Consensus in blockchains: Overview and recent results

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Overview

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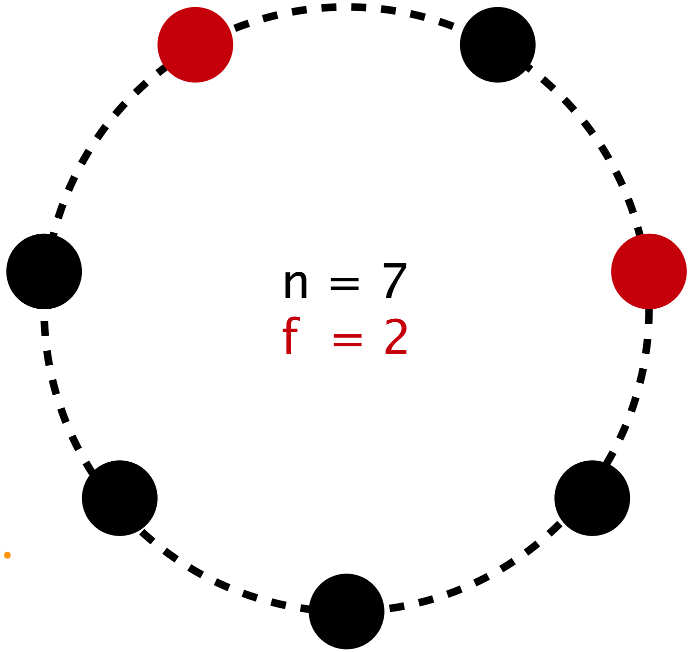
- **for** *model* $\in$ all kinds of blockchain consensus **do**
  - describe *model*

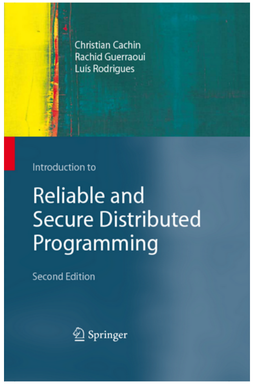
- **while** time lasts **do**
  - select some *result* $\in$ `https://crypto.unibe.ch/pub`
  - present *result*

- Answer your questions

1 – Threshold trust

- Trust by numbers
  - n nodes total
  - f faulty (Byzantine) nodes
- Homogeneous and symmetric
- Requires n > 3f
- Tendermint, DiemBFT, Quorum ...





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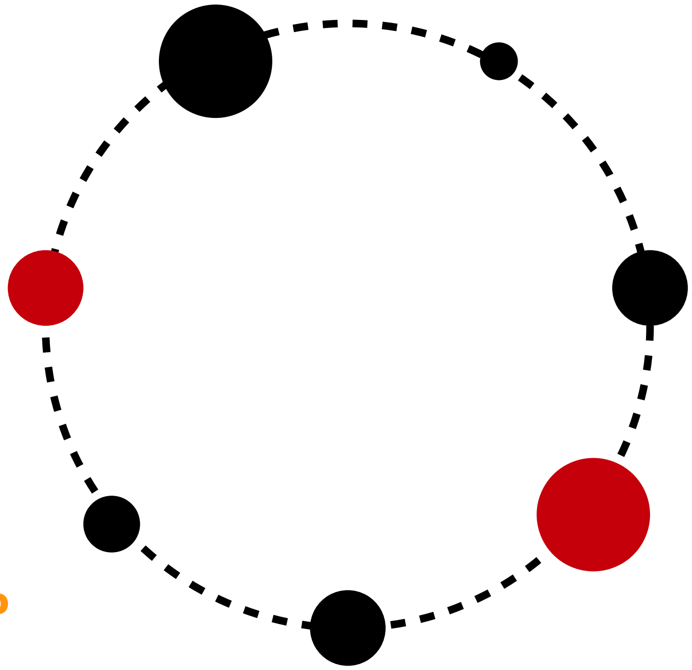
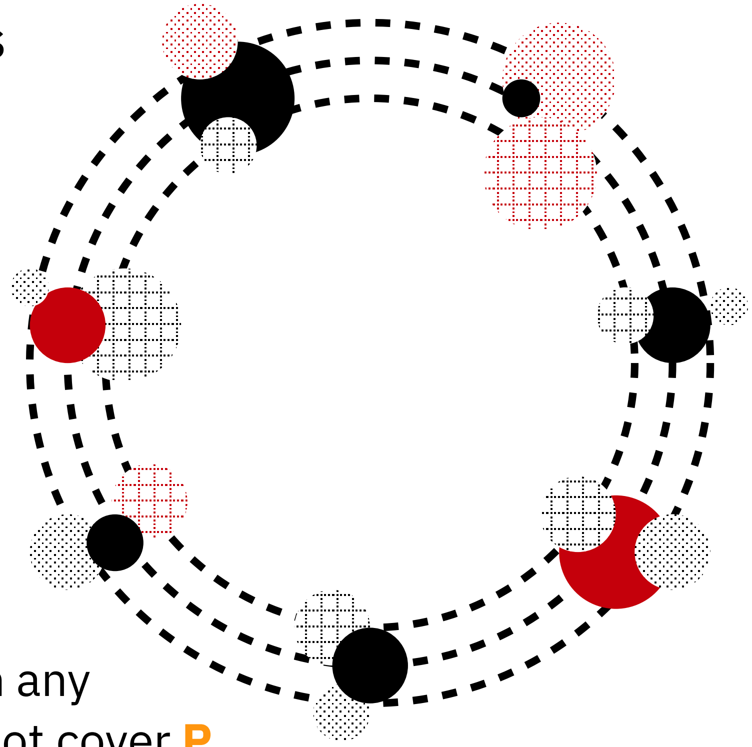
2 – Generalized trust

- Trust by generalized quorums
  - Set of nodes **P**
  - Fail-prone sets consisting of possibly Byzantine nodes
  - Byzantine quorum system
- Heterogeneous and symmetric
- Requires Q3-property
  - Any fail-prone sets must not cover **P**
- Not used by any cryptocurrency (!)



