Lecture 5: Consensus 101

Joachim Neu

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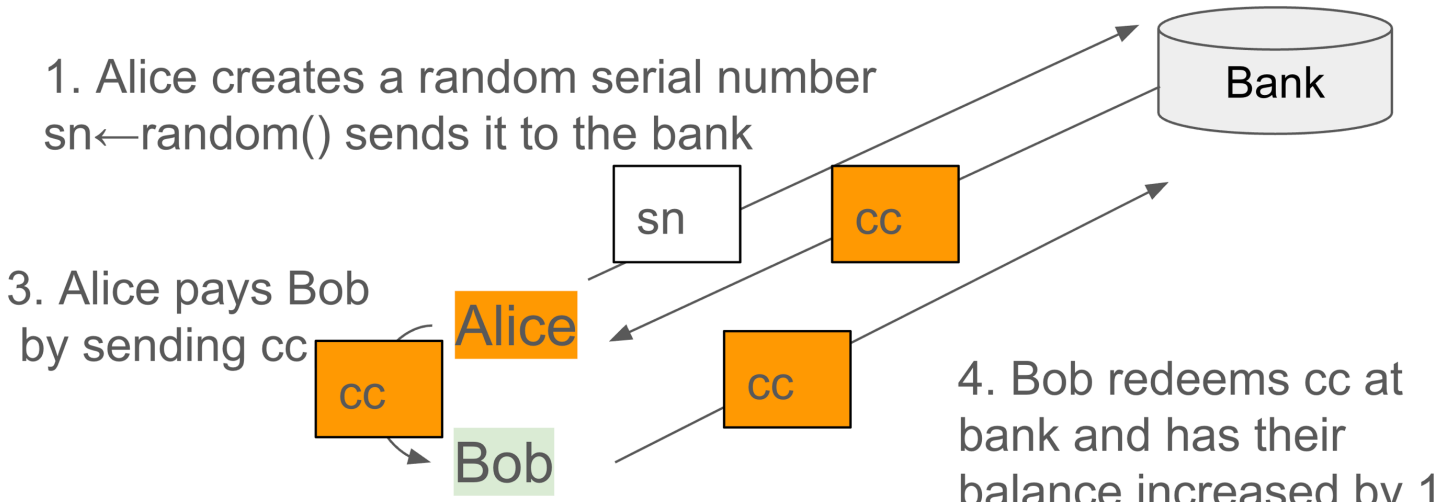
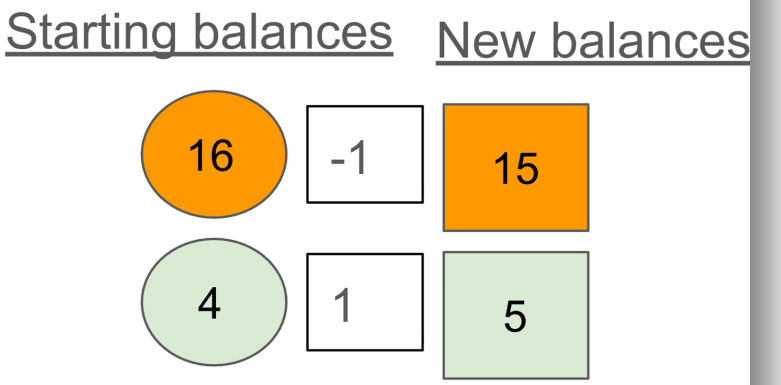
Recap

eCash (but with no privacy)

2. Bank signs sn to create a coin (cc)
Deducts 1 coin from Alice's balance

1. Alice creates a random serial number
sn←random() sends it to the bank





eCash bank issues and redeems coins

Recap

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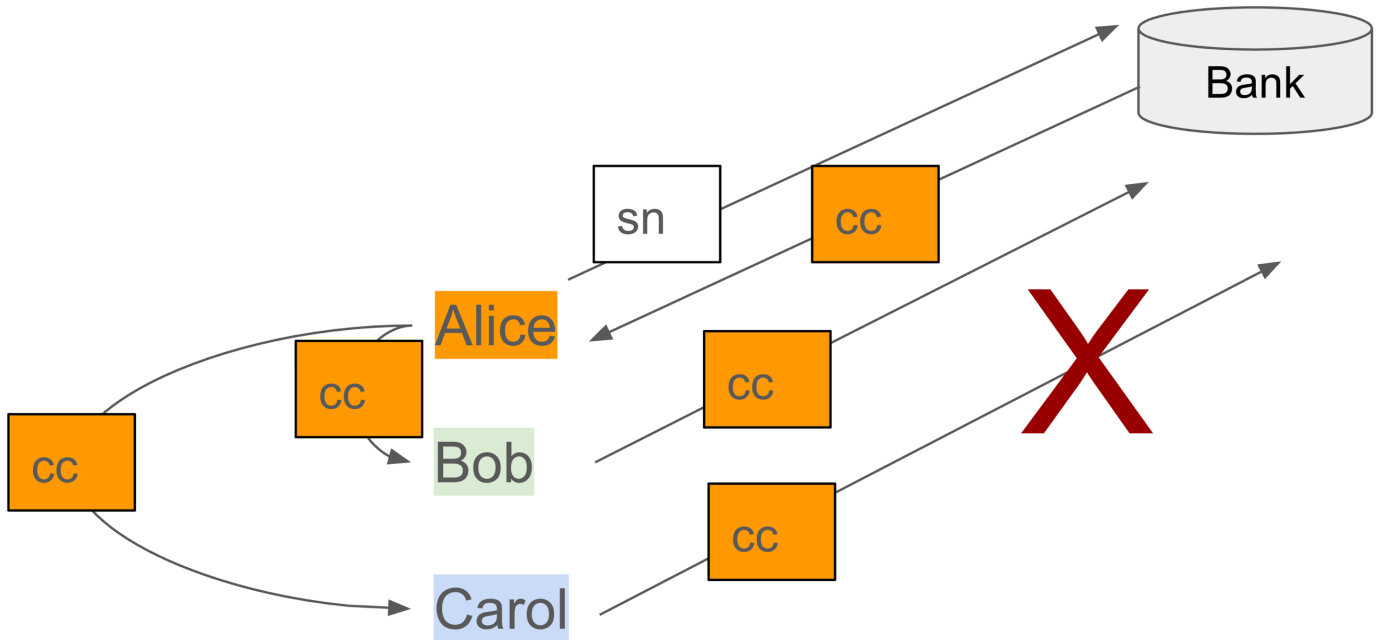

Bank has a list of spent serial numbers (sn). If bank has already redeemed this sn, it does not credit the account

What if Alice Doublespends?

Recap

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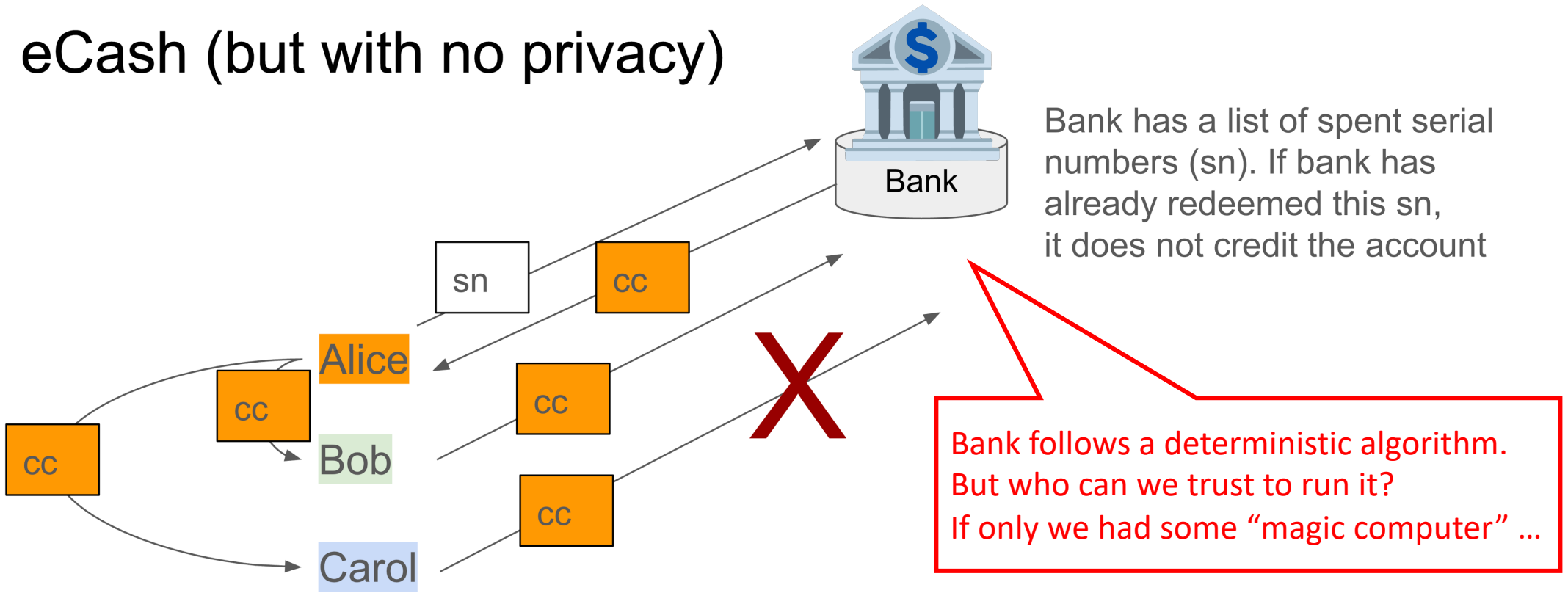

Bank has a list of spent serial numbers (sn). If bank has already redeemed this sn, it does not credit the account

Bank follows a deterministic algorithm.
But who can we trust to run it?
If only we had some "magic computer" …

What if Alice Doublespends?

Magic Computer

Everybody can (using egalitarian interface) { **read** state and **provide** input

Nobody can { **stop** or **corrupt** } execution

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Magic Computer In The Sky

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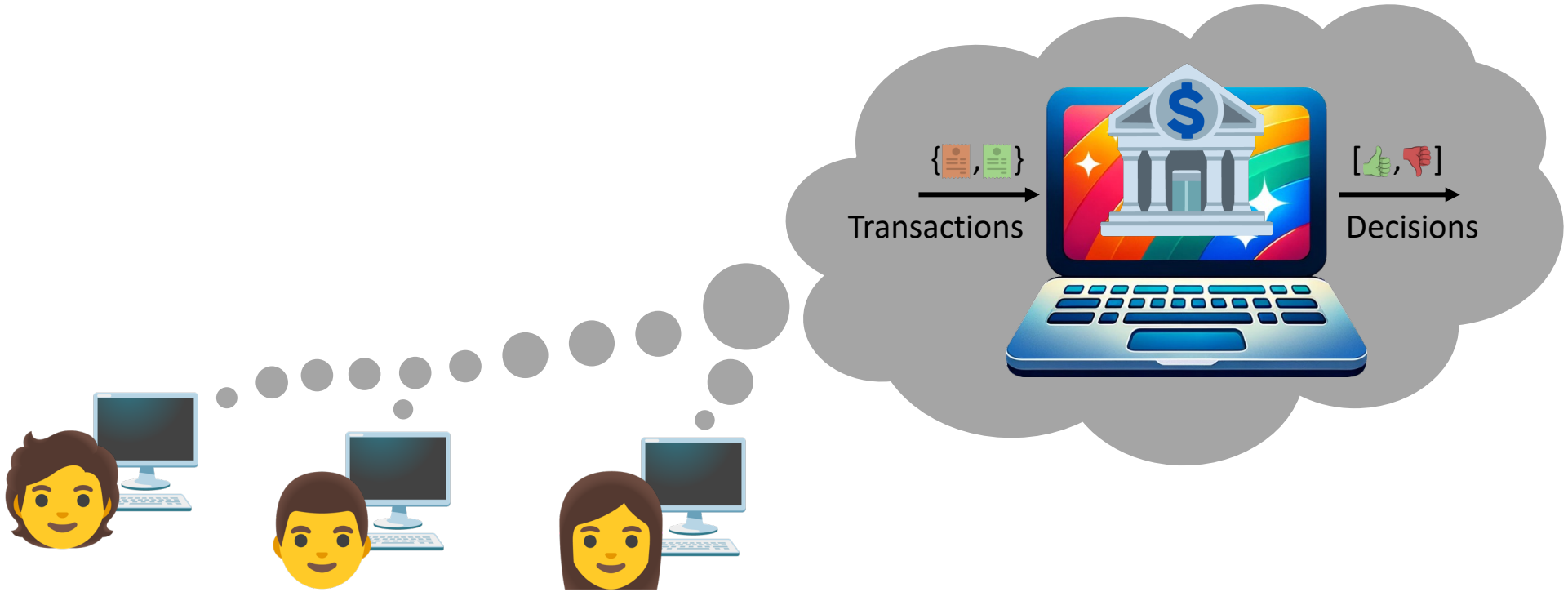

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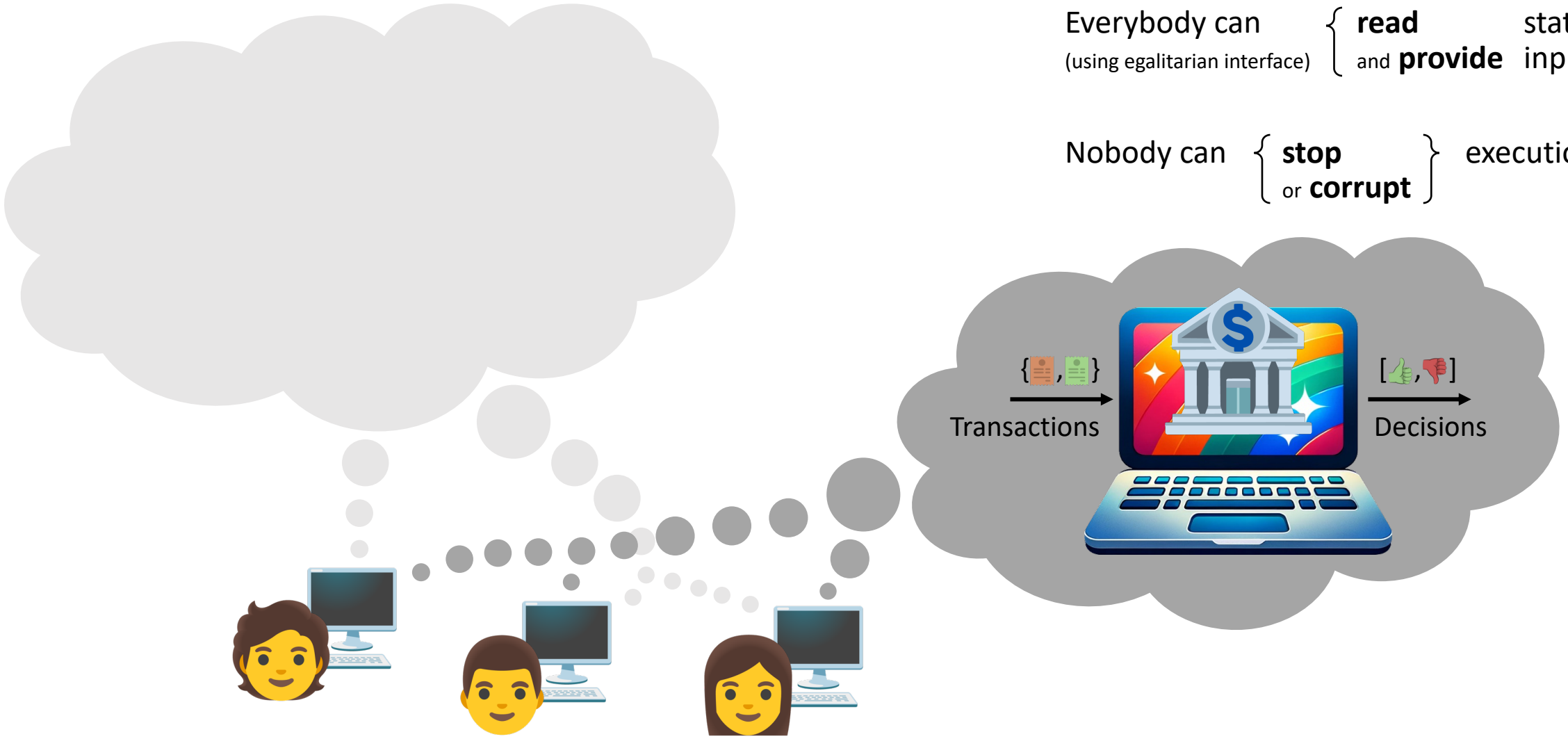

