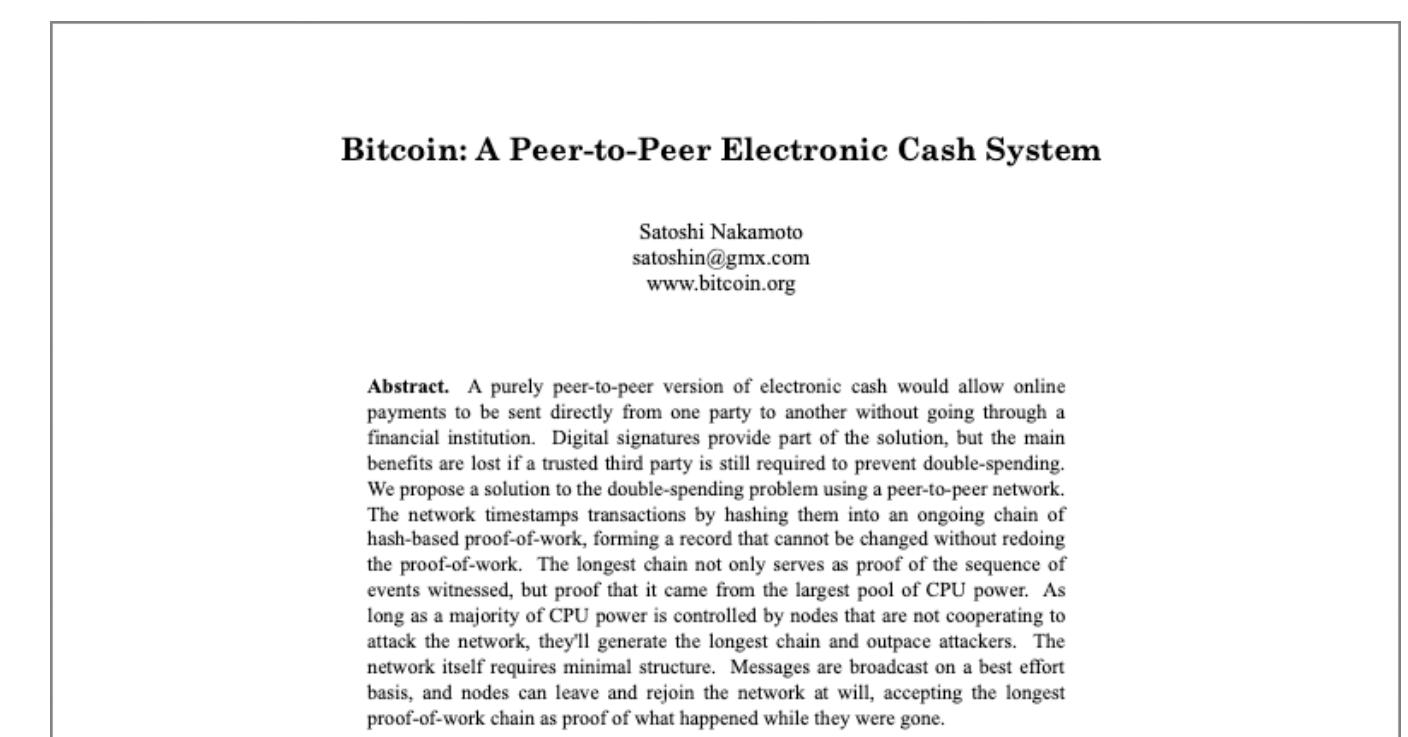
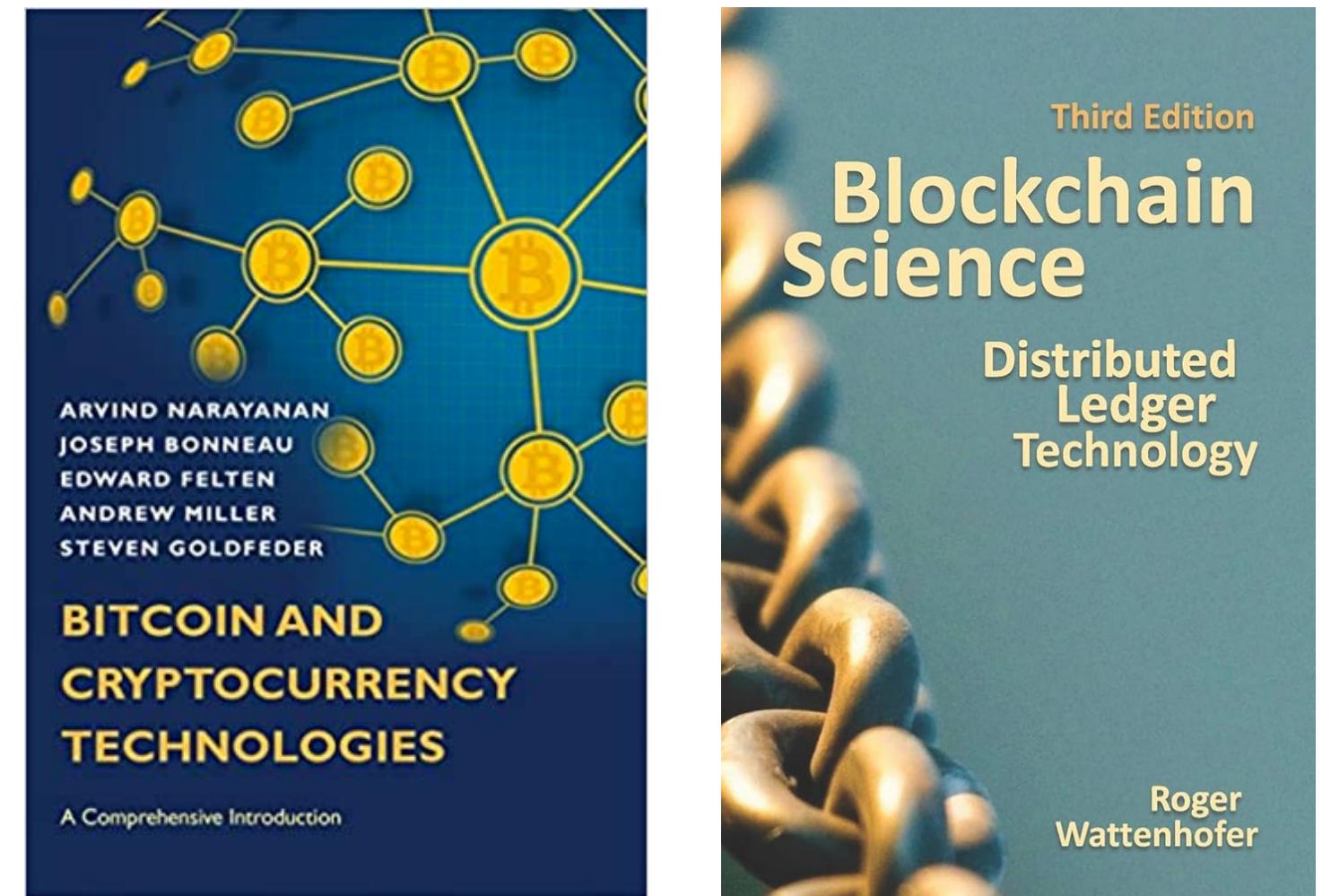
Problem	Solution	Examples
Lack of Privacy: can't store secrets on a blockchain	Zero-knowledge Proofs	ZCash, Privacy Pools, StarkNet, ...
Poor scalability: “secure, scalable, decentralized: choose two”	Layer-2 rollups, AppChains, Payment channels	Cosmos, Arbitrum, Optimism, Lightning, ...
Security vulnerabilities in smart contracts	Use safer languages and abstractions	Rust (Solana, ICP, NEAR, ...), Move (Sui, Aptos), ...
(Mobile/Web) clients must trust servers to access the blockchain	Stateless “light clients”, compact inclusion proofs, decentralized RPC protocols, ...	Verkle trees, Mina protocol, Celestia, Portal network, ...
Silos: assets stored on one blockchain cannot be used on another	Cross-chain “bridges”, atomic swaps (hashed time-locked contracts), ...	Inter-blockchain Communication (IBC) protocol, Wormhole, ...
Oracles: how to get trustworthy, reliable access to off-chain data?	Decentralized Oracle Networks (DONs)	Chainlink, ...