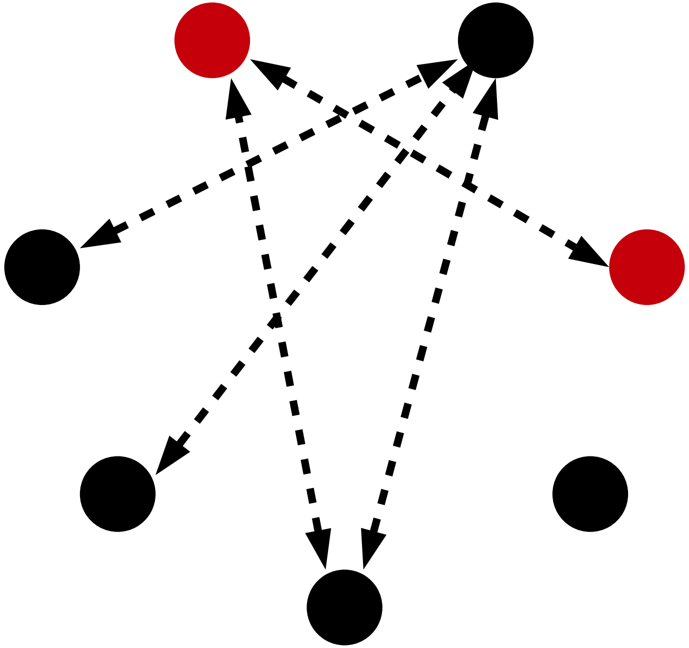
3 – Asymmetric trust

- Subjective generalized quorums
- Every node has its own Byz. quorum system on **P**
- Consistency across nodes' quorum systems
- Requires B3-property
  - ∀ p, p' : any fail-prone set of p with any set of p' and any set of both must not cover **P**
- Ripple, Stellar, [CT19]



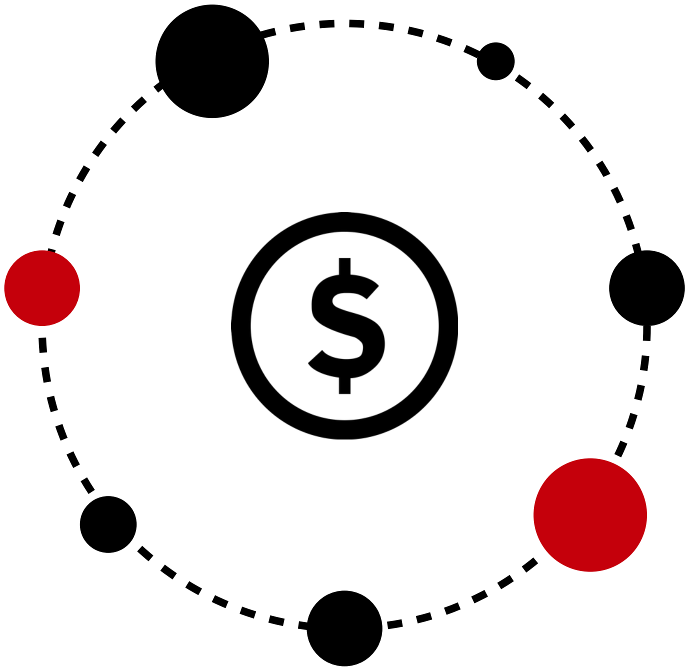
4 – Unstructured, probabilistic voting

- Random sampling of peers
- Exchange information and votes
- Usually coupled with a DAG on transactions
- Avalanche, Conflux, IOTA-Tangle



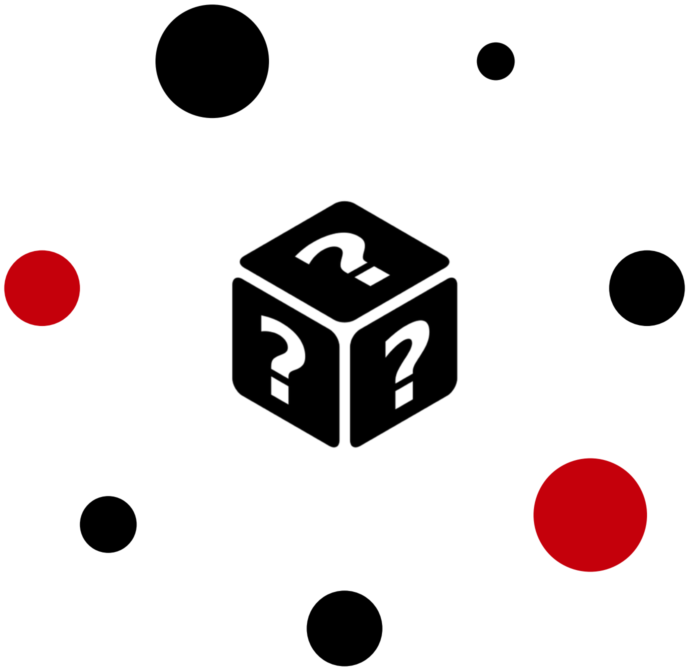
5 – Stake-based voting

- Stake determines voting power
- Protocols generalized from symmetric voting
- Cosmos, EOS, NEO, Aptos, SUI ...



6 – Stake-based probabilistic choice

- Lottery according to stake
- Probabilistic leader election
- Cryptographic sortition using a verifiable random function (VRF)
- Cardano/Ouroboros ...



