Distributed Systems and Consensus

50.037 Blockchain Technology

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“A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable.”

–Leslie Lamport

Intro

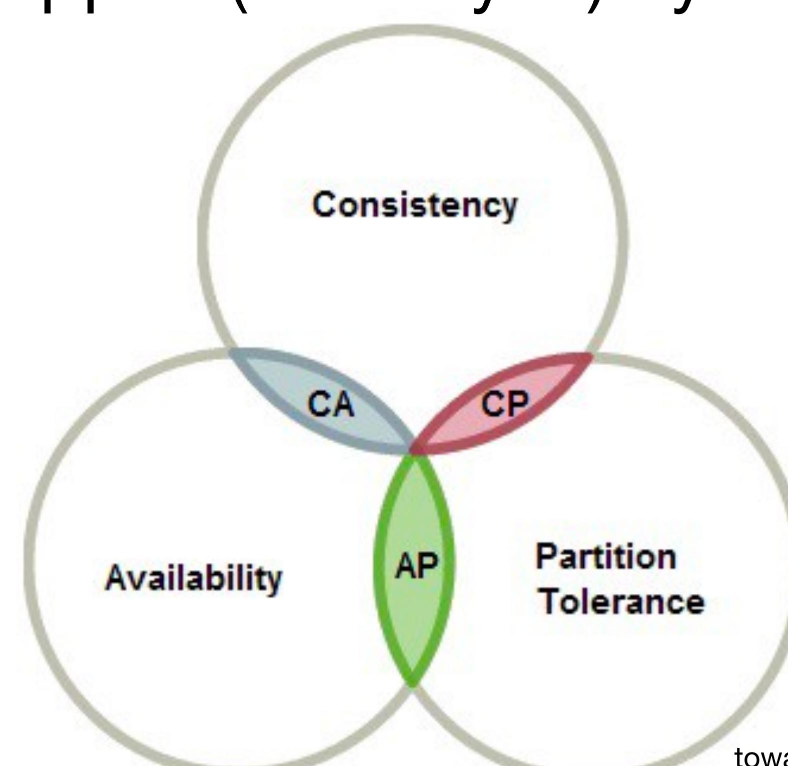
- Systems get large and complex
- Distributed system (selected topics)
  - CAP Theorem
  - Naming
  - Failure Tolerance and Consensus
  - PBFT-like Consensus
  - Nakamoto Consensus

Goal: Public Ledger

- Properties
  - Immutability, Transparency, Availability, Censorship-resistance, …
- Potential
  - General-purpose global database (with arbitrary processing logic on the top)
  - All kinds of transactions, notaries, timestamping, state encoding, …
- Challenge
  - How to provide these properties with (de)centralized systems?
    - Node have to *trusted* in some scope (e.g., availability)
    - Censorship-resistance may be problematic too
  - But then how to build a distributed ledger? Such that everyone can *write*
    - A large-scale consensus mechanism is inevitable
  - Incentives: who and why would run such an open infrastructure?

CAP theorem

- "*it is impossible for a distributed data store to simultaneously provide more than two out of the following three guarantees*" - Eric Brewer
  - Consistency: Every read receives the most recent write or an error
  - Availability: Every request receives a (non-error) response – without guarantee that it contains the most recent write
  - Partition tolerance: The system continues to operate despite an arbitrary number of messages being dropped (or delayed) by the network between nodes
- Examples?



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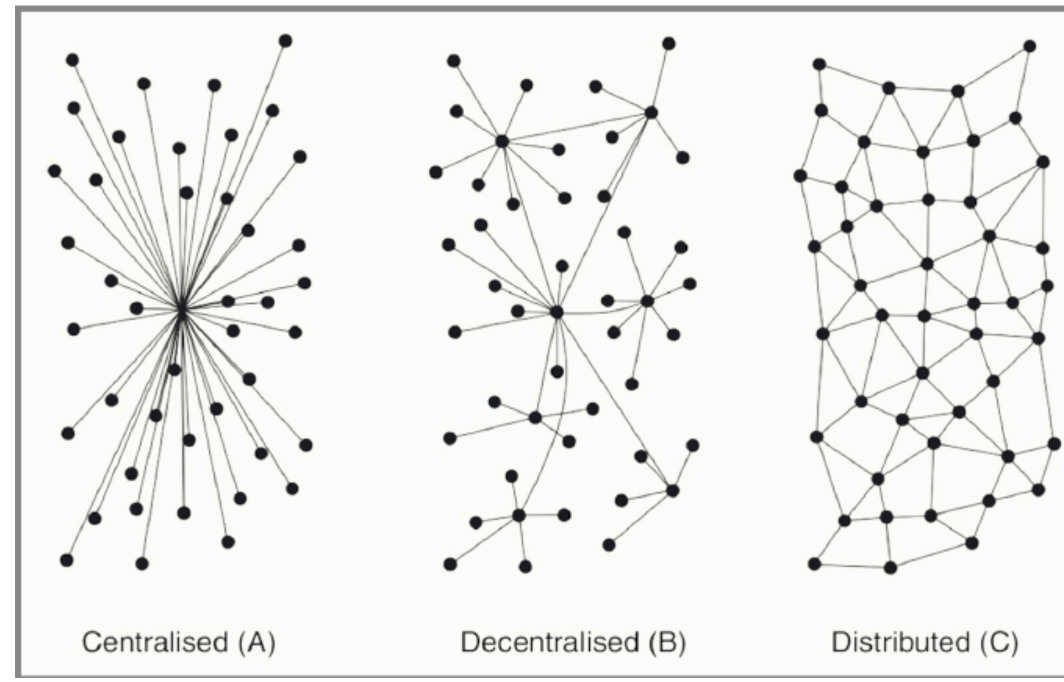
System Types