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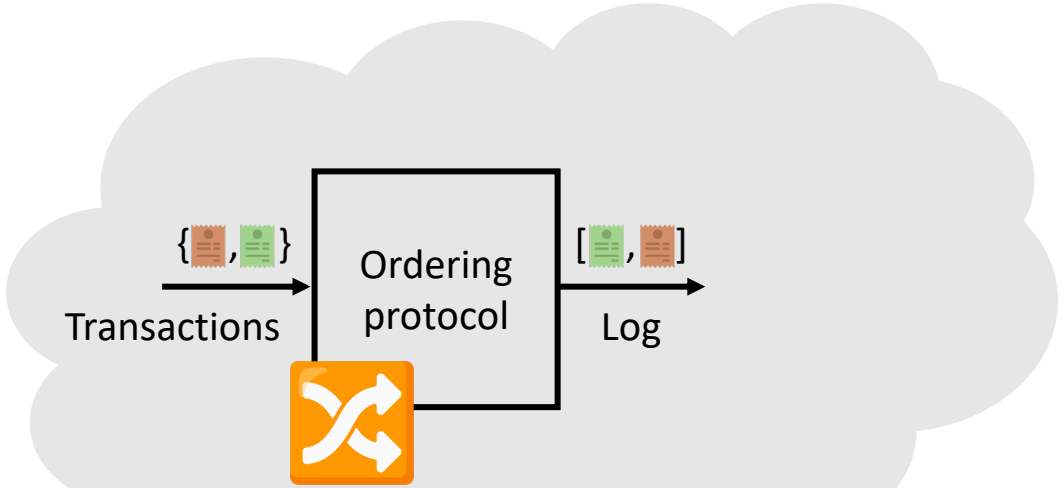

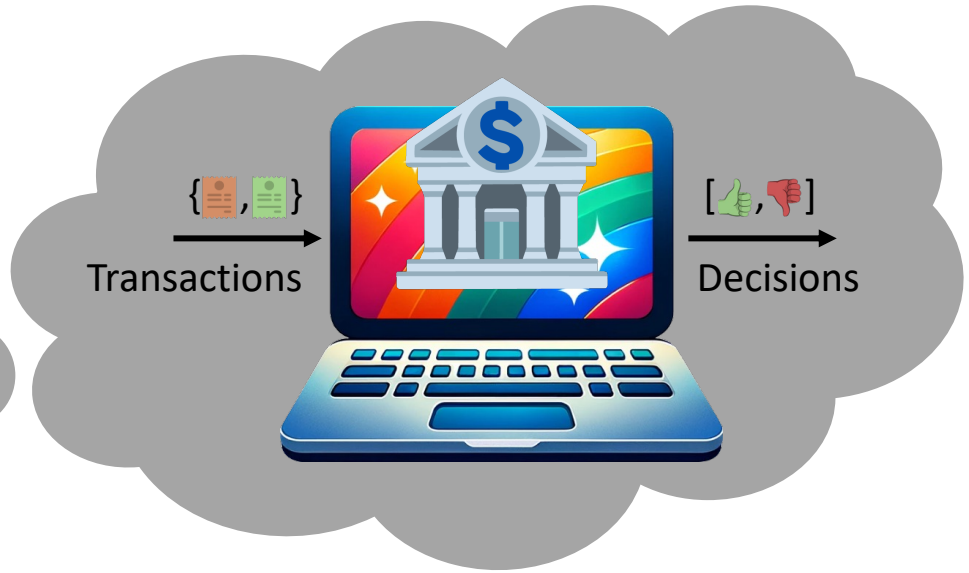

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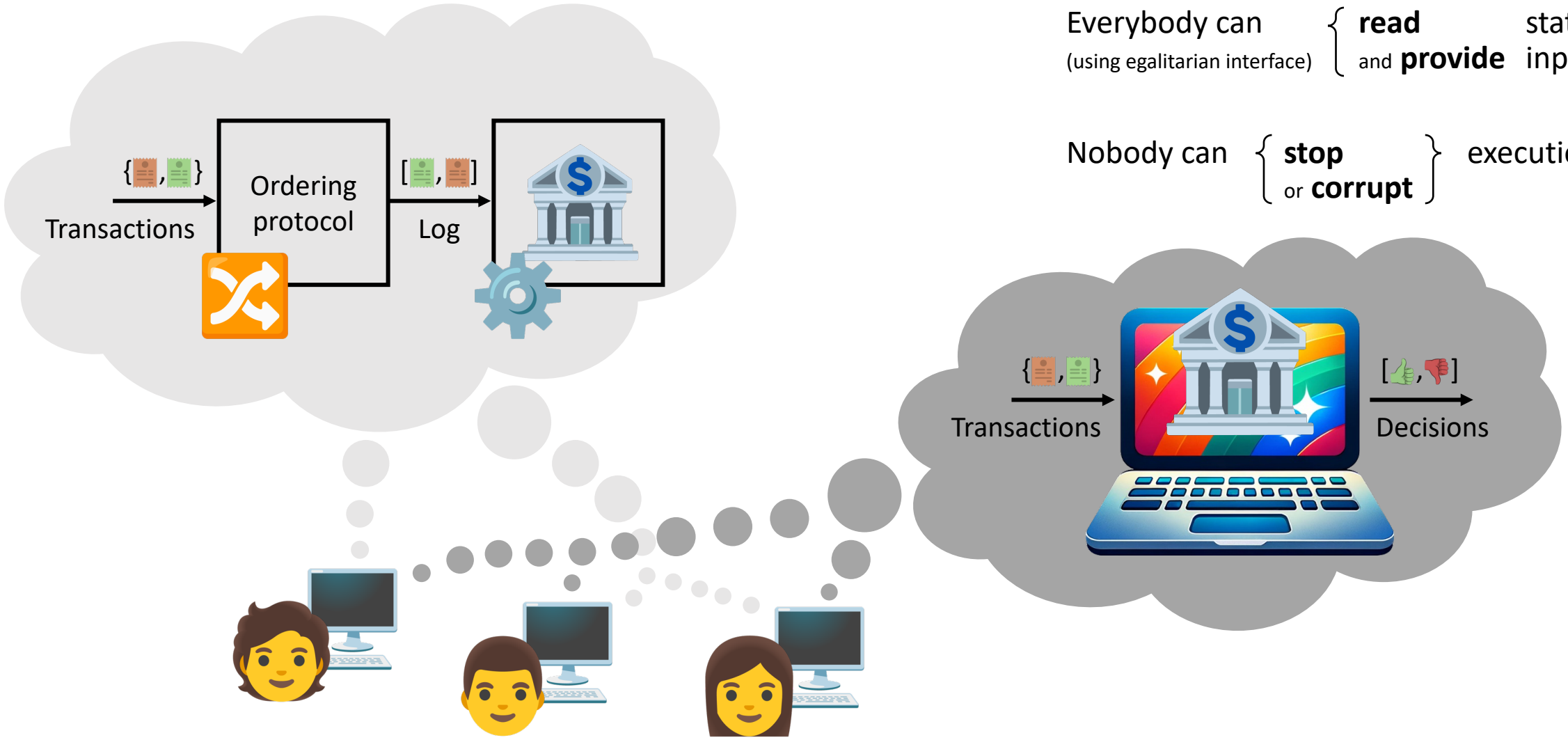
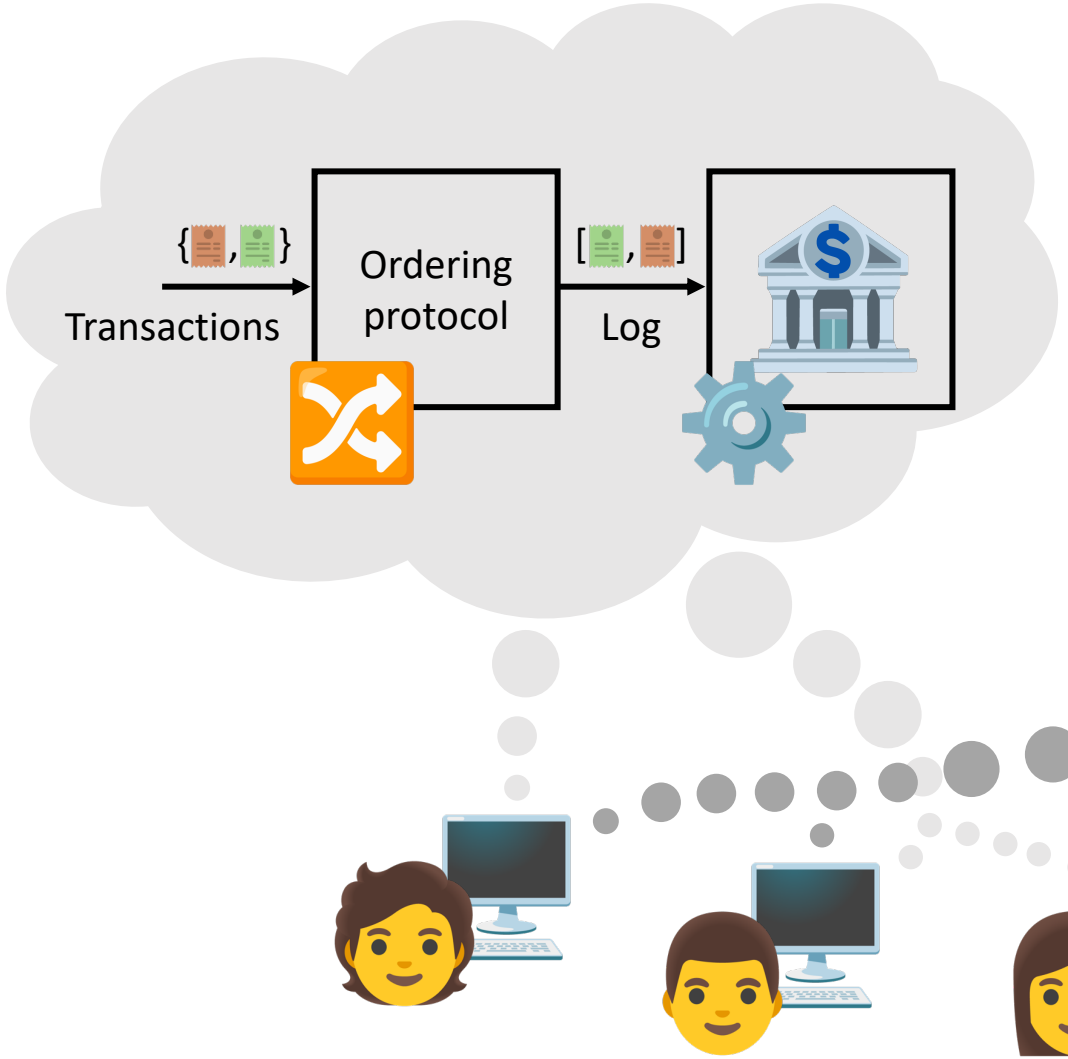


State-Machine Replication



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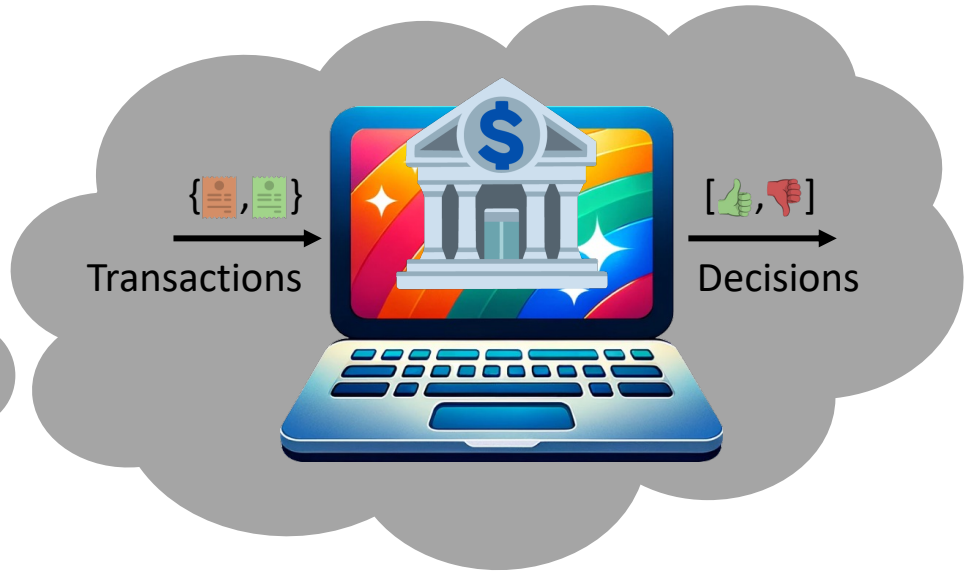