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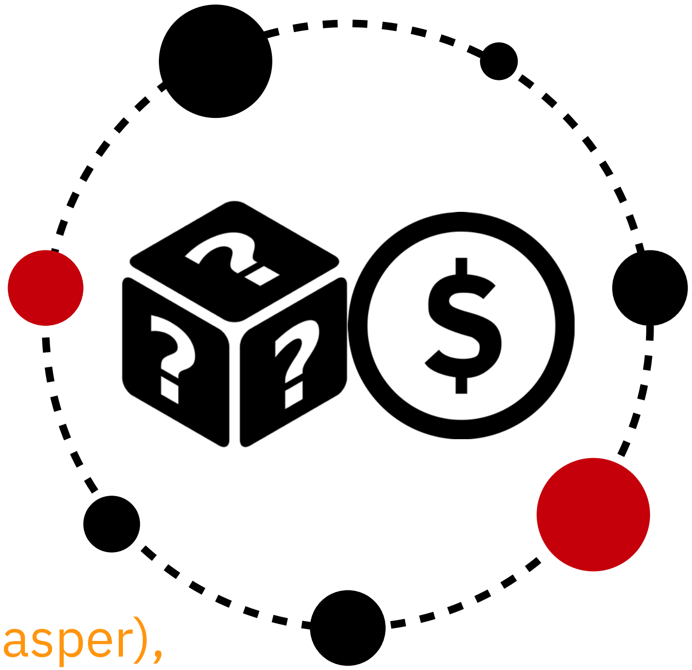
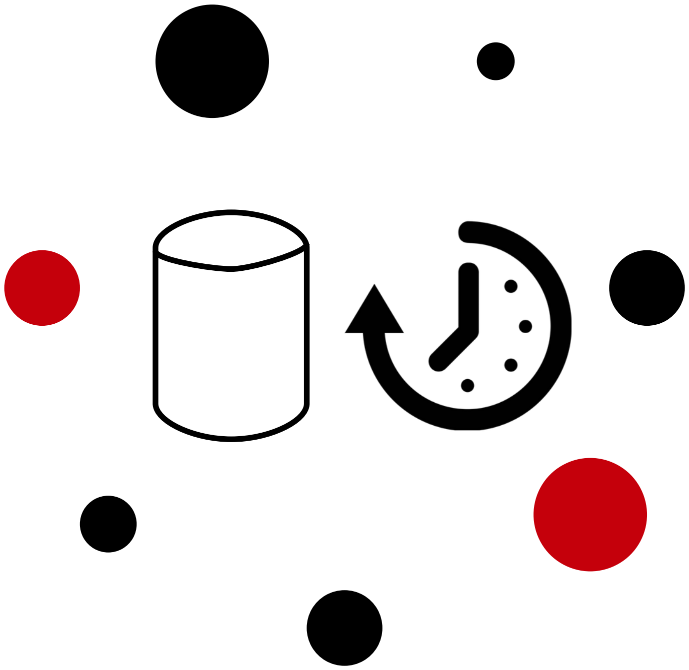
7 – Hybrid prob. choice and stake voting

- Stake determines probability or voting power
- Mix of random choice with voting
- Slashing of invested stake upon detection of misbehavior
- Ethereum (LMD-GHOST & FFG-Casper), Polkadot (BABE & GRANDPA), Algorand ...



8 – Proof-of-space and proof-of-delay

- Storage space as resource
- Cryptographic ZK proofs for storage at particular time
- Time delay to prove storage investment over time
- Filecoin, Chia, Storj ...



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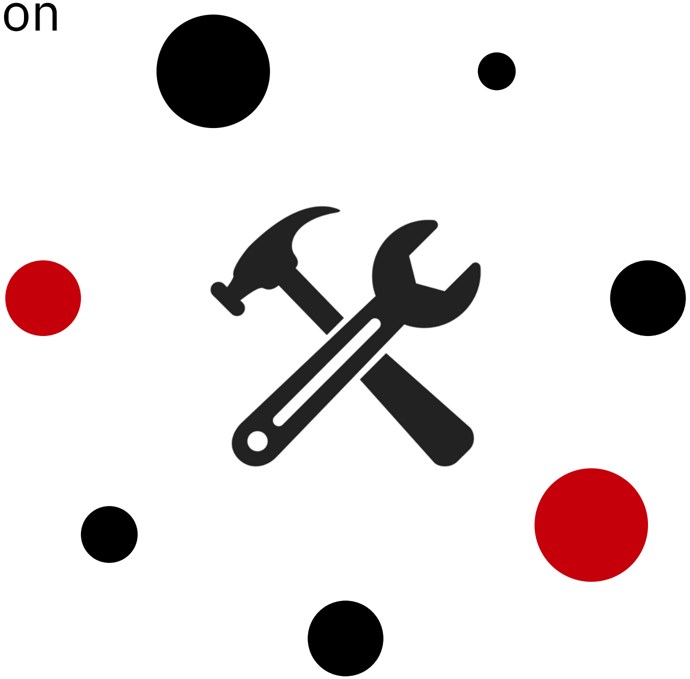
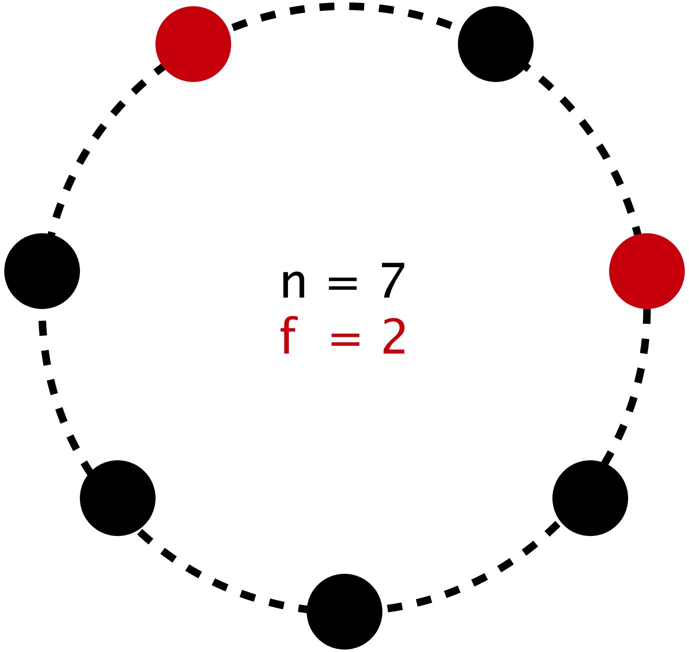
9 – Proof-of-work

- Demonstrate invested computation
- Nakamoto consensus
- Bitcoin ...