- Computing, Trust, Network, Decision making, …
- Centralized/Monarchy/Monopoly
  - One trusted node decides (can be replicated)
- Decentralized/Oligarchy/Oligopoly
  - Multiple trusted nodes can decide (each individually)
- Distributed/Open
  - Nodes collectively decide (no node is individually trusted)

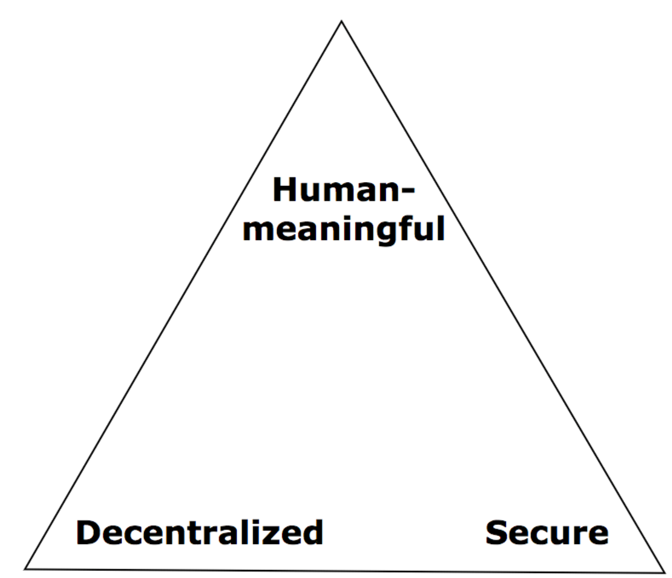


Distributed Naming

- Naming in distributed systems is hard
  - Especially for security
- How to name machines, organizations, persons, entities, … ?
  - Name collision may lead to authentication/authorization failures
- Names exist in contexts
- What namespaces do you know?

Zooko's Triangle

- No single kind of name can achieve more than two:
  - Human-meaningful: Meaningful and memorable (low-entropy) names are provided to the users.
  - Secure: The amount of damage a malicious entity can inflict on the system should be as low as possible.
  - Decentralized: Names correctly resolve to their respective entities without the use of a central authority or service.
- Examples
  - DNSSec
  - .onion and Self-certifying File System (SFS)



- It is believed that open and distributed consensus (blockchains) relaxes it

Consensus

Goals

- How N nodes can achieve consensus in the presence of faulty nodes?
  - (nodes are also called processes, actors, participants, hosts, …)
  - Different equivalent problem formulations (all about agreement)
- Properties
  - Safety: something bad will never happen
    - Agreement: all correct nodes select the same value
  - Liveness: something good will happen eventually
    - Termination: all correct nodes eventually decide

System Models

- Network: fully connected with message ordering controlled by adversary
- Timing
  - Synchronous: message sent at T is delivered by T+d, where d is known
  - Eventually Synchronous: message sent at T is delivered by max(T+d, T_g+d), where T_g is unknown
  - Asynchronous: sent messages are eventually delivered
- Faults: f nodes can be faulty (usually, relative to N)
  - Crash: would be honest but is (sometimes) unavailable
  - Byzantine: arbitrary (e.g., adversarial) behaving
- What would you assume for the Internet?

Many Bounds

- Two generals
  - Two-party agreement over unreliable medium is impossible
  - msg, ack, ack of ack, ack of ack of ack, …
- Fischer, Lynch, and Patterson (FLP) Impossibility
  - *No (deterministic) consensus can be guaranteed (liveness and safety) in an asynchronous communication system in the presence of any failures*
  - Intuition: cannot distinguish between failing and slow nodes
  - What to do then?
    - Tweak the model a bit (timing, randomness, failure detectors,…)
- … and much more: “A Hundred Impossibility Proofs for Distributed Computing”

Byzantine Consensus

Byzantine Nodes Bound

- Byzantine Failure Tolerance (Lamport, Shostak, and Pease)
  - *N* generals defending Byzantium, *f* of whom are malicious
    - Network with authentic and confidential (peer2peer) messages
  - What is max *f* that can be tolerated? N >= 3f + 1
    - Node with inconsistent info cannot determine who is faulty (note, however, that with digital signatures it can be solved easily.)