Recap: course topics

- The **origins** of Blockchain
- What are the **cryptographic building blocks** of a blockchain?
- How does a blockchain process transactions? **Life of a blockchain transaction.**
- **Consensus** in blockchain networks: Proof-of-Work, Proof-of-Stake, BFT Consensus
- **Permissioned** versus **Permissionless** blockchain networks
- Blockchains as trusted computers: **smart contracts** and **Ethereum**
- Building **decentralized applications** using blockchains

Further reading - good introductory resources on Blockchain

- Narayanan *et al.* “Bitcoin and Cryptocurrency Technologies” Princeton University Press, 2016 - preprint available for free online at: <https://bitcoinbook.cs.princeton.edu/>
- Roger Wattenhofer (ETH Zurich), “Blockchain Science”, 2019
- Satoshi Nakamoto, “Bitcoin: A Peer-to-Peer Electronic Cash System” a.k.a. the “Bitcoin whitepaper” (2008)



Further reading - good introductory resources on Ethereum

- Ethereum official project website: <https://ethereum.org/>
- Ethereum whitepaper: <https://ethereum.org/en/whitepaper/>
- Etherscan block explorer: <https://etherscan.io/>
- Remix, an online IDE and playground for Solidity: <https://remix.ethereum.org/>
- Solidity by Example: <https://solidity-by-example.org/>
- OpenZeppelin reusable contracts: <https://www.openzeppelin.com/contracts>
- Awesome-Ethereum: <https://github.com/ttumiel/Awesome-Ethereum>

Work Projects

Work projects

- Project 1: **build** an end-to-end **decentralized application** on Ethereum
- Project 2: perform a **comparative study of consensus protocols** for blockchains

Project 1: build a decentralized application on Ethereum

- Pick your own application use case, or elaborate on the Crowdfunding example
- Components to build:
 - **Front-end** (website UI, wallet integration)
 - **Back-end** (web-server, gateway to blockchain)
 - **Smart contract** (Solidity program, deployed on a test-network)
- Things to consider:
 - **Development:** use a developer framework like Hardhat
 - **Testing:** write unit tests to test the important interactions
 - **Static analysis:** use a static analysis tool for Solidity to find bugs
 - **Stretch goal:** look into **formal verification** of key safety / liveness properties

Project 2: comparative study of consensus protocols for blockchains

- Compare the consensus protocols of 5 real-world blockchains (2 classic, 3 modern):
 - **Bitcoin**'s original Proof-of-Work based protocol
 - **Ethereum**'s modern Proof-of-Stake based protocol
 - **Solana**'s Proof-of-History based protocol
 - **Internet Computer**'s ICC consensus protocol
 - **Sui**'s Mysticeti protocol
- Focus on:
 - **History**, origins
 - **Performance** (throughput, latency)
 - **Scalability** in terms of network size
 - **Security** thresholds (safety, liveness)

Blockchain and Distributed Ledgers

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Questions?
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