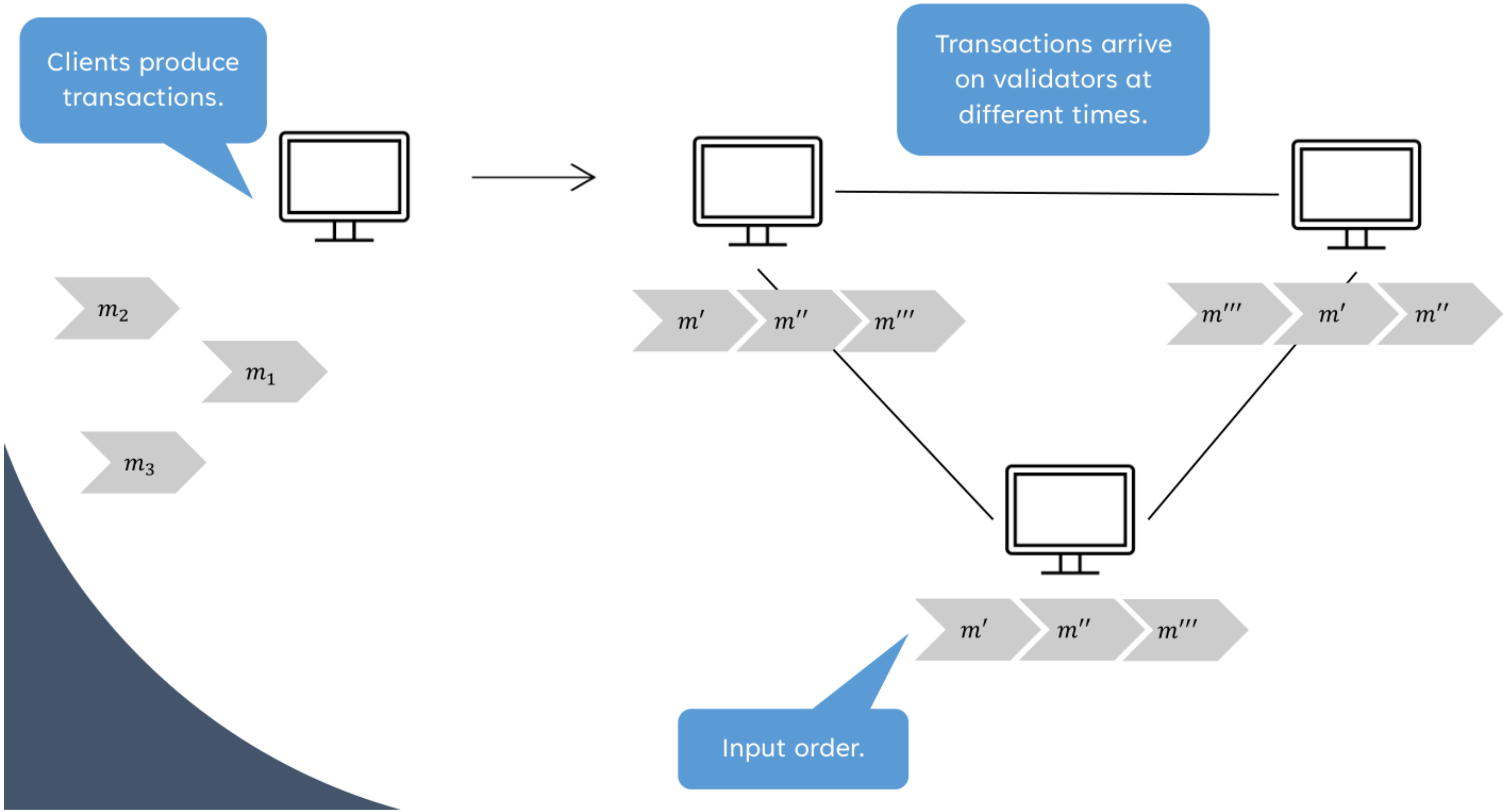
Model 1: Threshold trust



Order fairness

- Front-running and transaction-reordering attacks in DeFi
- Maximal extractable value (MEV)
- Validity of consensus (total-order broadcast) leaves actual order open
- Validator nodes exploit their freedom and choose a profitable order

Order fairness: Respect the receive-order



Condorcet: A fair order may not exist

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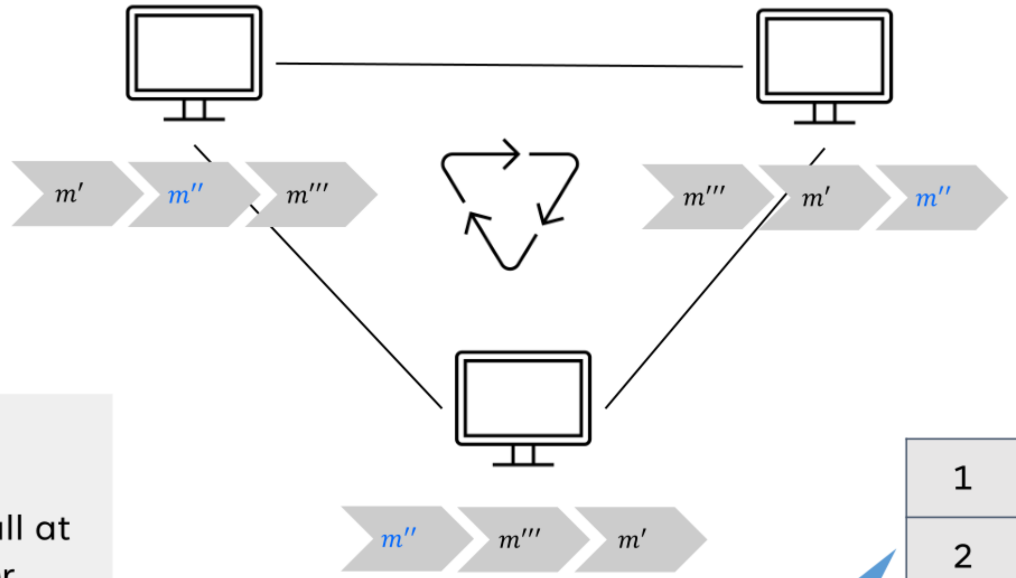

Cycle in the order preferences!

[KZGJ20]: Fair order = deliver all at the “same time” = “block-order fairness”

1	...
2	m', m'', m'''
3	...

Output order.

Differential (block-)order fairness [CMSZ22]

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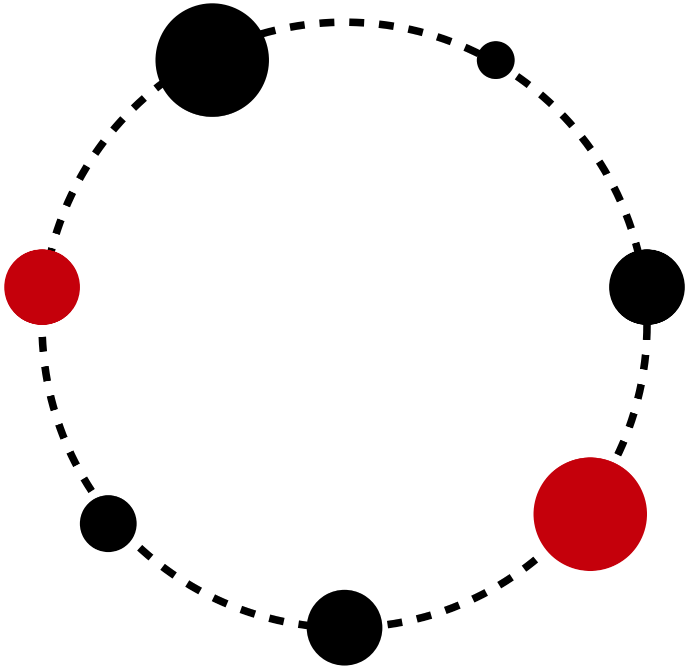
- $b(m,m')$: number of correct nodes that *receive as input* m before m'

- f out of n corrupted nodes

- **Differential order fairness**: If $b(m,m') > b(m',m) + 2f$, then no correct node *delivers* m' before m. (But protocol may *deliver* m and m' together, in same block.)