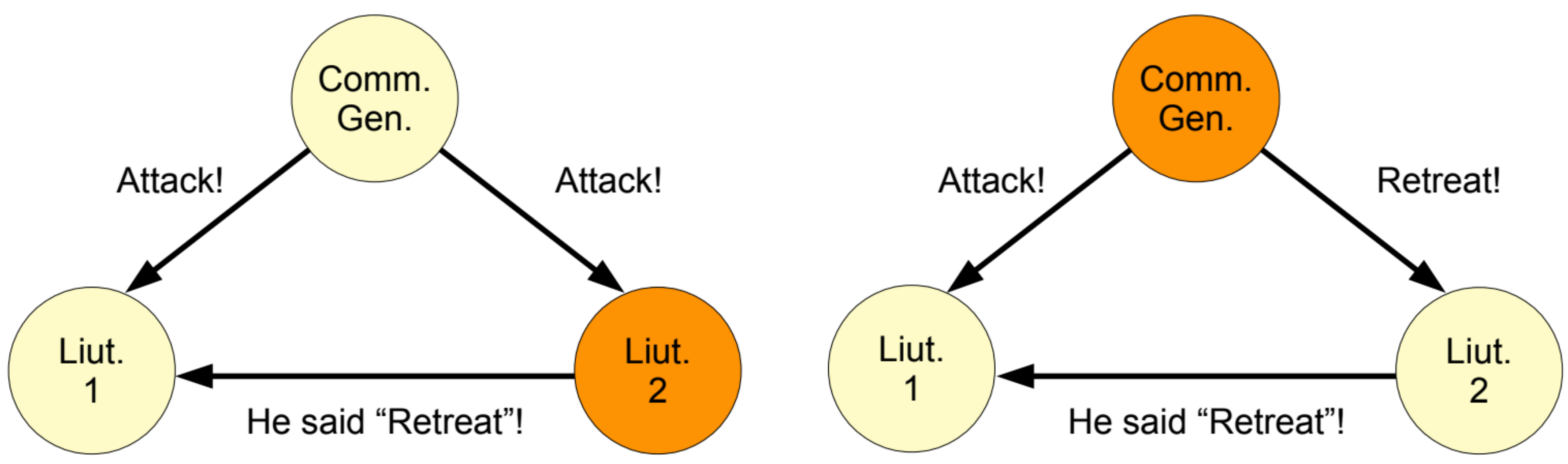


Fig: http://disi.unitn.it/~montreso/

Best-Effort Broadcast

<u>Sender:</u>

```
on input(x)
  multicast (send, x)
```

<u>Receiver:</u>

```
on receiving (send, x)
  output x
```

Issues?

- unreliable communication?
- how does sender know which nodes received x ?

Consistent Broadcast

- Sender has an input x to be broadcast
- Termination: if sender is honest, then every honest node outputs x
- Agreement: if any two nodes output x and y, then x=y
- Model
  - Asynchronous network
  - Byzantine faults with $f < N/3$

Consistent Broadcast

Sender:

on input(x)
  multicast (send, x)

Receiver:

on receiving (send, x)
  multicast (echo, x)

on receiving (echo, x) from >= (N+f+1)/2 nodes
  output x

Liveness:
With honest sender, N-f honest nodes receive (send, x)
  thus N-f correct nodes multicast (echo, x)
    thus each honest node receives N-f echo msgs

Safety:
Assume two honest nodes outputting a!=b
  Must have received (N+f+1) echo msgs in total
    At least f+1 nodes sent two conflicting echo msgs
    That cannot happen as only f nodes can be faulty

Do you see any problem(s) of that protocol?
Faulty sender?

PBFT

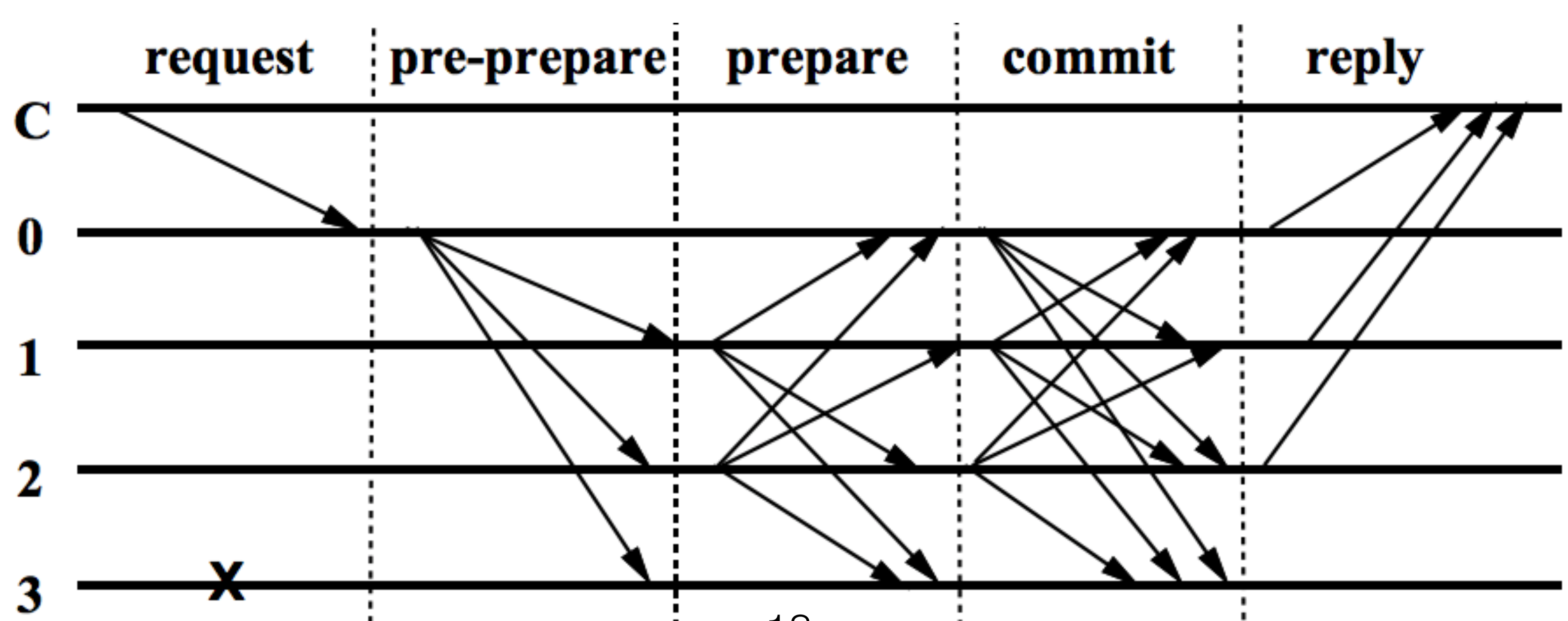
- Castro and Liskov “Practical Byzantine Fault Tolerance”, 1999