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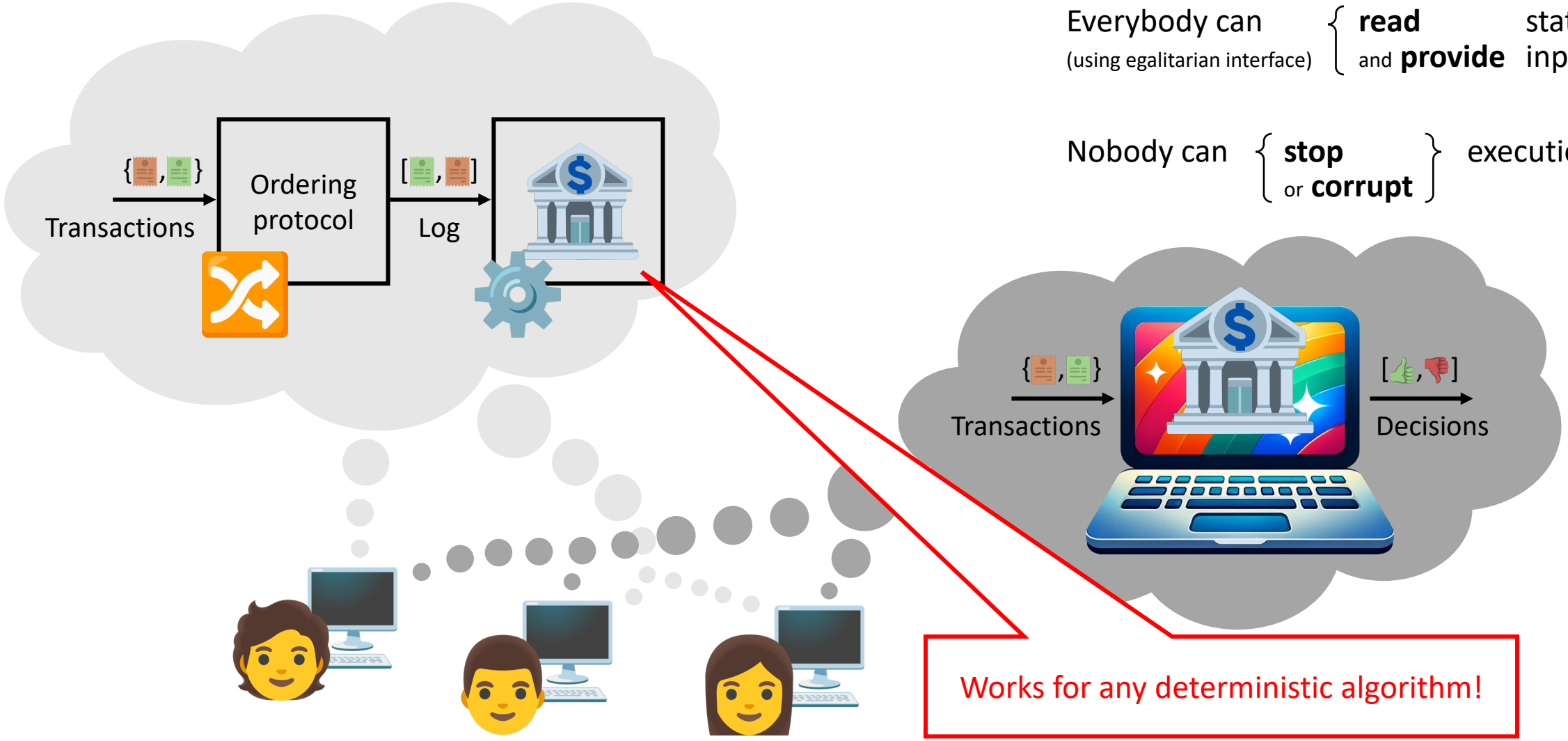

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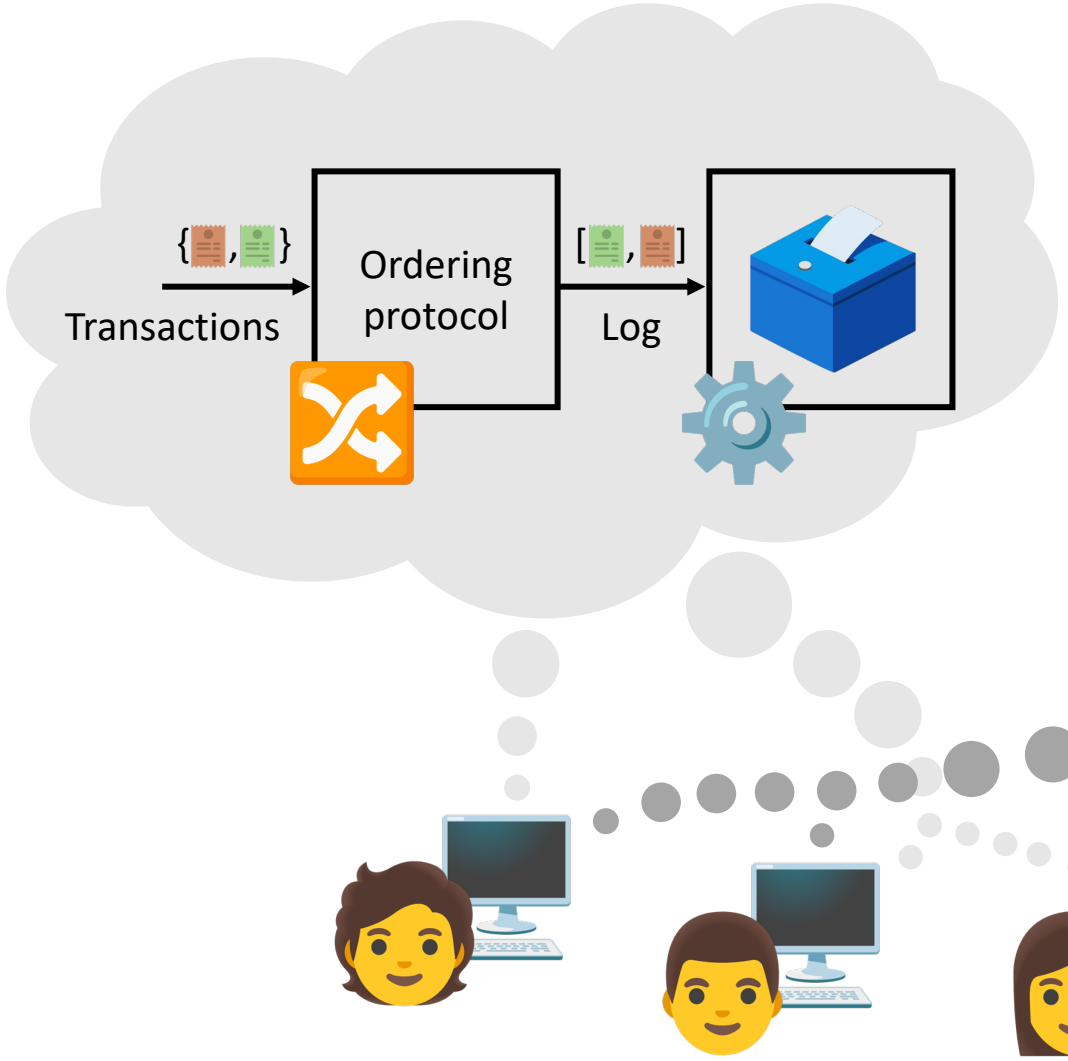

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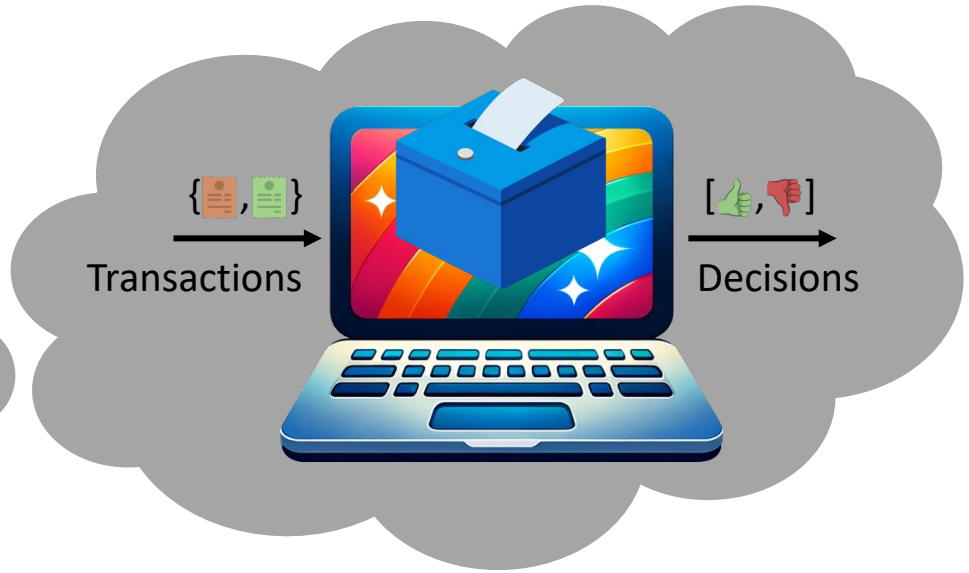

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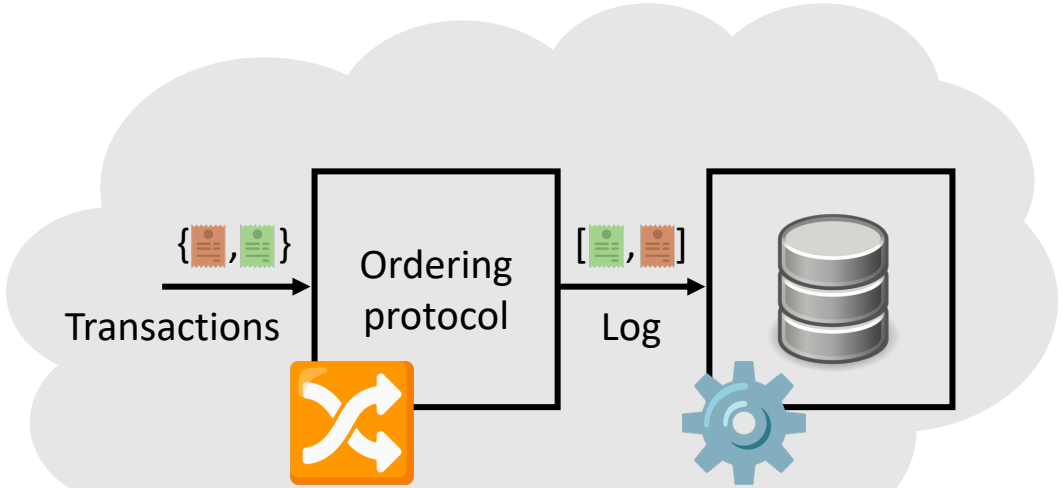

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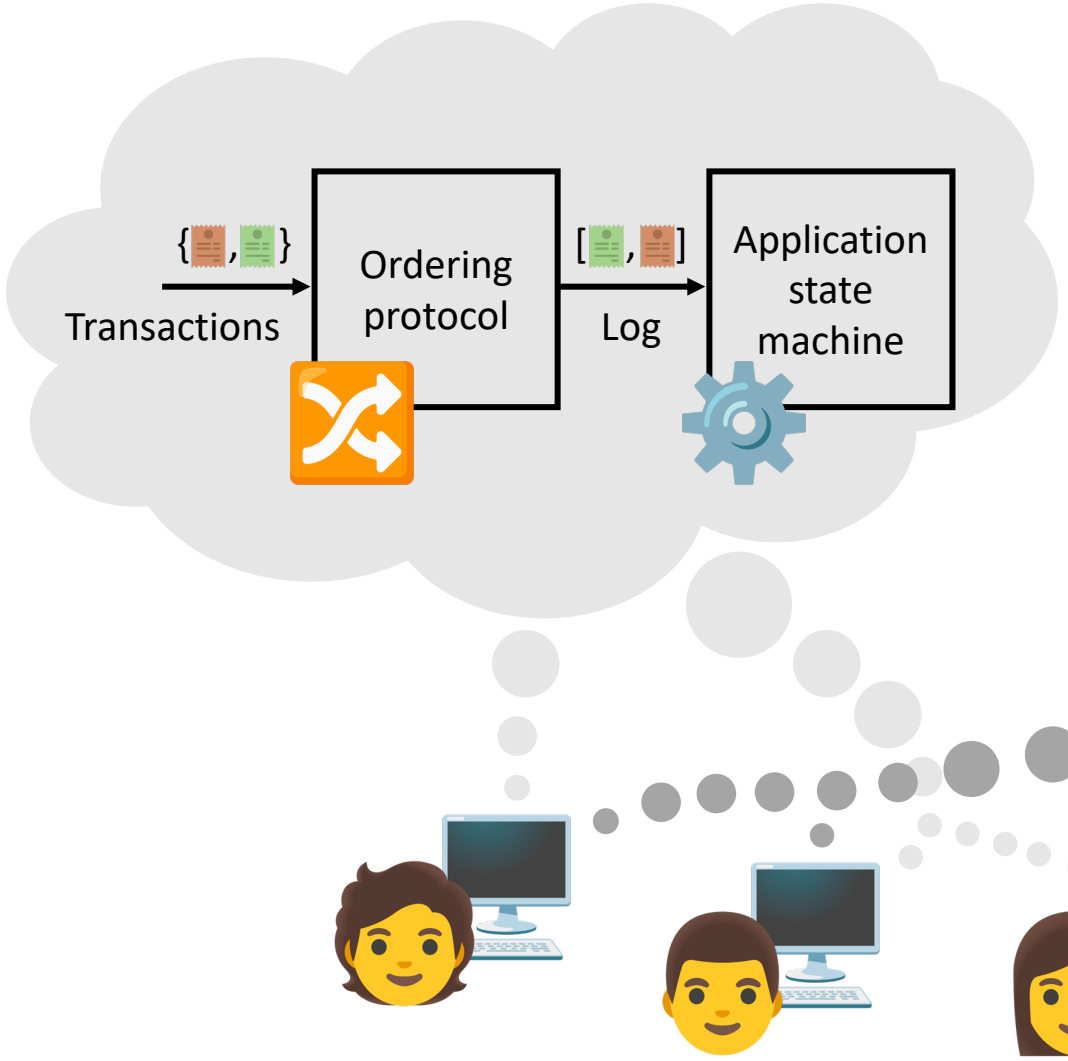