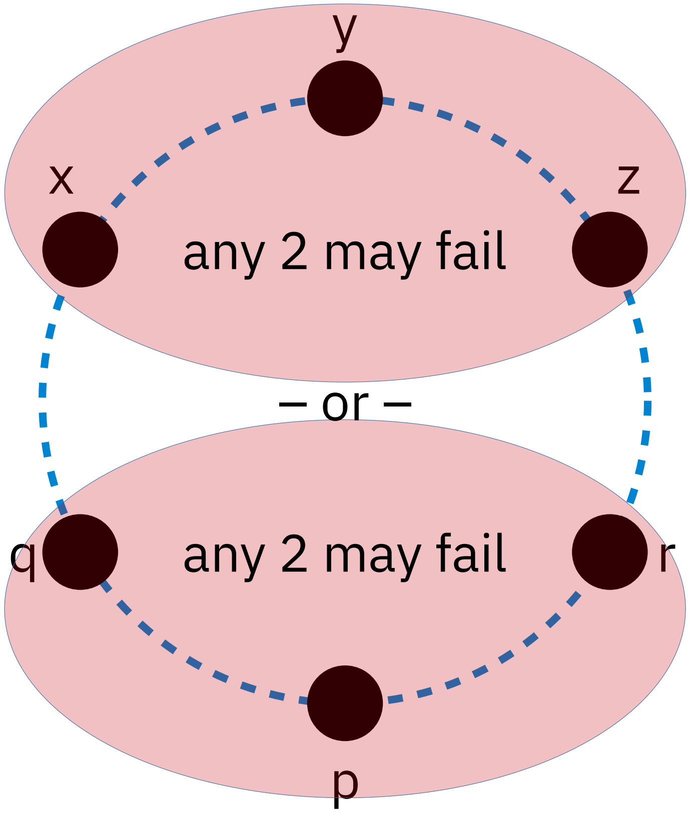
- Implemented by the quick order-fair atomic broadcast protocol, for $n > 3f$

Model 2: Generalized trust



Generalized trust – Byz. quorum systems

- Set of nodes **P** = {p_1, ..., p_n}
- Fail-prone system **F** ⊆ $2^{\mathbf{P}}$:
  – All F ∈ **F** may fail together
- Quorum system **Q** ⊆ $2^{\mathbf{P}}$, any Q ∈ **Q** is a "quorum" [MR98, HM00]
- **F** = {pq, pr, qr, xy, xz, yz}
- **Q** = {rxyz, qxyz, pxyz, pqrz, pqry, pqrx}
- Nodes are trusted **differently**
- All nodes trust **equally**



Do not trust in numbers [AC22]

- Distributed cryptography beyond the threshold model

- Theoretically well-known, practically never explored

- Example access structure (quorum set) of a validator in Stellar (SDF1)

```
{  "select": 6,
   "out-of": [
      {"select": 2, "out-of": ["Blockdaemon1", "Blockdaemon2", "Blockdaemon3"]},
      {"select": 2, "out-of": ["SDF1", "SDF2", "SDF3"]},
      {"select": 2, "out-of": ["WirexSingapore", "WirexUK", "WirexUS"]},
      {"select": 2, "out-of": ["CoinqvestFinland", "CoinqvestHongKong", "CoinqvestGermany"]},
      {"select": 2, "out-of": ["SatoshiPayUS", "SatoshiPaySG", "SatoshiPayDE"]},
      {"select": 2, "out-of": ["FranklinTempleton1", "FranklinTempleton2", "FranklinTempleton3"]},
      {"select": 3, "out-of": ["LOBSTR1", "LOBSTR2", "LOBSTR3", "LOBSTR4", "LOBSTR5"]},
      {"select": 2, "out-of": ["Hercules", "Lyra", "Boötes"]}
]}
```

Do not trust in numbers [AC22]

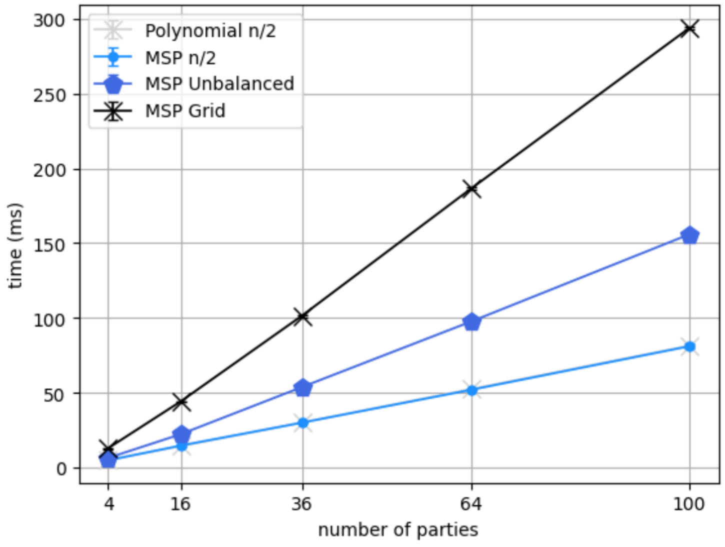
- Practical implementation of generalized cryptosystems
  - Monotone span programs (MSP)

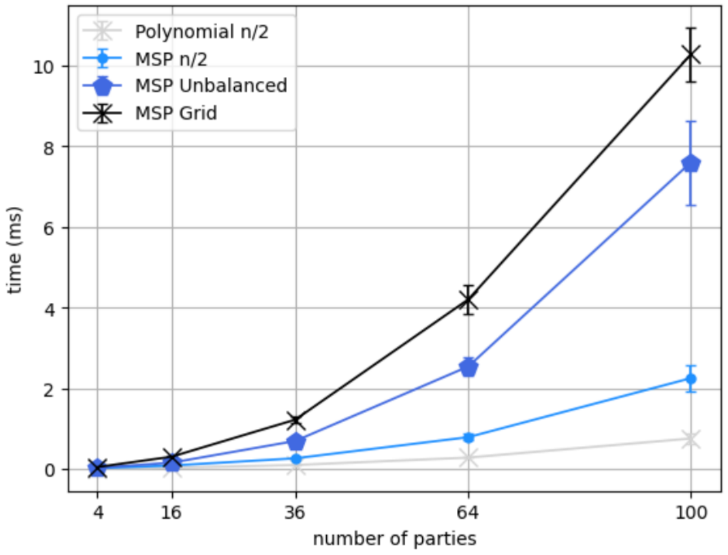
- Verifiable secret sharing (VSS)
- Common coin
- Distributed signatures