    1. A client sends a request to invoke a service operation to the primary

    2. The primary multicasts the request to the backups

    3. Replicas execute the request and send a reply to the client

    4. The client waits for *f+1* replies from different replicas with the same result; this is the result of the operation.



How to use?

- Implement a distributed key:value storage (filesystem)
  - Universal (easy to implement other primitives on top)
    - Distributed locks
    - Leader election (often protocols provide it by default)
    - Membership enumeration
    - …
- Easy to combine with other services, load balancers, etc…
- Easy to implement a distributed ledger

Distributed Ledger

- Collect transactions to commit
- Elect leader and let the leader to append her view of transactions
    - Leader can be changed every round (why helpful?)
    - If leader dies new leader is elected
    - Everyone synchronizes transactions and keeps replicated state of the system

Other protocols

- Paxos (prior PBFT)
  - Synchronization problem
  - Used by Google (Chubby, Spanner, Megastore, …)
  - OpenReplica, IBM SAN Volume Controller, …
- Raft
  - Designed as an alternative to Paxos
  - More understandable

Properties

- Scale to large # of transactions
  - Up to (several) thousands
- Scale only to small # of nodes
  - Only several to tens, due to $O(N^2)$ message complexity
- Resilient to 1/3 malicious nodes
- Needs known and static set of participants (identities)
  - Authority has to allow nodes to participate

Open Consensus

- So far consensus is closed/permissioned
    - Someone has to allow us to participate
- Can we just do it open/permissionless by allowing anyone to participate ?
    - PBFT-like protocols have limited scalability in # of nodes
    - but even if (somehow) we can solve scalability, can we really open the protocol to anyone?
    - Voting, reputation systems, ….

Sybil Attack

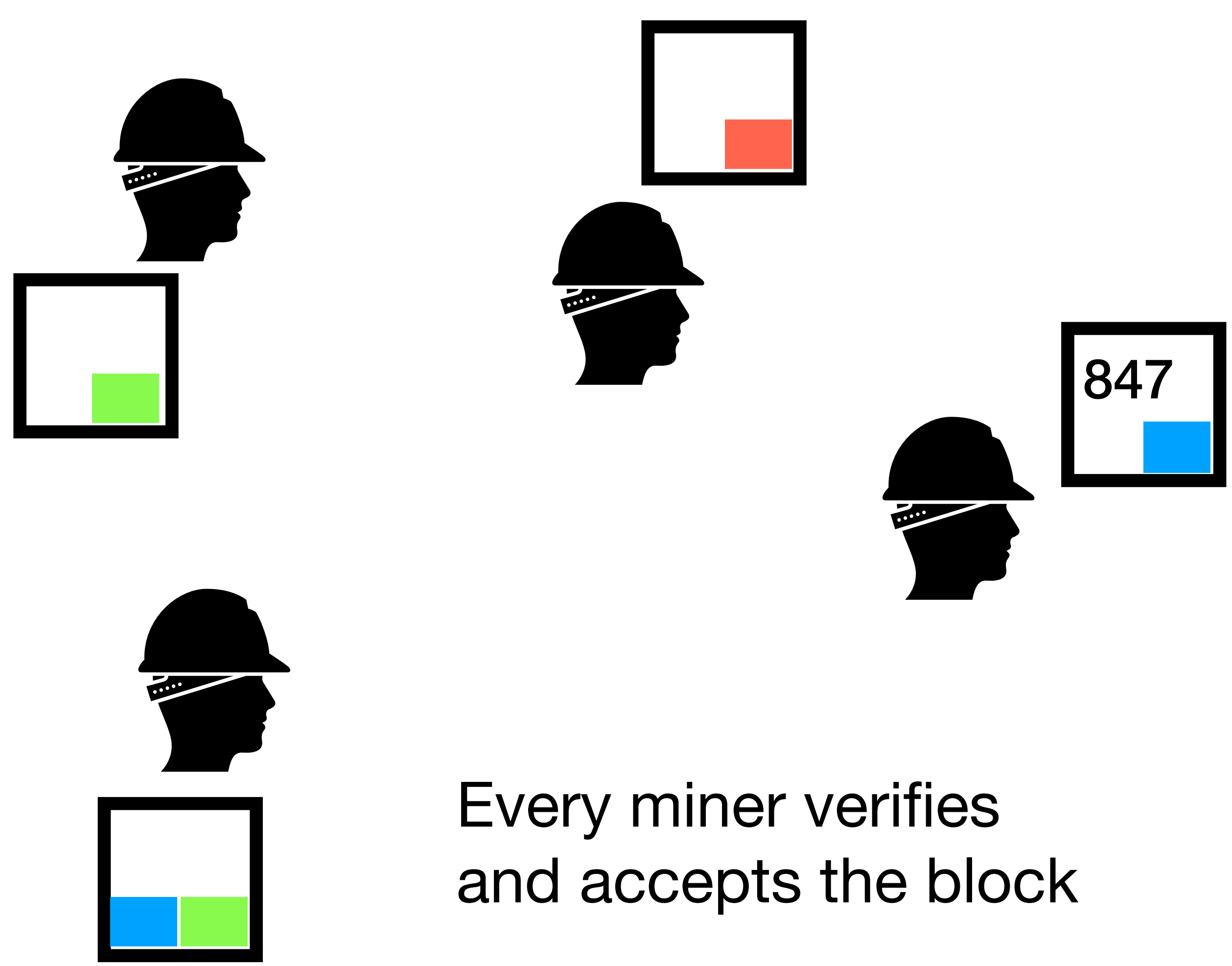
- Generic attack against open voting/reputation/p2p systems
  - No trusted authority that vouches identities
- Adversary creates many identities to attack system
  - It is cheap to create multiple identities in open system
    - e.g., generate keypairs, create email accounts, create multiple connections, imitate browser instances, …
- How to validate identities in such a system?
  - It has to be based on resources (assuming adversary with limited resources)
    - Time (CPU), Space (Memory), and Bandwidth (Network Connection)