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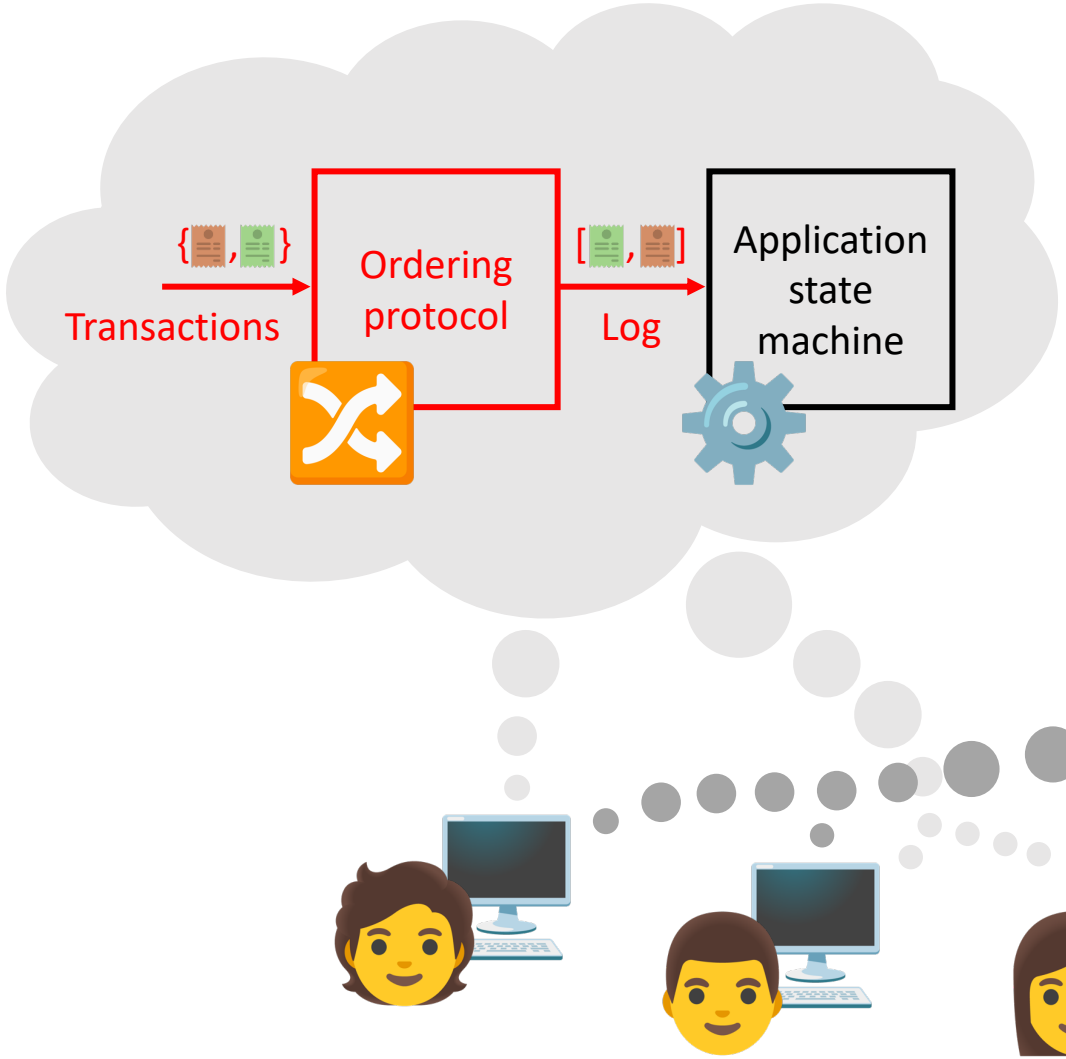

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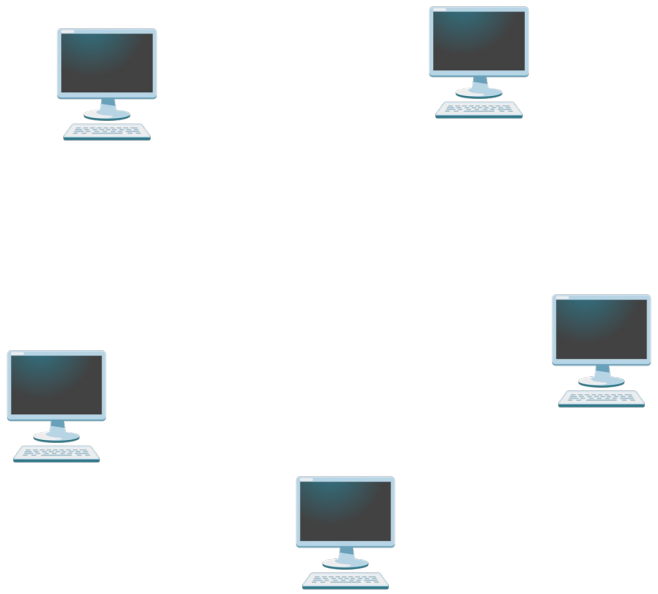
State-Machine Replication (SMR) Consensus Protocol

State-Machine Replication (SMR): Interface

Nodes



State-Machine Replication (SMR): Interface

Input transactions

Nodes

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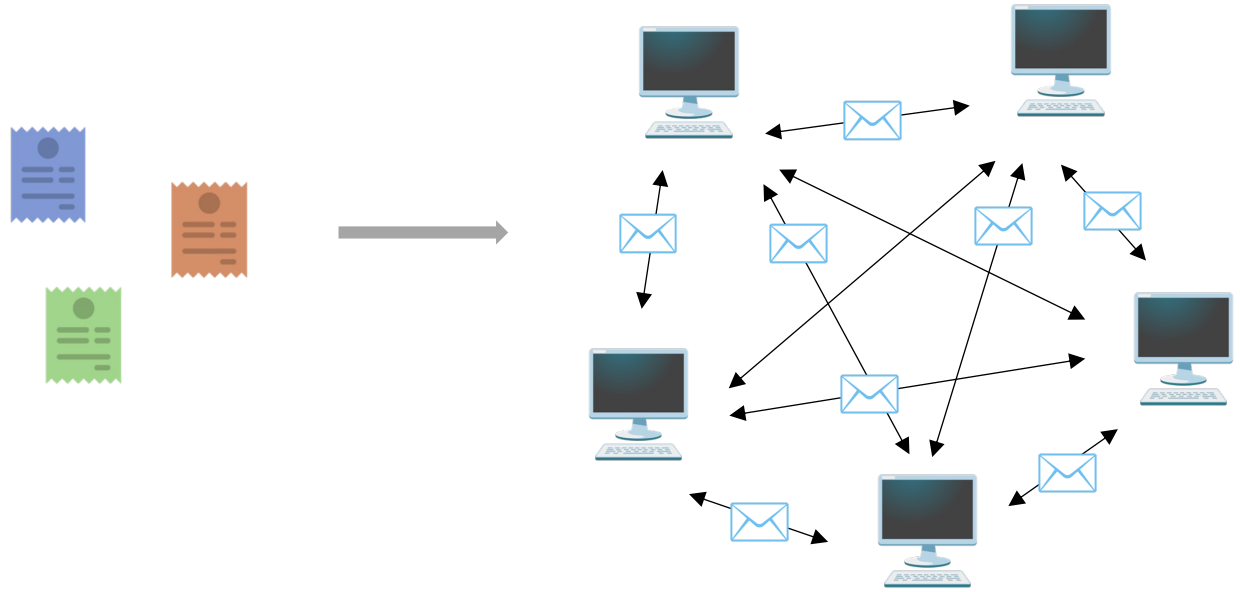

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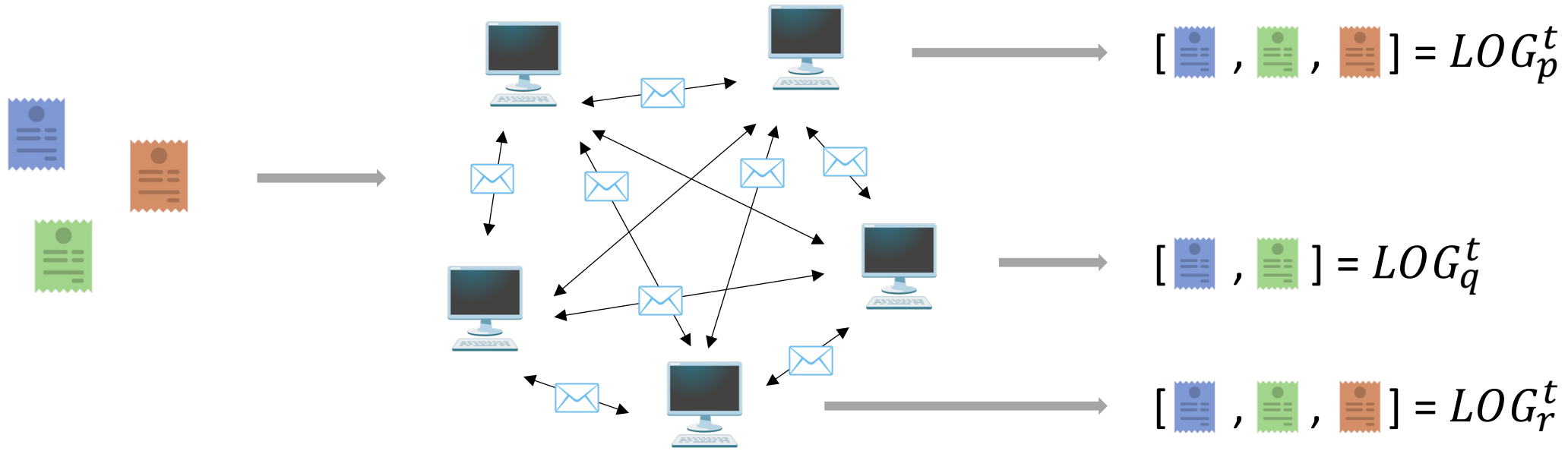

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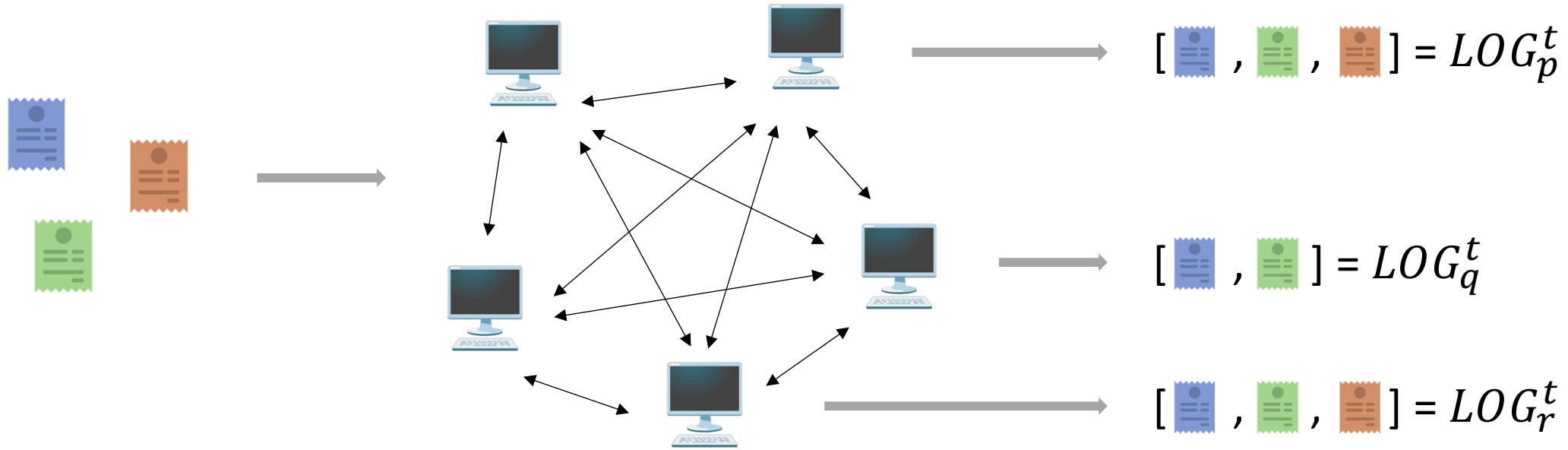

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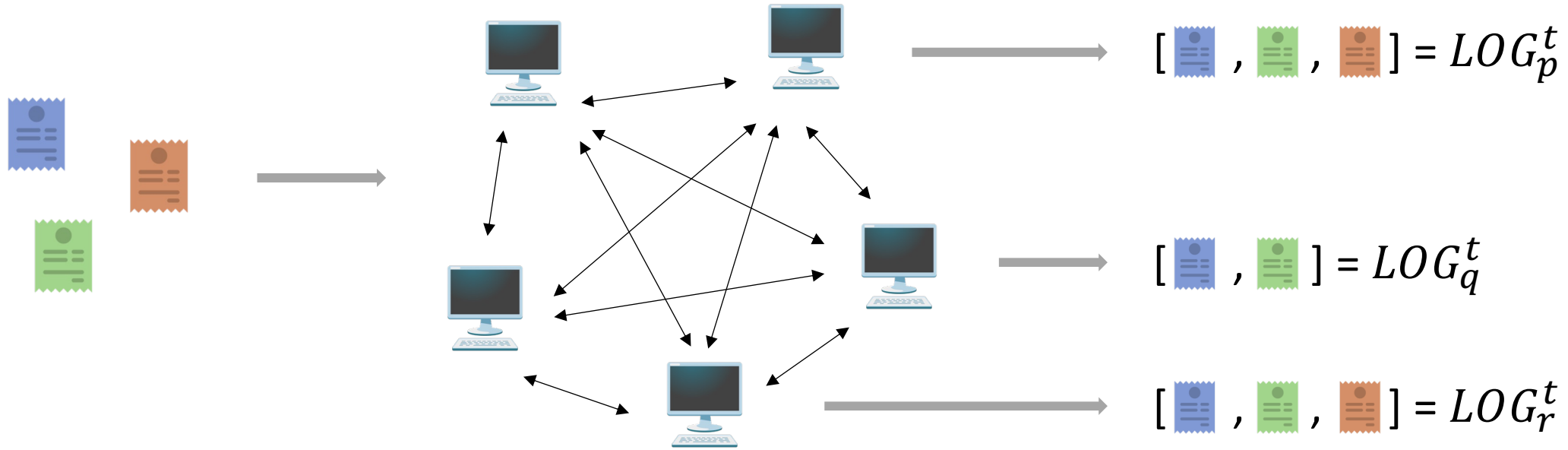

Requirements

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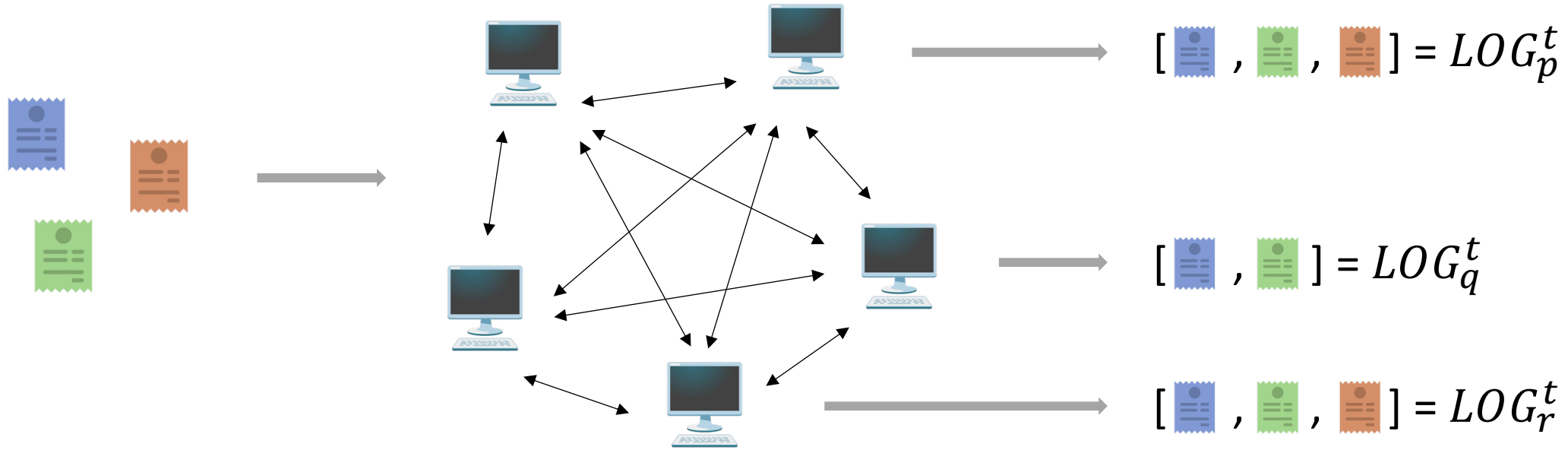