- Tools to generate MSP from a configuration file

- Benchmarks show the approach is practical

Do not trust in numbers: Verifiable Secret Sharing [AC22]





- Share and Reconstruct steps of generalized verifiable secret sharing
- Polynomial (n/2), MSP (n/2), MSP (unbalanced) and MSP (grid) structures

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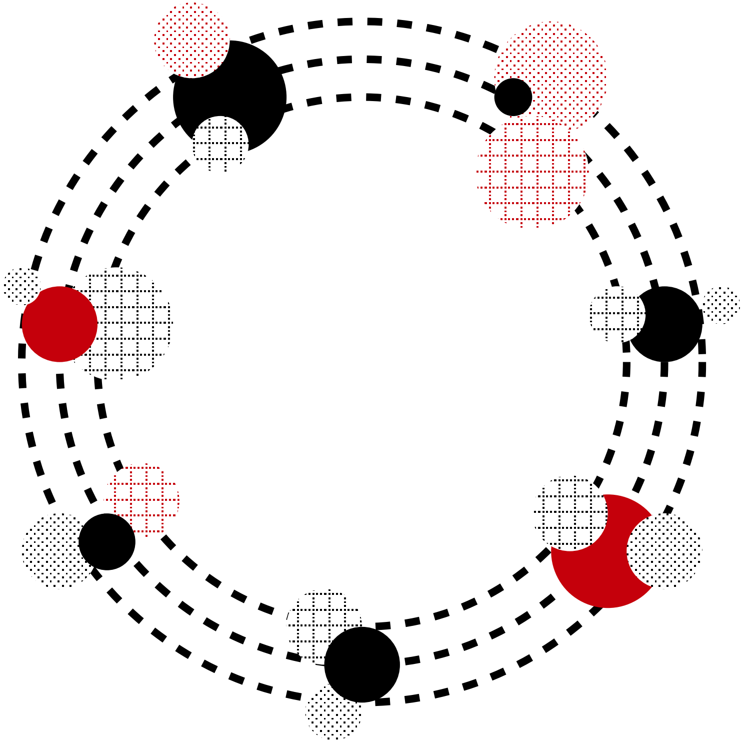
Model 3: Asymmetric trust



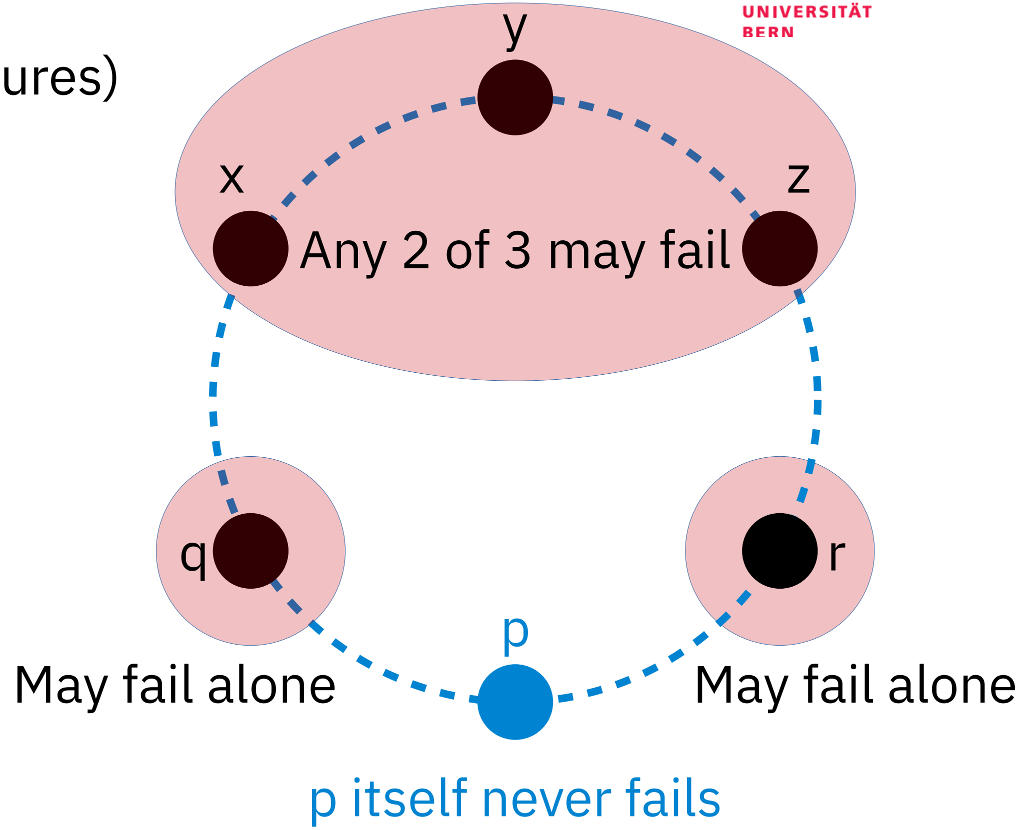
Asymmetric trust

- Subjective trust assumption of p (via failures)
  - p itself never fails
  - Neighbor nodes q and r

    May fail alone, not together with others
  - Remote nodes x, y, x

    Any 2 of these 3 may fail together
- Fail-prone system of node p

  {q, r, xy, yz, xz}



- Each one of the 6 nodes uses its own subjective trust like this

  → Asymmetric quorums

- Nodes are trusted **differently**.

Nodes trust **differently** (asymmetric).

Why asymmetric trust?

- For Romans:
  - *De gustibus non est disputandum.*
    (One cannot argue about taste.)