Nakamoto Consensus

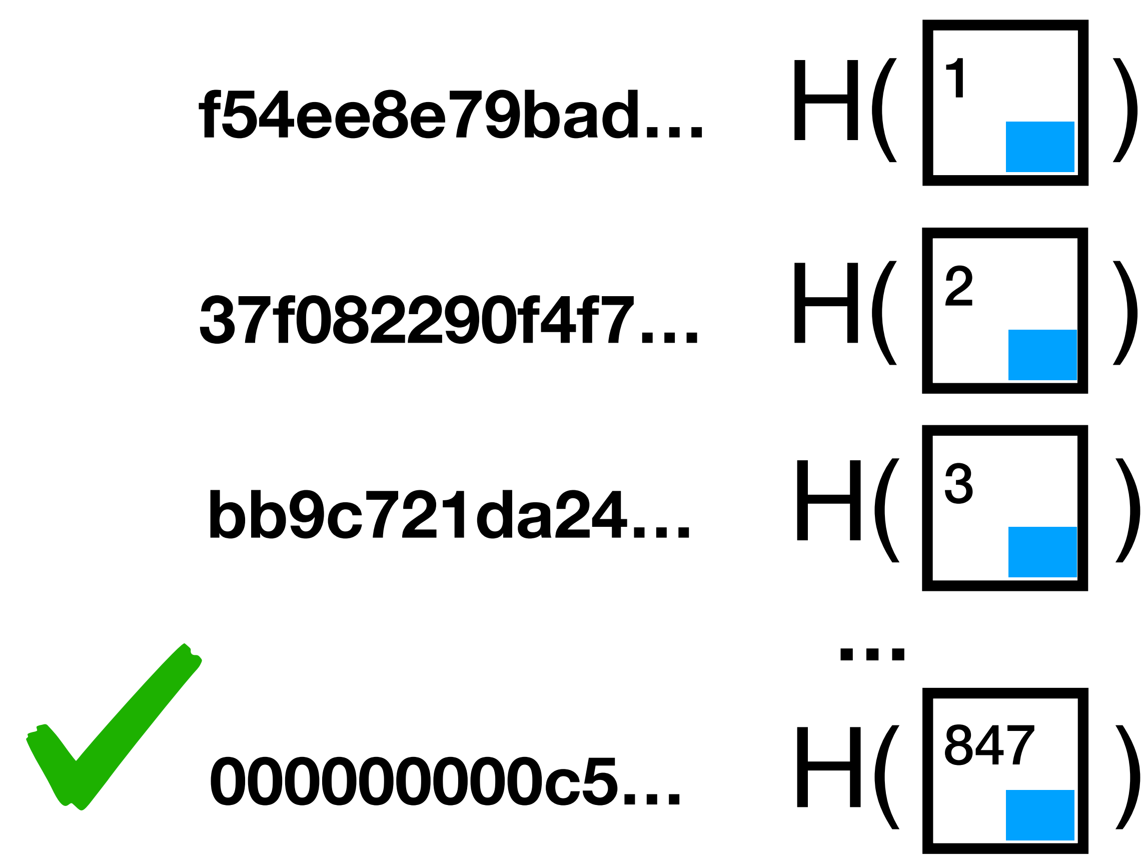
Consensus via PoW

- Leader election per transactions set (block)
- Leaders are self-elected (vote for themselves)
- Voting is via PoW
  - Finding a block whose hash < target