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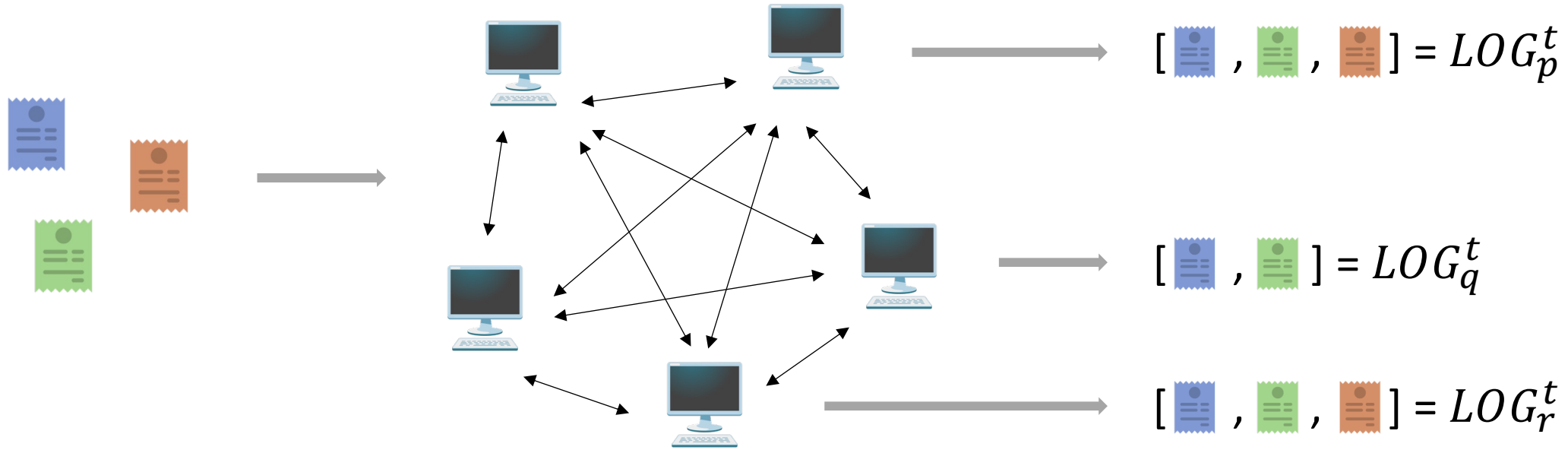

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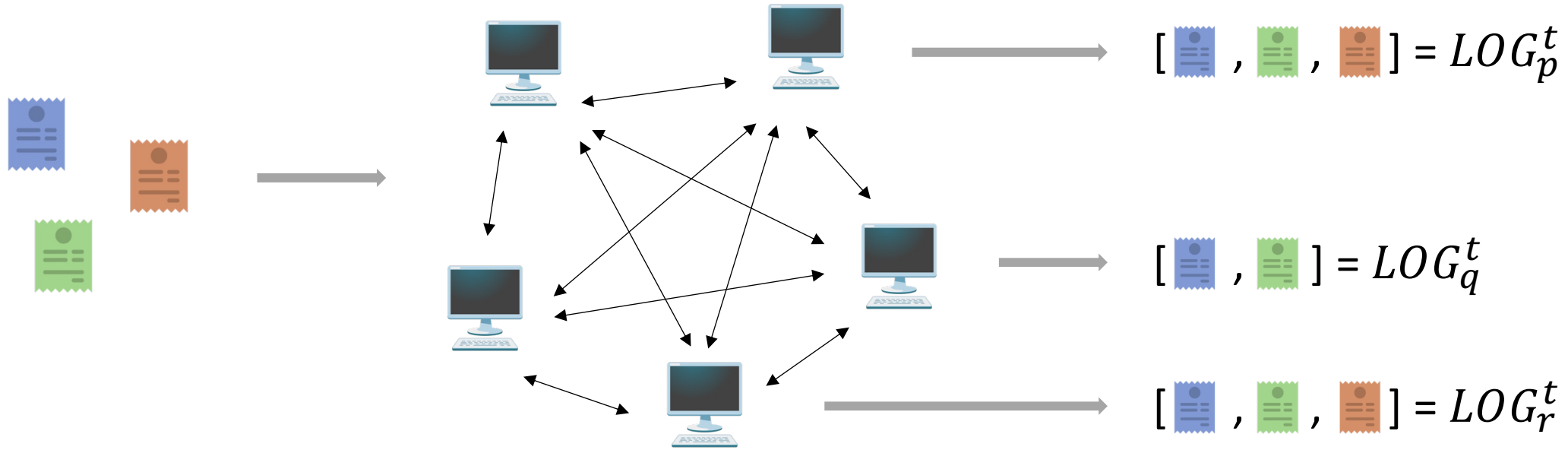

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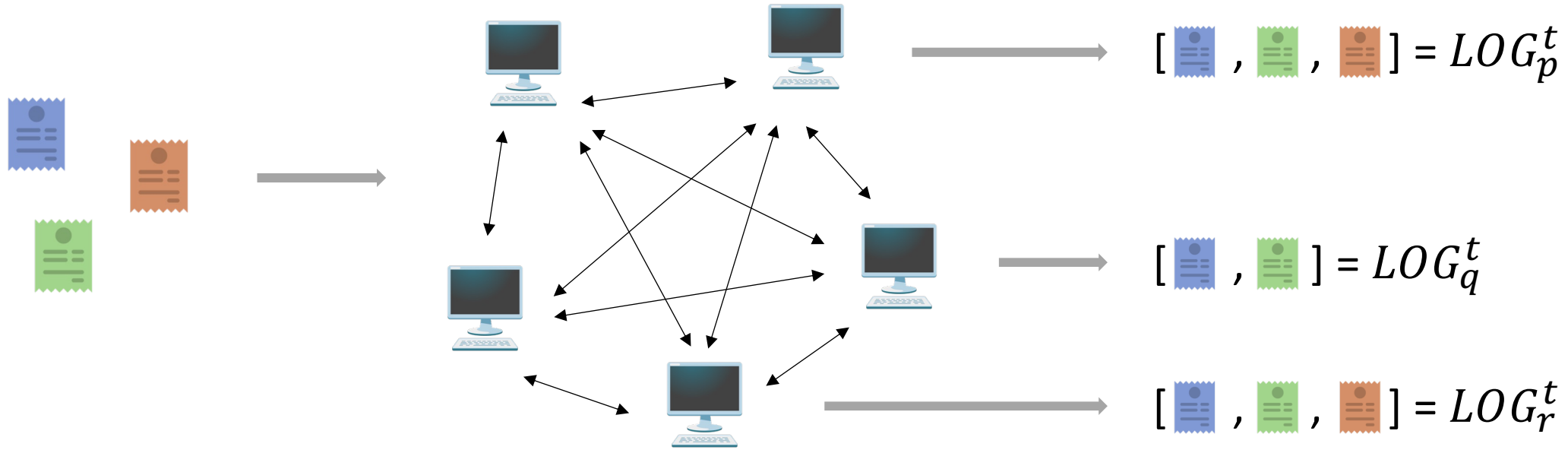

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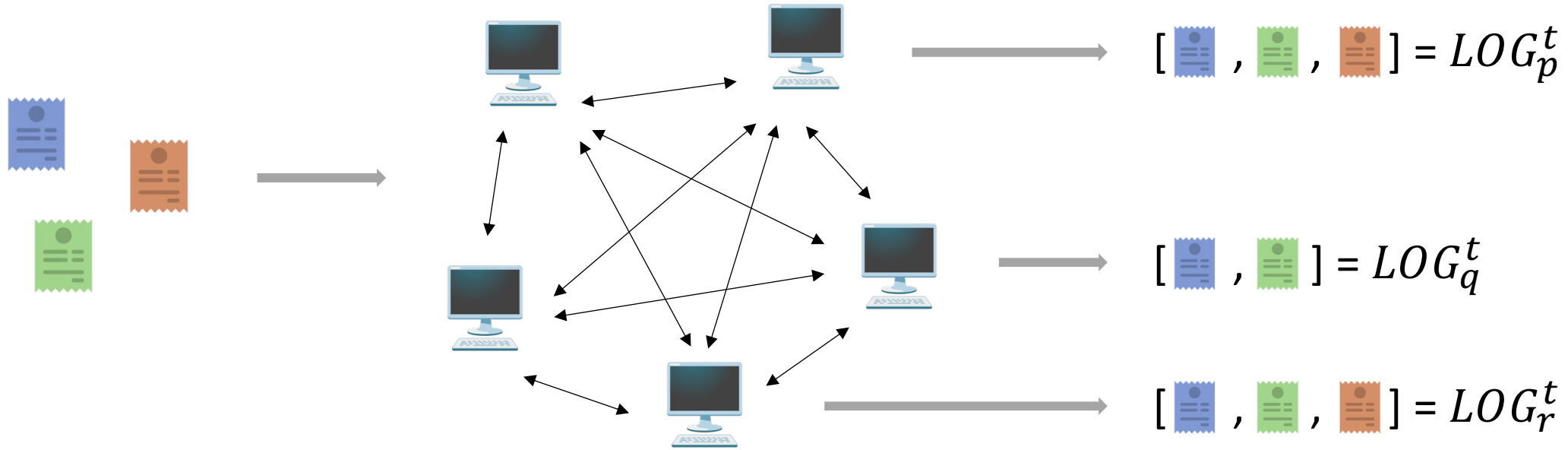

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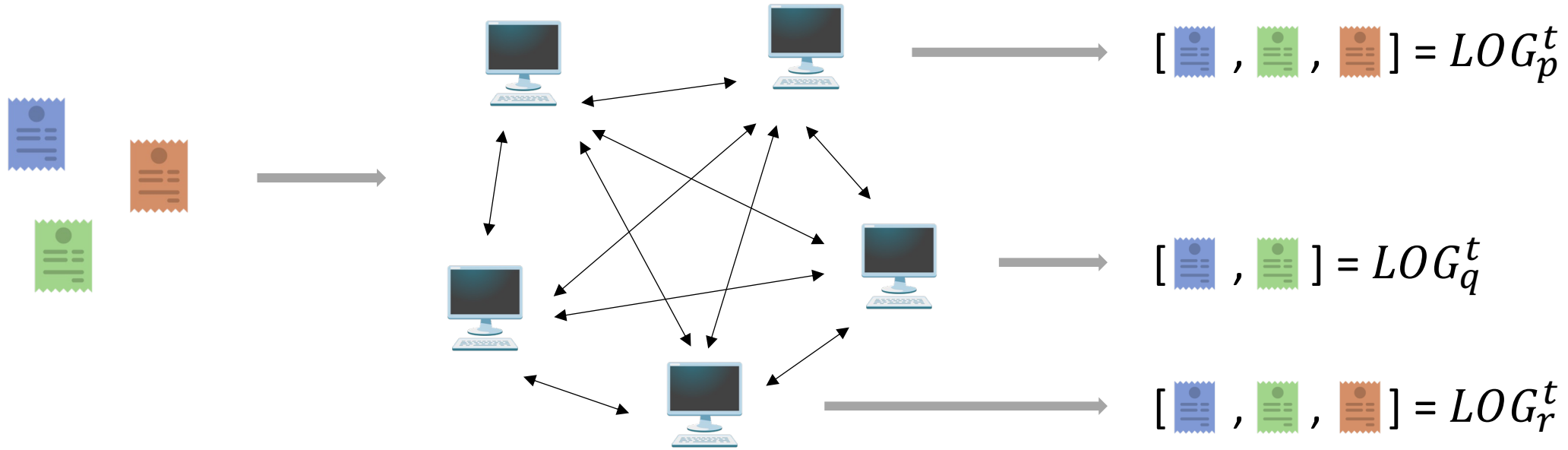

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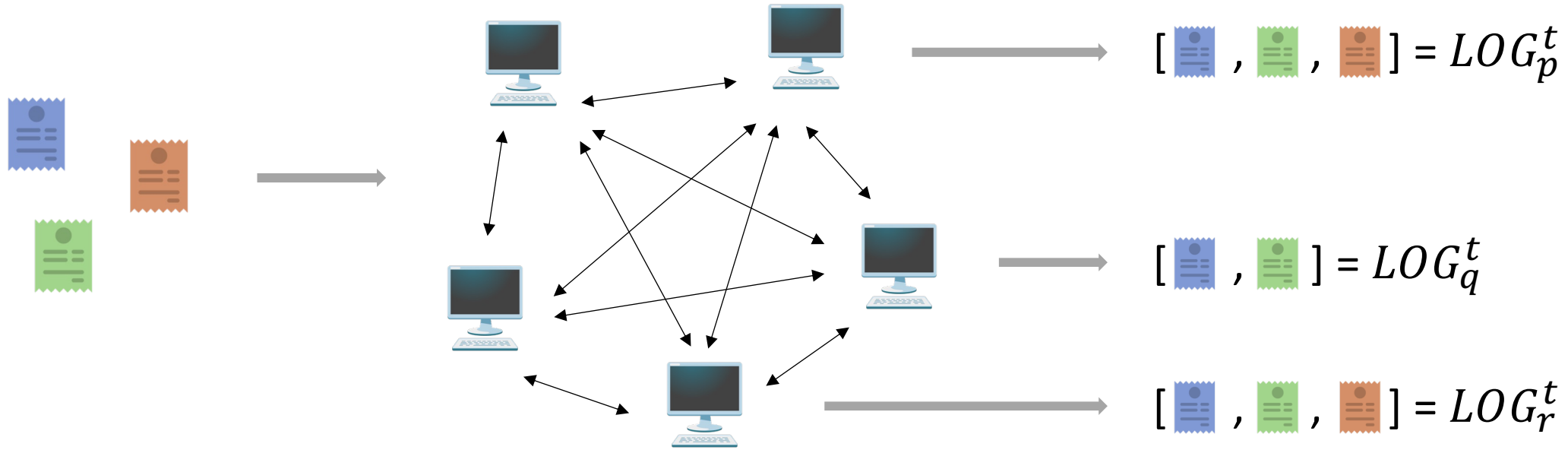