- For CISOs:
  - *One cannot argue about security assumptions.*

- For blockchainers:
  - *A node counts only the votes of nodes that it trusts. (Ripple, 2014)*
  - *Every node has a different idea about which other nodes are important. (Stellar, 2016)*

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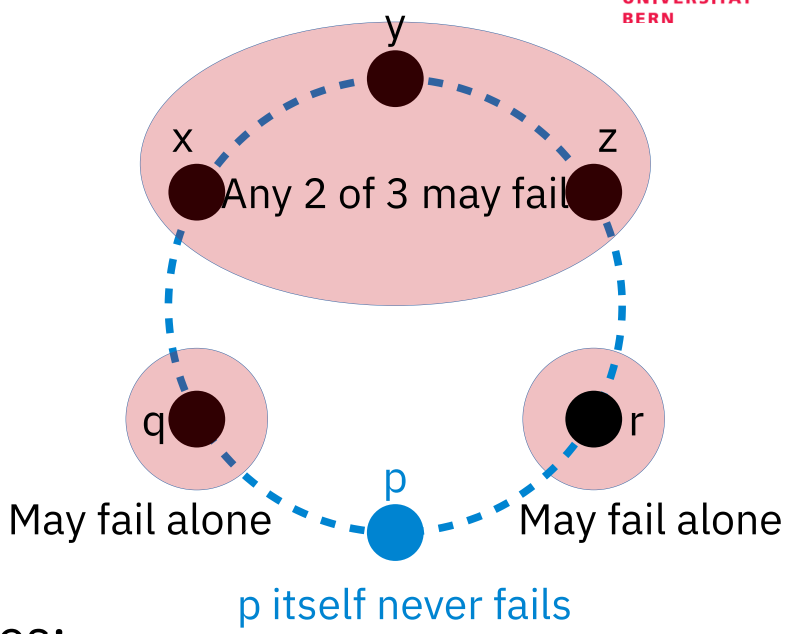
Example asymmetric quorum system

- Six nodes, arranged in a ring
- Failure assumptions of node p as shown
- All others are (rotation-)symmetric to p

- Satisfies B3 property
  ⇔
  There is an asymmetric quorum system

- Each node mistrusts some 2-set of other nodes: impossible with threshold Byzantine quorums!



Execution model

- An execution defines the actually faulty nodes F

- A node p_i is one of
  - Faulty – $p_i \in F$
  - Naive p_i – $p_i \notin F$ and $F \notin$ $\mathbf{F_i}^*$
  - Wise p_i – $p_i \notin F$ and $F \in$ $\mathbf{F_i}^*$

- Safety and liveness hold only for wise nodes
  - Naive nodes may be cheated
    (cf. ordinary, symmetric model, when $f \geq n/3$: all nodes are naive!)

- Liveness depends on existence of a guild
  - A guild is a set of wise nodes that contains one quorum for each member node

SWMR regular register protocol with Byzantine processes (process p_i).

State

wts: sequence number of write operations, stored only by writer p_w
rid: identifier of read operations, used only by reader
ts, v, σ: current state stored by p_i: timestamp, value, signature

upon invocation *write*(v) **do** // only if p_i is writer p_w
$wts \leftarrow wts + 1$
$\sigma \leftarrow_\$ sign_w(\text{WRITE}\|w\|wts\|v)$
send message $[\text{WRITE}, wts, v, \sigma]$ to all $p_j \in \mathcal{P}$
wait for receiving a message $[\text{ACK}]$ from *more* than $\frac{n+f}{2}$ processes

upon invocation *read* **do** // only if p_i is reader p_r
$rid \leftarrow rid + 1$
send message $[\text{READ}, rid]$ to all $p_j \in \mathcal{P}$
wait for receiving messages $[\text{VALUE}, r_j, ts_j, v_j, \sigma_j]$ from *more* than $\frac{n+f}{2}$ processes **such that**
$r_j = rid$ **and** $verify_w(\sigma_j, \text{WRITE}\|w\|ts\|v_j)$
return *highestval*$(\{(ts_j, v_j)\})$

upon receiving a message $[\text{WRITE}, ts', v', \sigma']$ from p_w **do** // every process
if $ts' > ts$ **then**
$(ts, v, \sigma) \leftarrow (ts', v', \sigma')$
send message $[\text{ACK}]$ to p_w

upon receiving a message $[\text{READ}, r]$ from p_r **do** // every process
send message $[\text{VALUE}, r, ts, v, \sigma]$ to p_r

Asymmetric SWMR regular register protocol (process p_i).

State

wts: sequence number of write operations, stored only by writer p_w
rid: identifier of read operations, used only by reader
ts, v, σ: current state stored by p_i: timestamp, value, signature

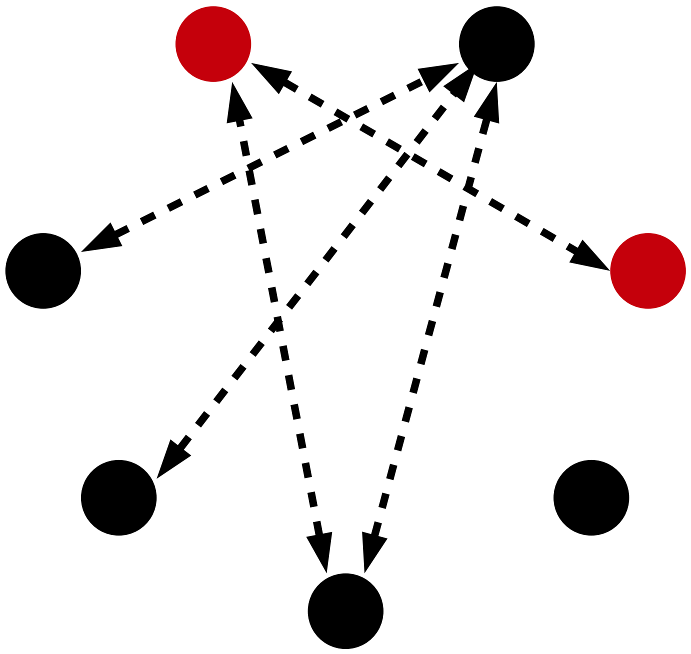
upon invocation *write*(v) **do** // only if p_i is writer p_w
$wts \leftarrow wts + 1$
$\sigma \leftarrow_{\$} sign_w(\text{WRITE}\|w\|wts\|v)$
send message $[\text{WRITE}, wts, v, \sigma]$ to all $p_j \in \mathcal{P}$
wait for receiving a message $[\text{ACK}]$ from all processes in some quorum $Q_w \in \mathcal{Q}_w$

upon invocation *read* **do** // only if p_i is reader p_r
$rid \leftarrow rid + 1$
send message $[\text{READ}, rid]$ to all $p_j \in \mathcal{P}$
wait for receiving messages $[\text{VALUE}, r_j, ts_j, v_j, \sigma_j]$ from all processes in some $Q_r \in \mathcal{Q}_r$ **such that**
$r_j = rid$ **and** $verify_w(\sigma_j, \text{WRITE}\|w\|ts\|v_j)$
return $highestval(\{(ts_j, v_j) | j \in Q_r\})$

upon receiving a message $[\text{WRITE}, ts', v', \sigma']$ from p_w **do** // every process
if $ts' > ts$ **then**
$(ts, v, \sigma) \leftarrow (ts', v', \sigma')$
send message $[\text{ACK}]$ to p_w

upon receiving a message $[\text{READ}, r]$ from p_r **do** // every process
send message $[\text{VALUE}, r, ts, v, \sigma]$ to p_r