Miners
(protocol participants)

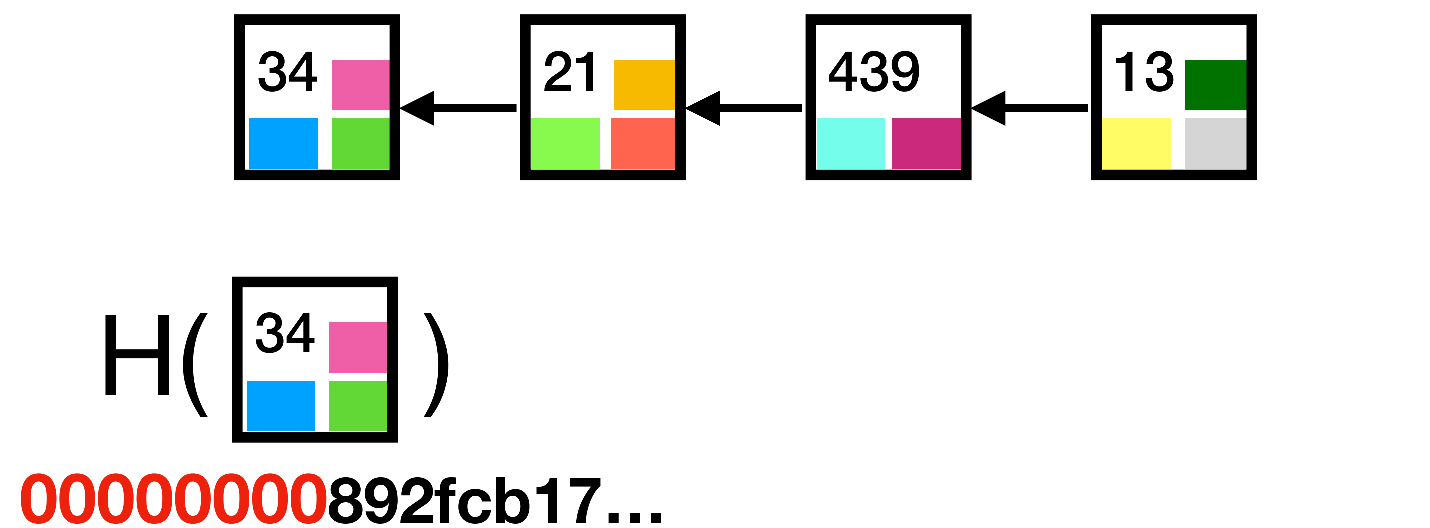


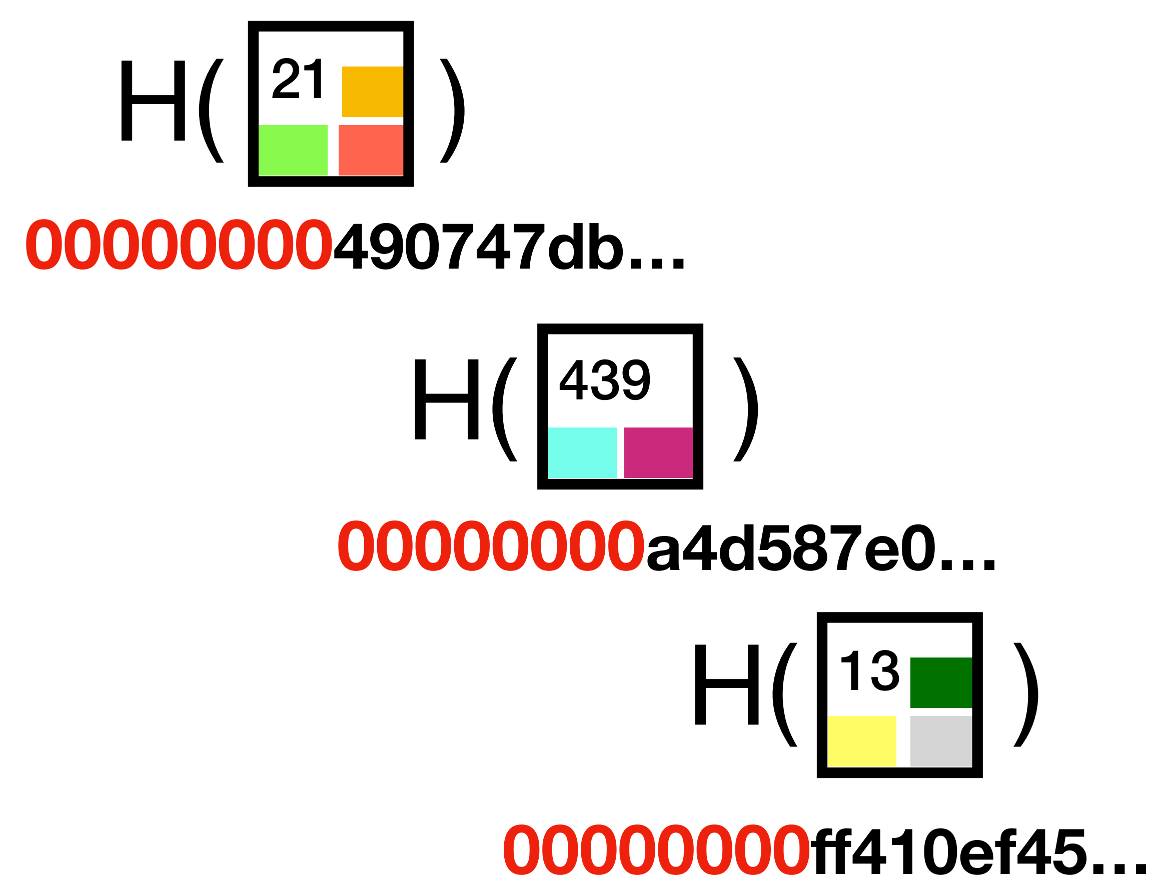
Every miner verifies
and accepts the block