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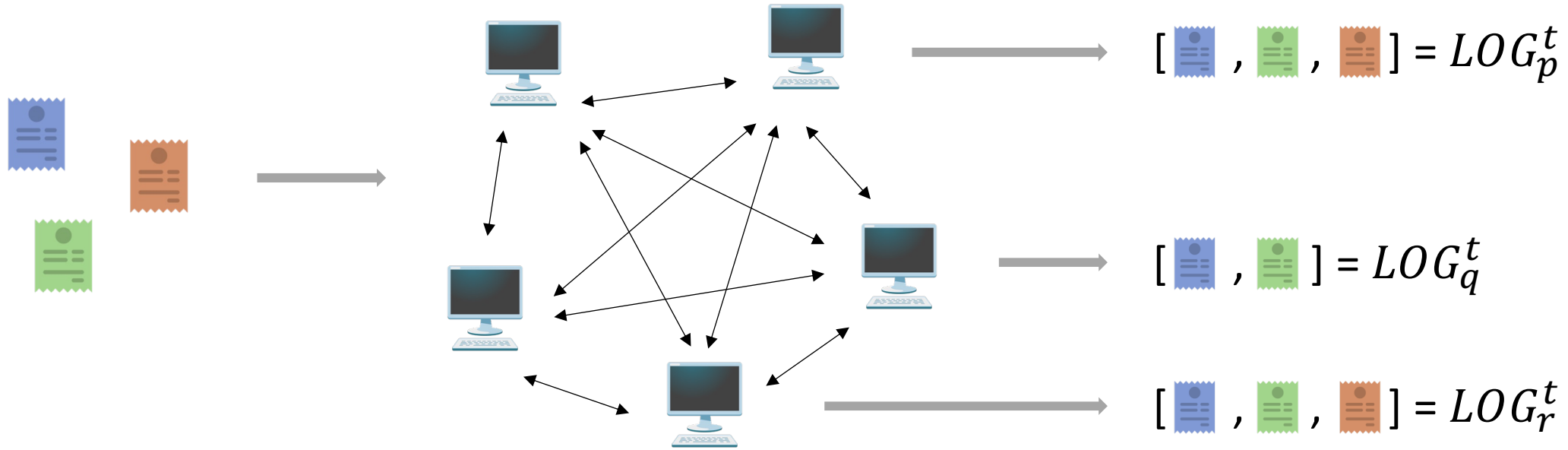

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Old computer science problem, studied since 1980s

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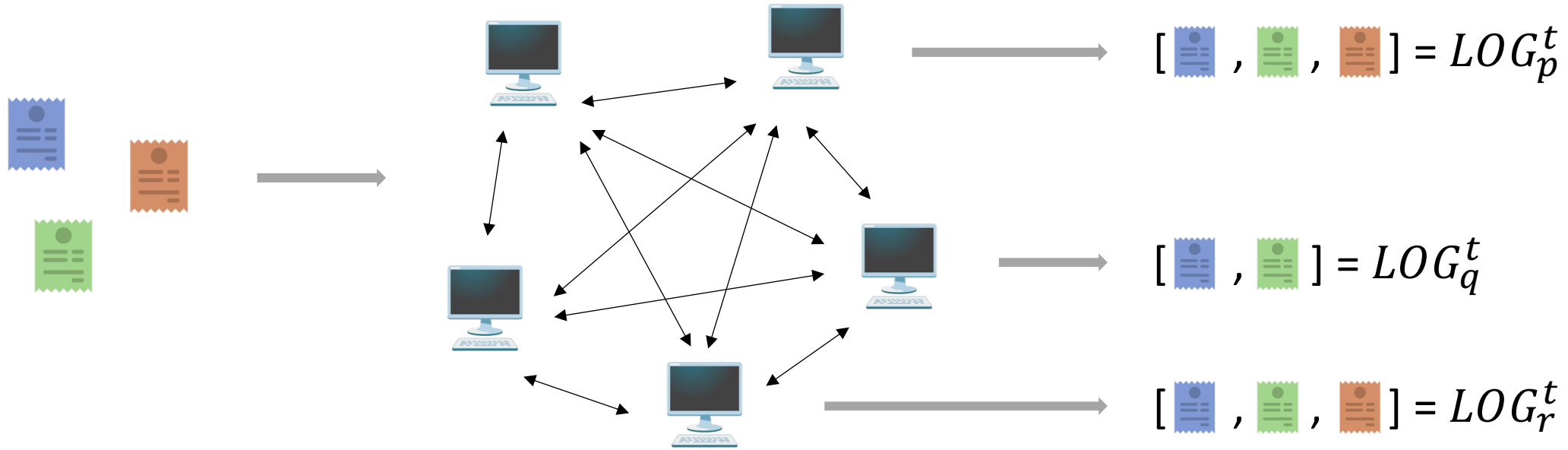

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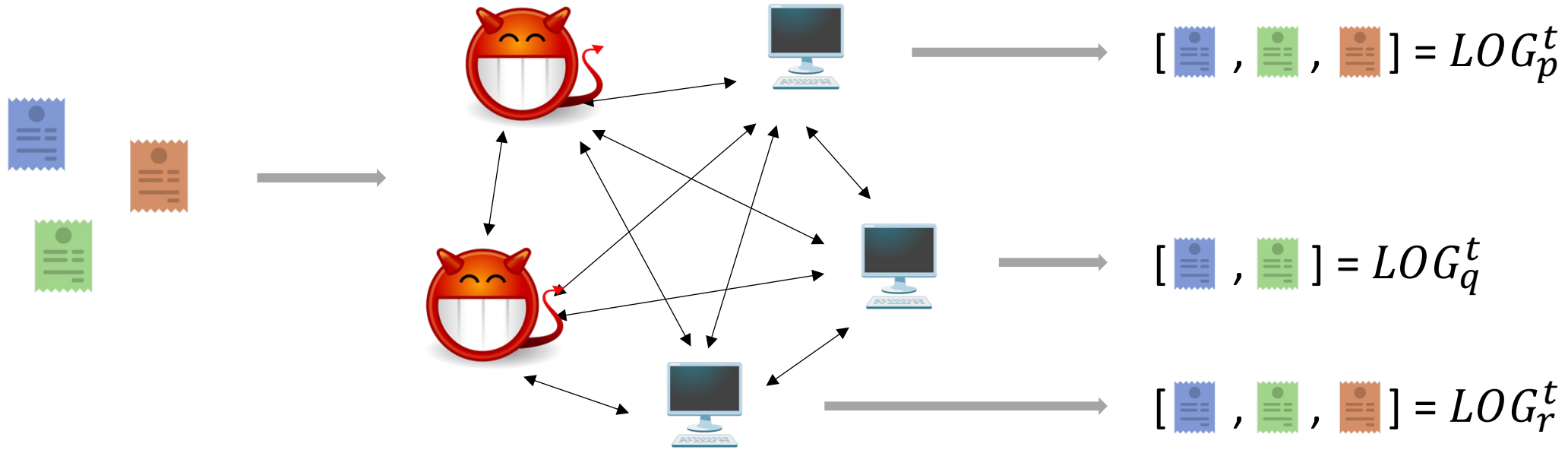

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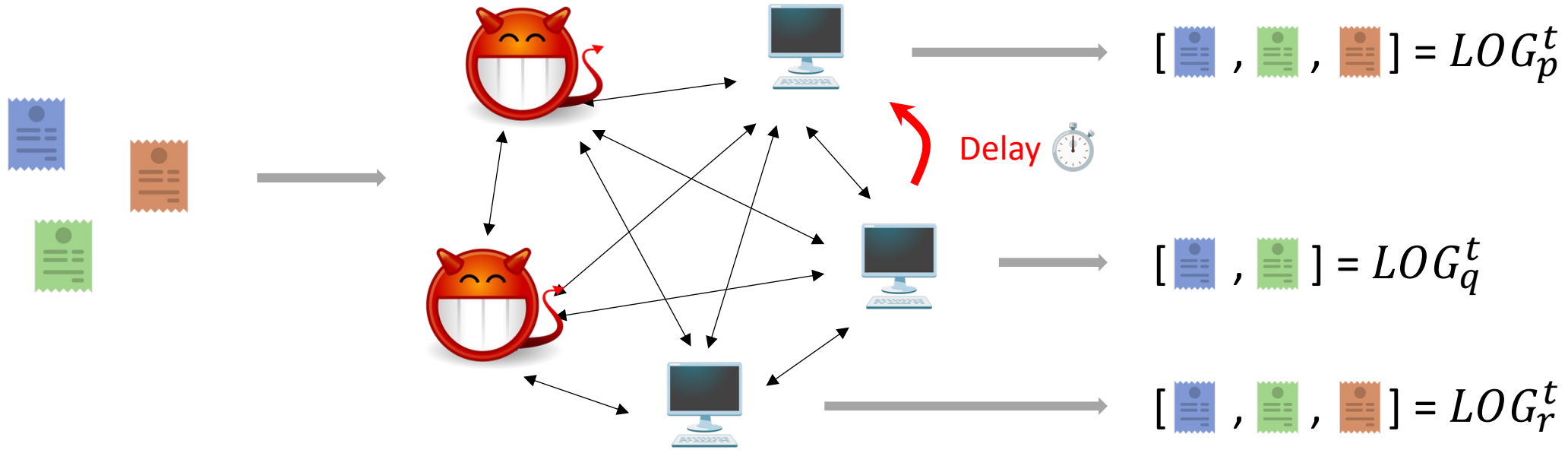

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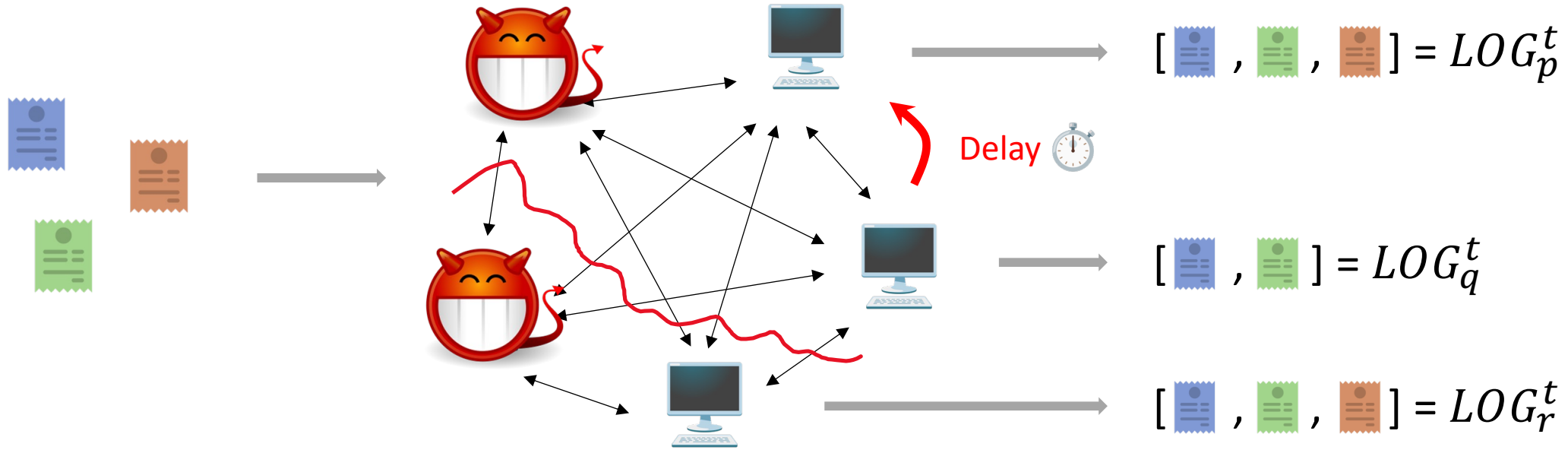

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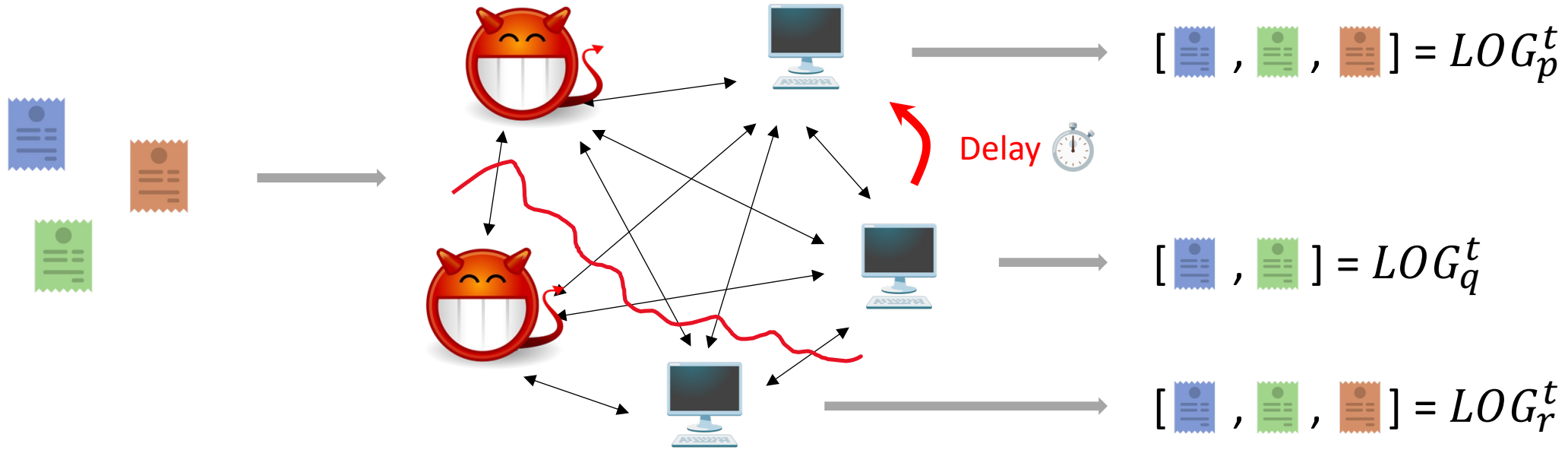

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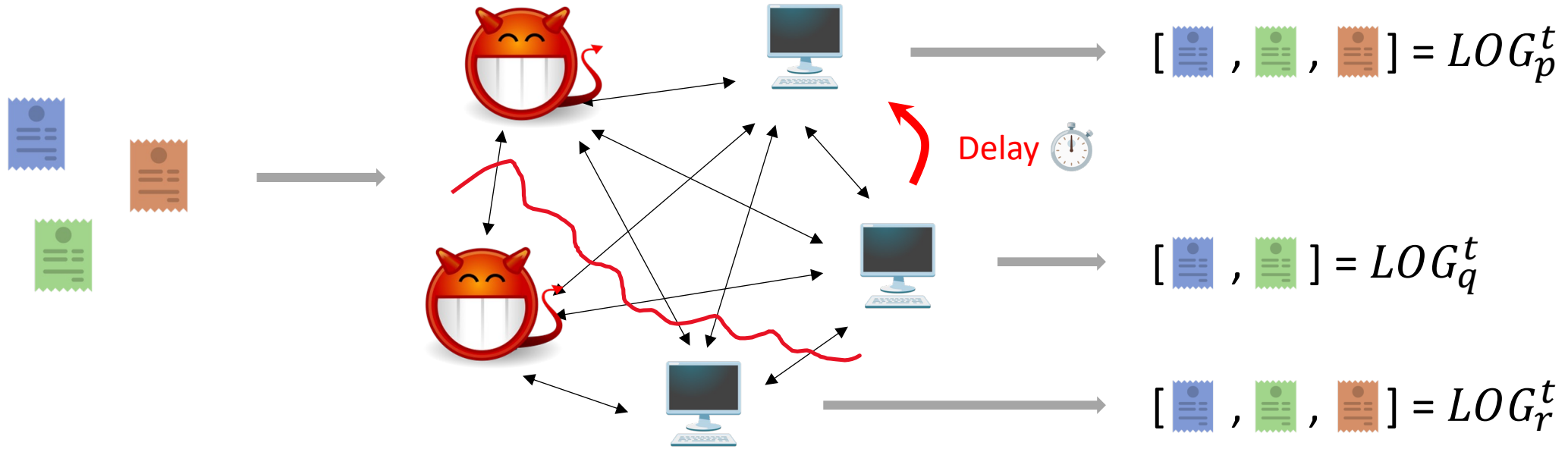