Model 4: Unstructured, probabilistic voting



Analysis of Avalanche consensus [ACT22]

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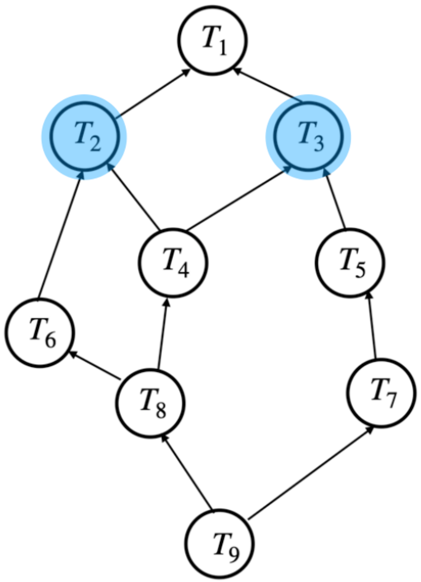
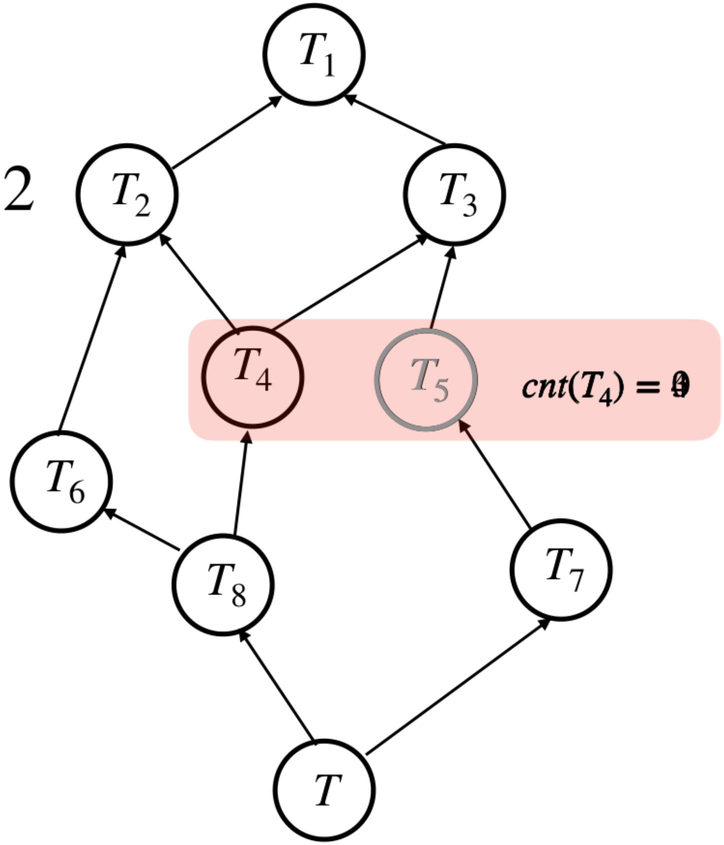
- Metastable consensus: Avalanche and the snow family of protocols
- Transactions form a DAG,
  a directed acyclic graph
- Transactions may conflict
- Nodes sample other nodes
  and ask for their opinion



Avalanche consensus

- While true do
  - Select a new transaction T
  - Query k parties with T
  - If more than α positive answers
    - Update the DAG and increment the counter for acceptance of every ancestor
  - Else
    - Reset the counter for acceptance of every ancestor to 0

$$2 \geq \alpha = 2$$



Analysis of Avalanche consensus [ACT22]

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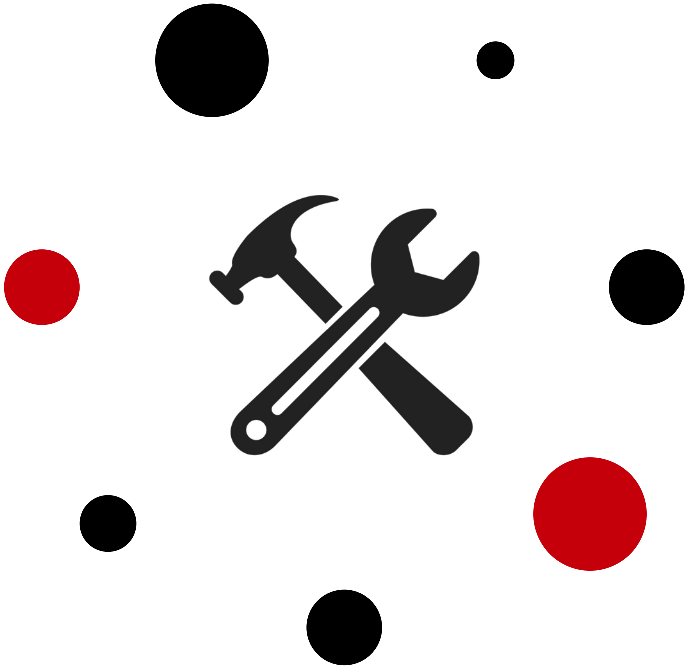
- Detailed pseudocode of Avalanche protocol
- Independent analysis
- Illustrates a potential problem
- For other reasons, Ava Labs/Avalanche abandons the DAG protocol in March '23

Model 9: Proof-of-work



Use any resource for consensus [ACLVZ22]

- Longest-chain consensus based on an abstract resource
- Formal model of a resource allocator
- Resources: work, stake, storage ...
- Which features must a resource have to enable consensus?

Thank you!

Web – https://crypto.unibe.ch/

Blog – https://cryptobern.github.io/

Twitter – https://twitter.com/cczurich/

References

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