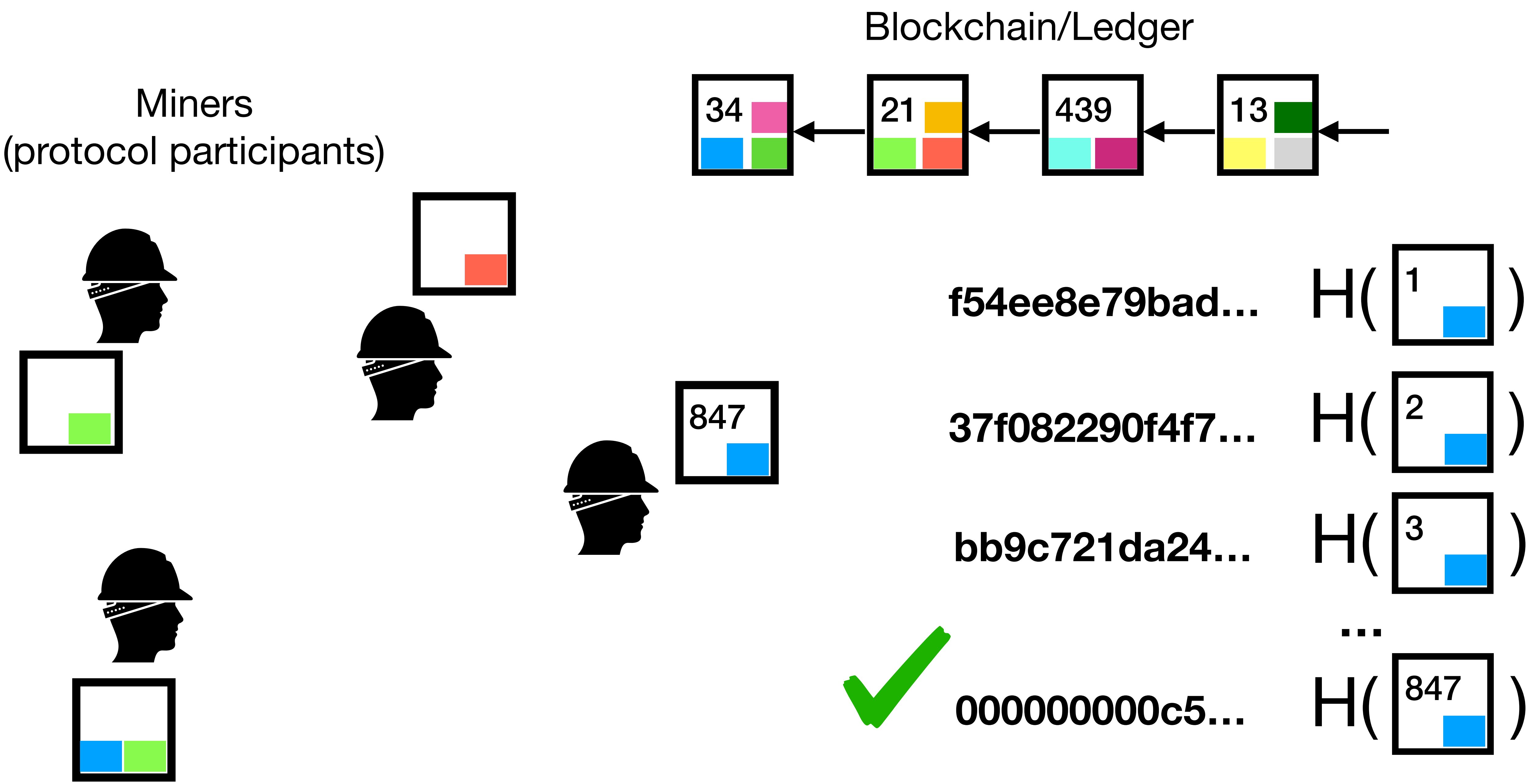
Blockchain/Ledger

- Hash chain of blocks
- Block
  - Set of transactions
    - Forming hash tree
  - Special number (Nonce)
  - Hash pointer/link to the previous block
- Proof of work
  - H(block) < target   (target defines difficulty)
    - You can see leading zeros in hashes