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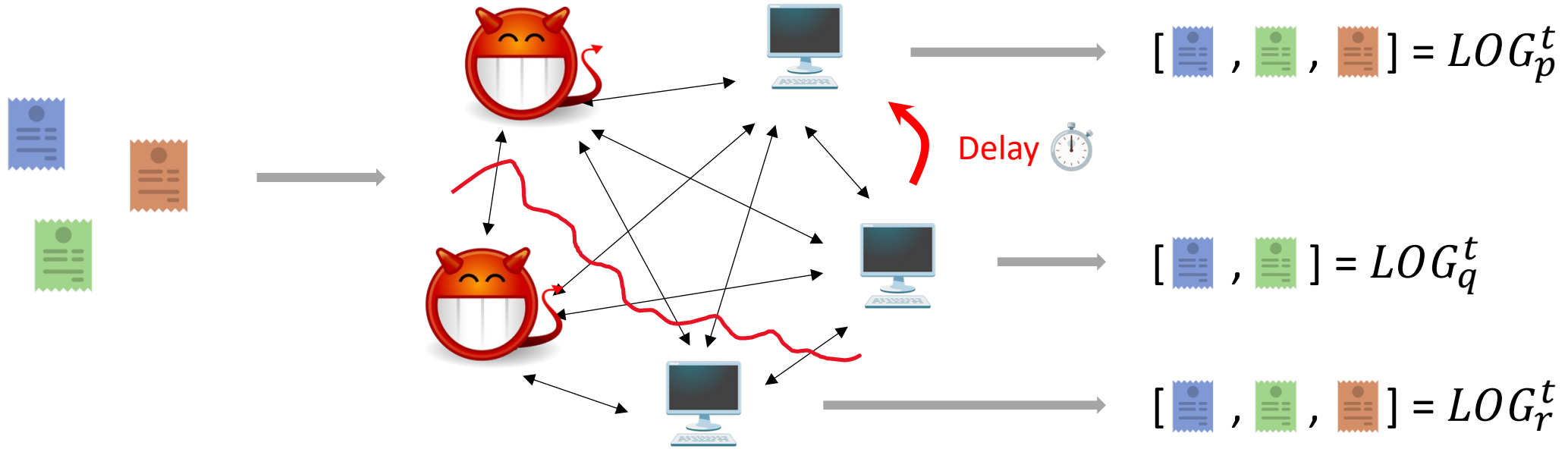

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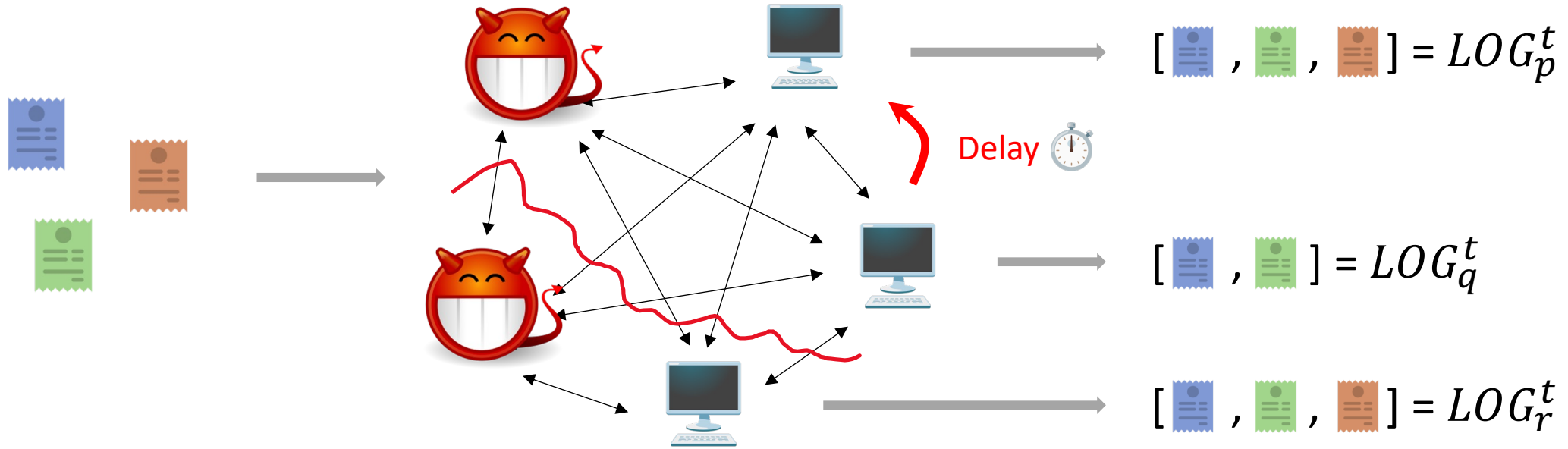

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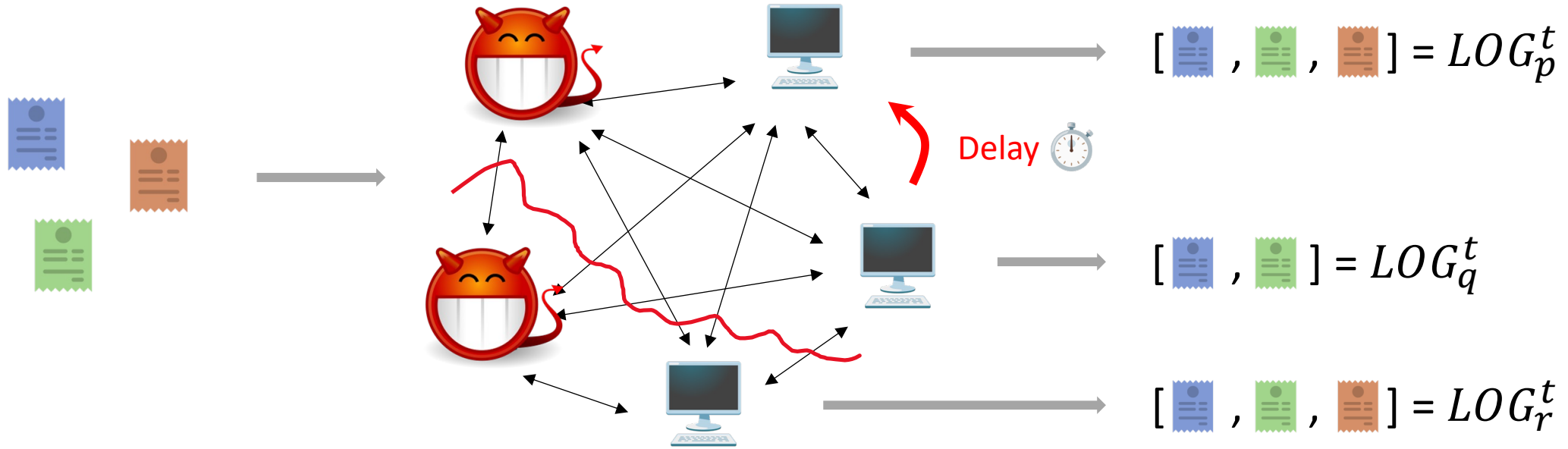

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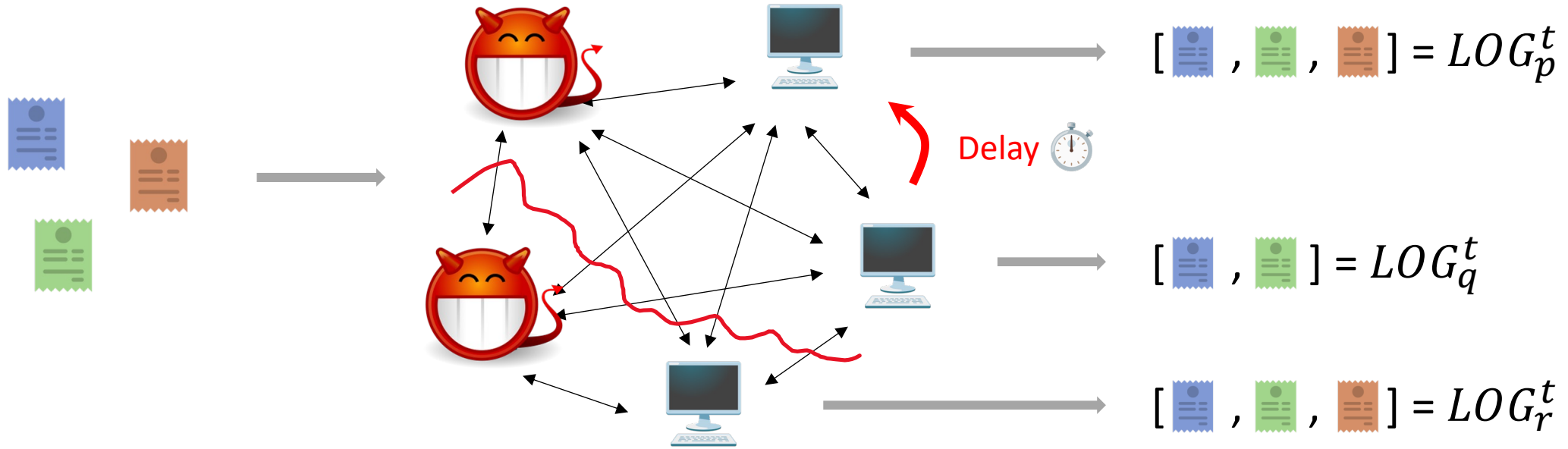
Liveness: Transactions make it into every honest node's log eventually ... under conditions on 😈, ⏱️.

$$\forall \text{input } tx \colon \quad \exists t_0 \colon \quad \forall t \geq t_0 \colon \quad \forall \text{honest } p \colon \quad tx \in LOG_p^t$$

State-Machine Replication (SMR): Interface



Requirements

Safety: Logs are consistent across honest nodes and times ... under conditions on 😈, ⏱️.

Liveness: Transactions make it into every honest node's log eventually ... under conditions on 😈, ⏱️.

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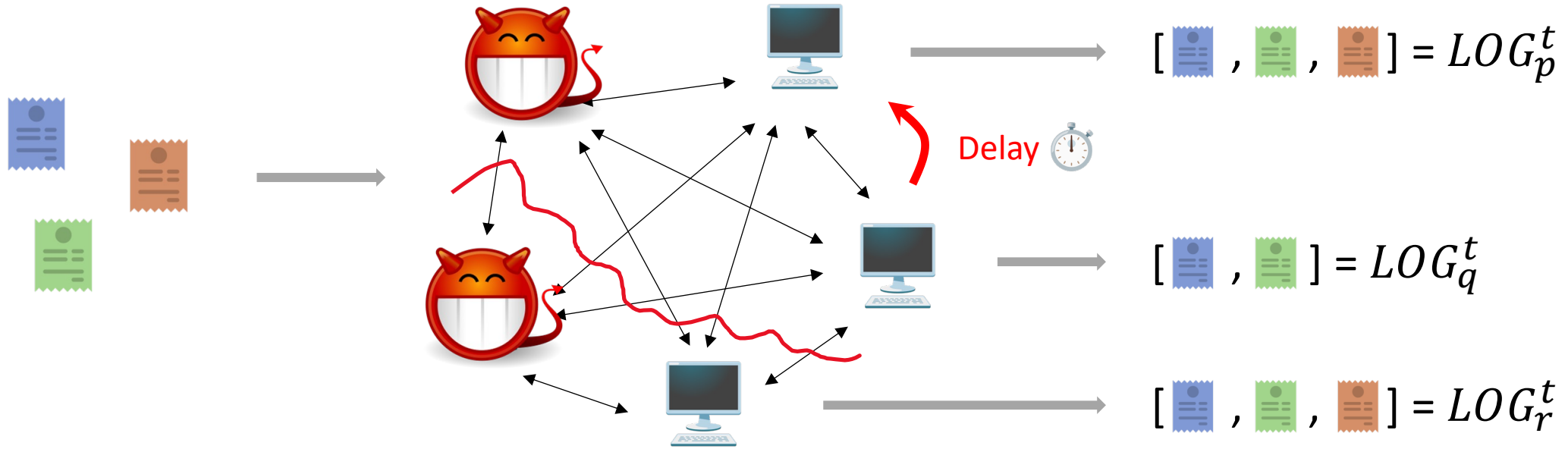

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Many variants of the consensus problem, depending on:
(1) What constitutes the set of nodes? (2) Network delay model. (3) Behaviors of adversarial nodes.
We will see some examples later!

(1) Set of Nodes

What constitutes “one node”? How to stop the adversary from pretending to have an inflated number of nodes (“Sybil attack”)? → “Sybil resistance mechanism”

- **Mostly historic: “authenticated point-to-point channels”** (“spoken model”)
  - n nodes; nodes “just know” which node they received a message from
- **Proof-of-work**
  - “One CPU, one vote”
  - Computational puzzles; solutions are found in proportion to compute power
  - See example later: hash puzzles in Bitcoin

Proof-of-work in consensus: new with Bitcoin

- **Permissioned** (cryptographic identities, “public key infrastructure”, “written model”)
  - n nodes, each with a secret/public key pair for a signature scheme
  - List of public keys is known to all nodes

“Permissioned consensus” ≠ “permissioned blockchains”

- **Proof-of-stake**
  - “One coin, one vote”
  - See example later: usually bootstrapped from permissioned setting

- **Proof-of-space, proof-of-useful-work/-space, …**

(2) Network Models

- **Synchronous network**

  There exists a delay upper-bound Δ, *known* to the nodes, so that every message sent between honest nodes at time t arrives by time $t + \Delta$.

Example protocols: Bitcoin, Cardano's Ouroboros, parts of Ethereum (LMD GHOST)

- **Partially synchronous network**

  There exists a delay upper-bound Δ, *known* to the nodes, *and an adversary-chosen "global stabilization time" GST*, so that every message sent between honest nodes at time t arrives by time $\max(GST, t) + \Delta$.

Example protocols: PBFT, Simplex, Tendermint, HotStuff, parts of Ethereum (Casper FFG)

- **Asynchronous network**

  Every message sent between honest nodes arrives *eventually*.