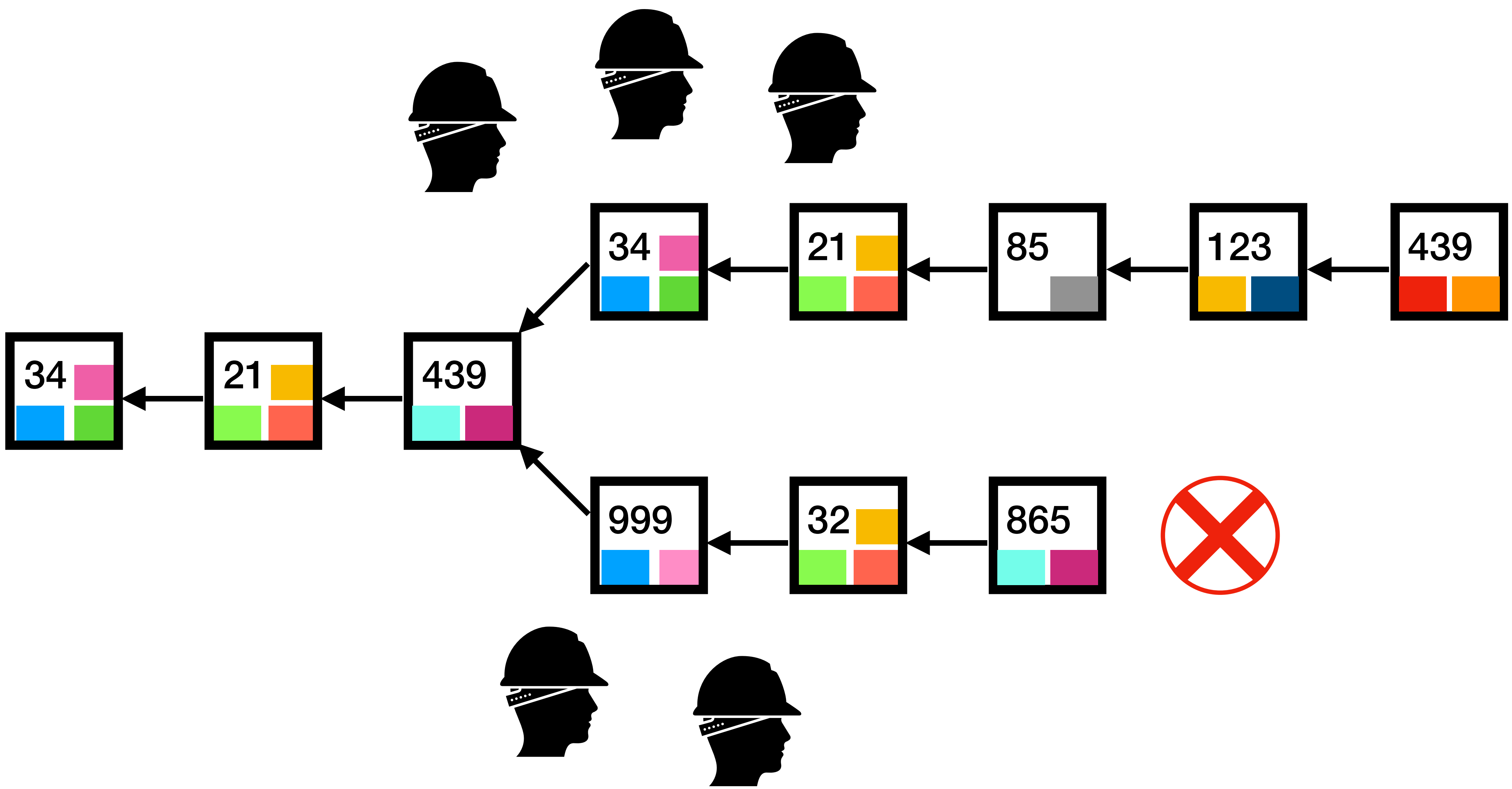
Consensus & Blockchain



Consensus & Blockchain

- PoW & Blocks
  - Permissionless Sybil-protection mechanism
  - Add new transactions
  - Confirm all previous block (and their transactions)
  - Prove the leader election (non-interactively)

Forks



The longest* chain wins.
* in reality it is the chain with the most PoW accumulated.

Properties

- Open/Permissionless
  - No identities required (but usually public-keys are used as identifiers)
  - Leader are self-elected and set of nodes can be large, dynamic, and unknown (anyone can join freely)
- Extremely Robust
  - Very simple, small communication overhead, dynamic membership, …
- Probabilistic: you never have 100% guarantee what the current chain is
  - To get a high evidence multiple confirmation blocks are required (e.g., 6 blocks ~ 1h)
- Security Assumption
  - Honest majority: 50% of mining power is honest (spoiler: actually, it is lower)
- Issues
  - Energy consumption: it should be non-trivial to find block (o/w many forks)
    - Target is adjusted to 10min/block, but that increases latency
      - Latency decreases scalability (# of transactions)

Reading

- Textbook: 1.4, 1.5, 2
- https://lpd.epfl.ch/site/_media/education/sdc_byzconsensus.pdf
- http://pmg.csail.mit.edu/papers/osdi99.pdf
- https://bitcoin.org/bitcoin.pdf
- https://arxiv.org/pdf/1707.01873.pdf
- https://www.freehaven.net/anonbib/cache/sybil.pdf