(3) Behaviors of Adversarial Nodes

- **Crash faults**

  Adversarial nodes stop protocol execution at some adversary-chosen time

- **Worst-case ("Byzantine") faults**

  Adversarial nodes follow adversary-chosen, computationally bounded behavior (→ cannot break cryptography), possibly coordinated across adversarial nodes

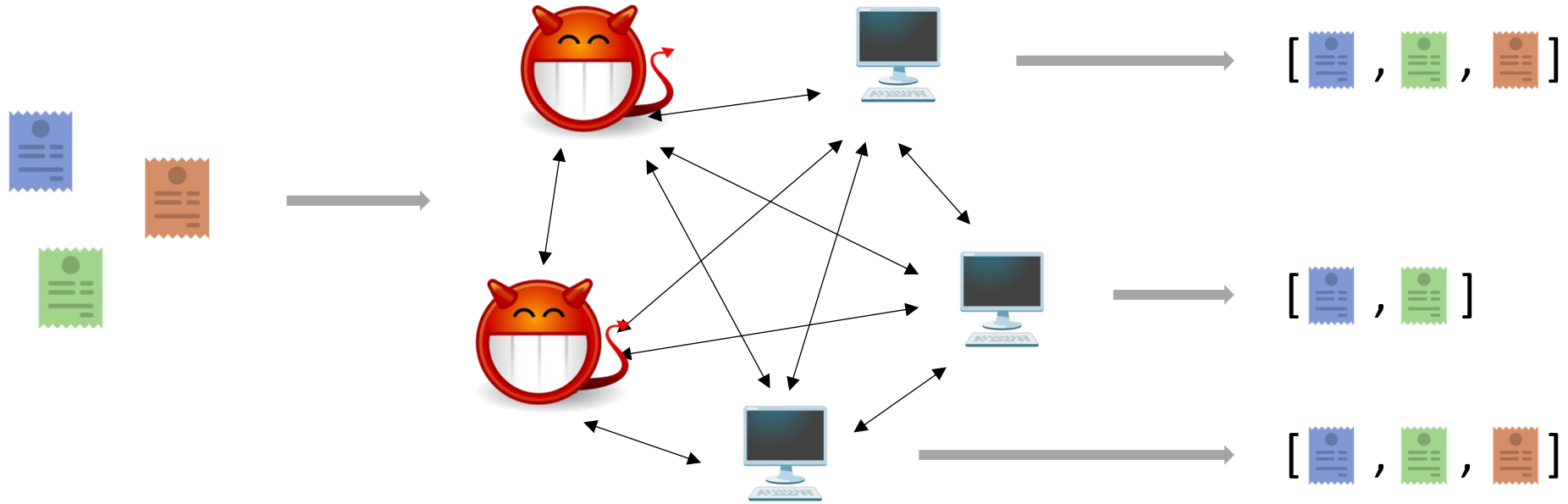
Model of choice for blockchains

- ~~**Profit-seeking ("rational") behavior**~~

  ~~Nodes seek to maximize their payouts from protocol rewards etc.~~

Incentives in consensus are a can of worms …

SMR Example 1: Proof-of-Work Nakamoto Consensus



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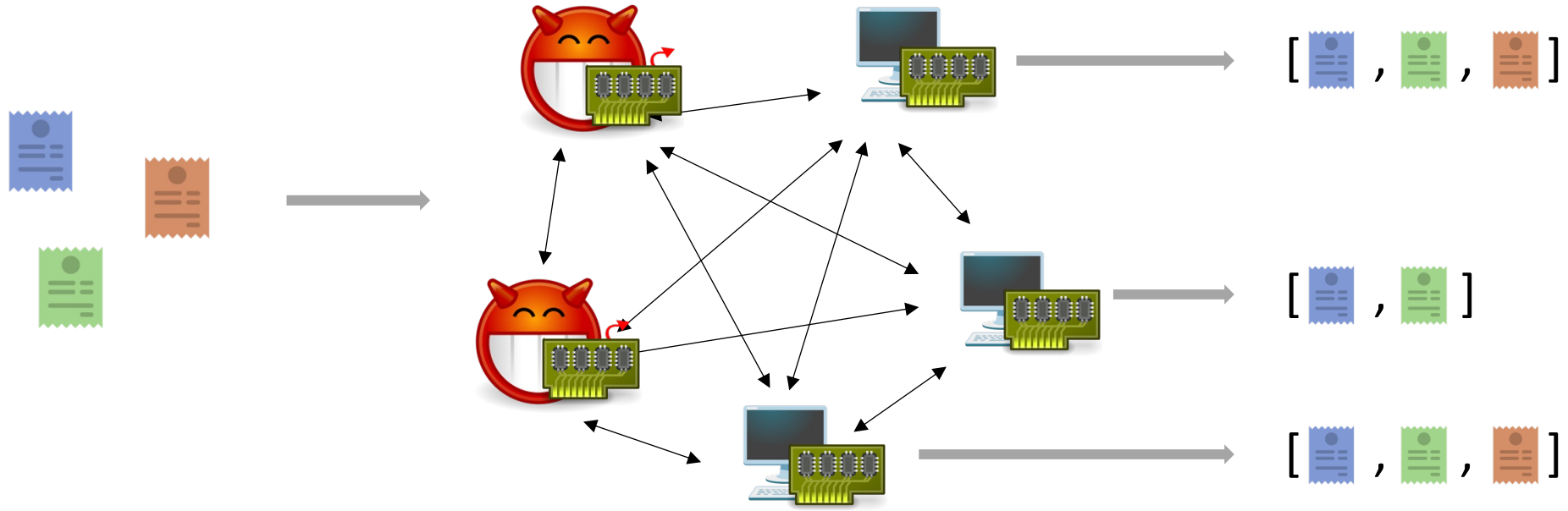

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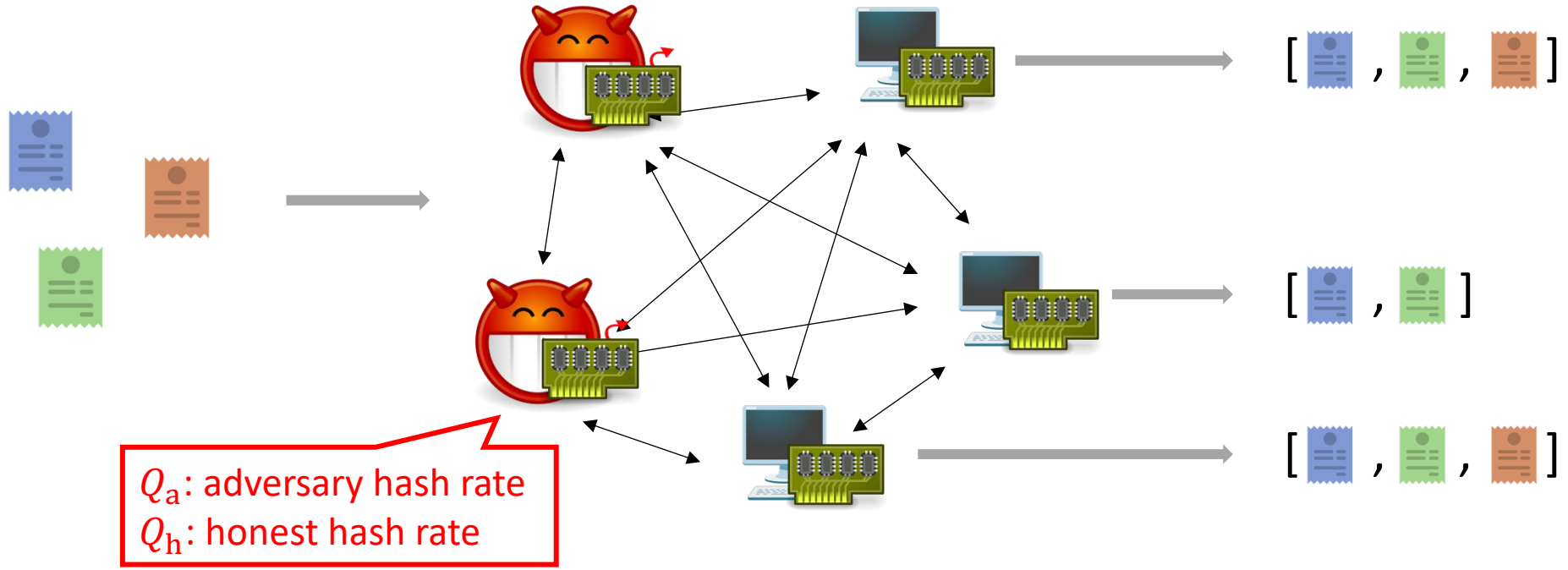

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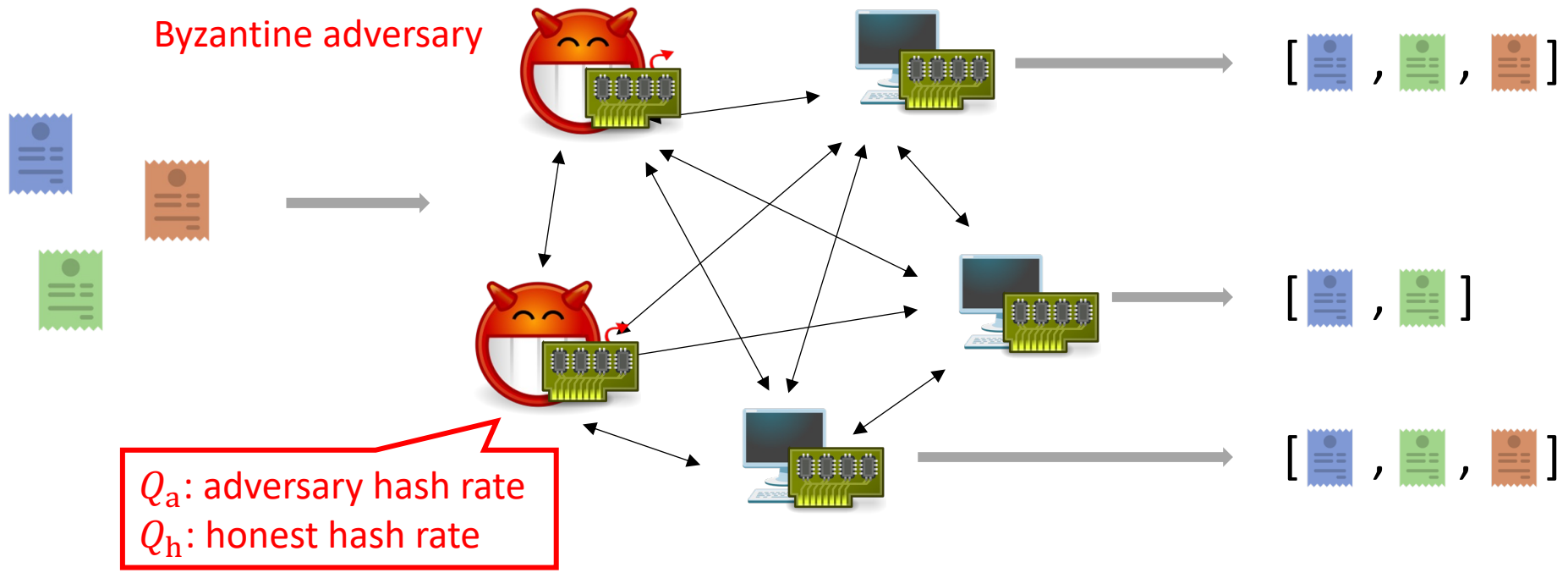

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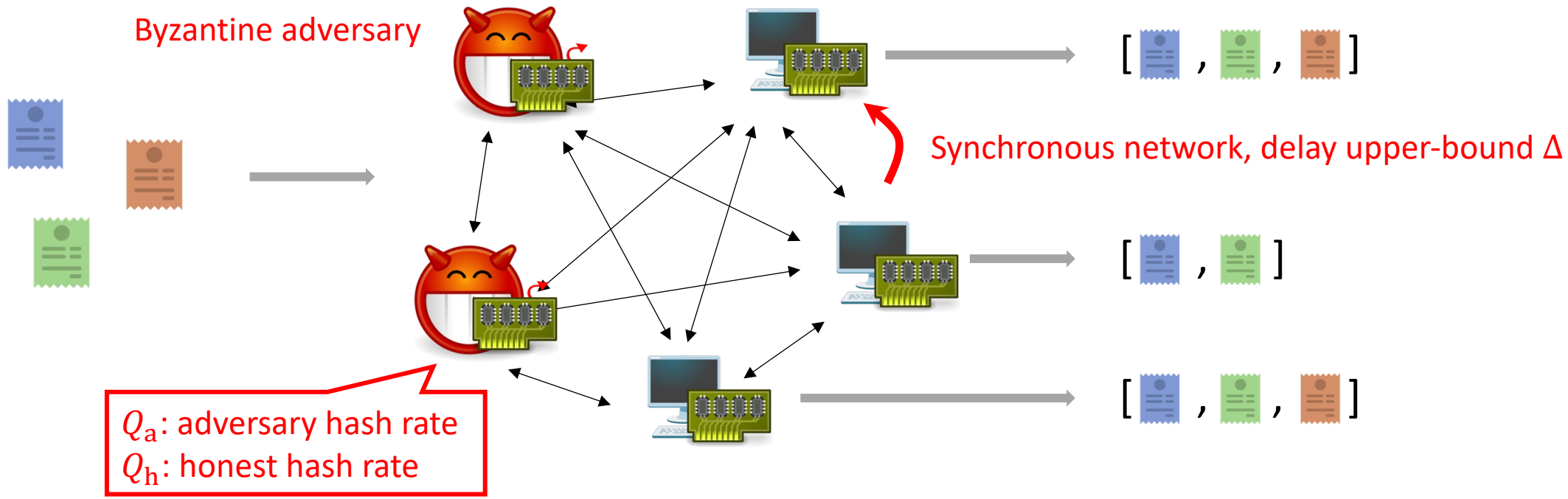

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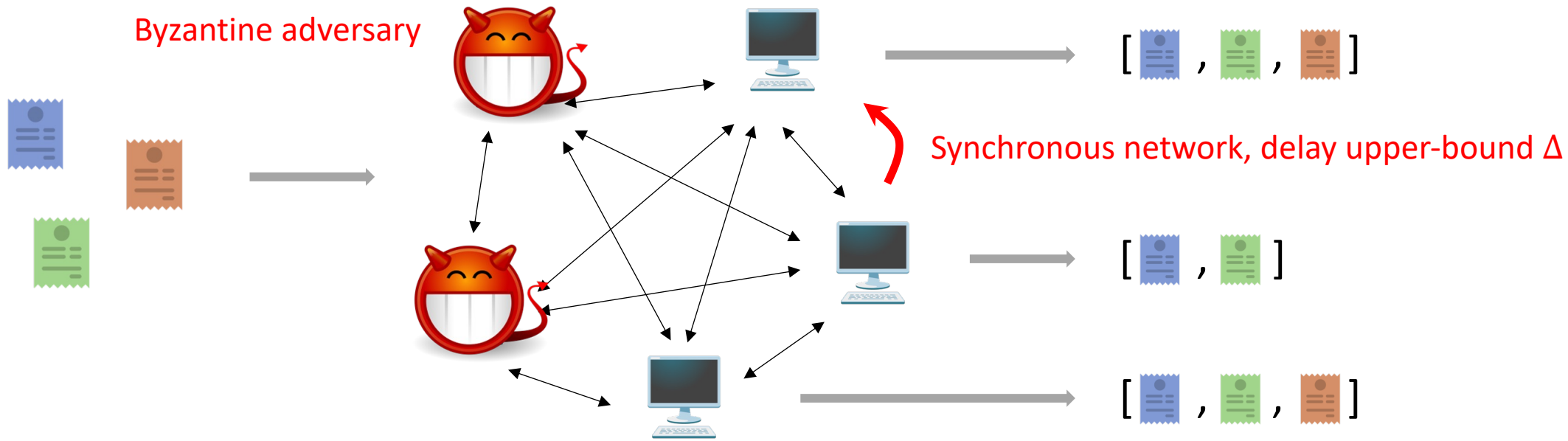

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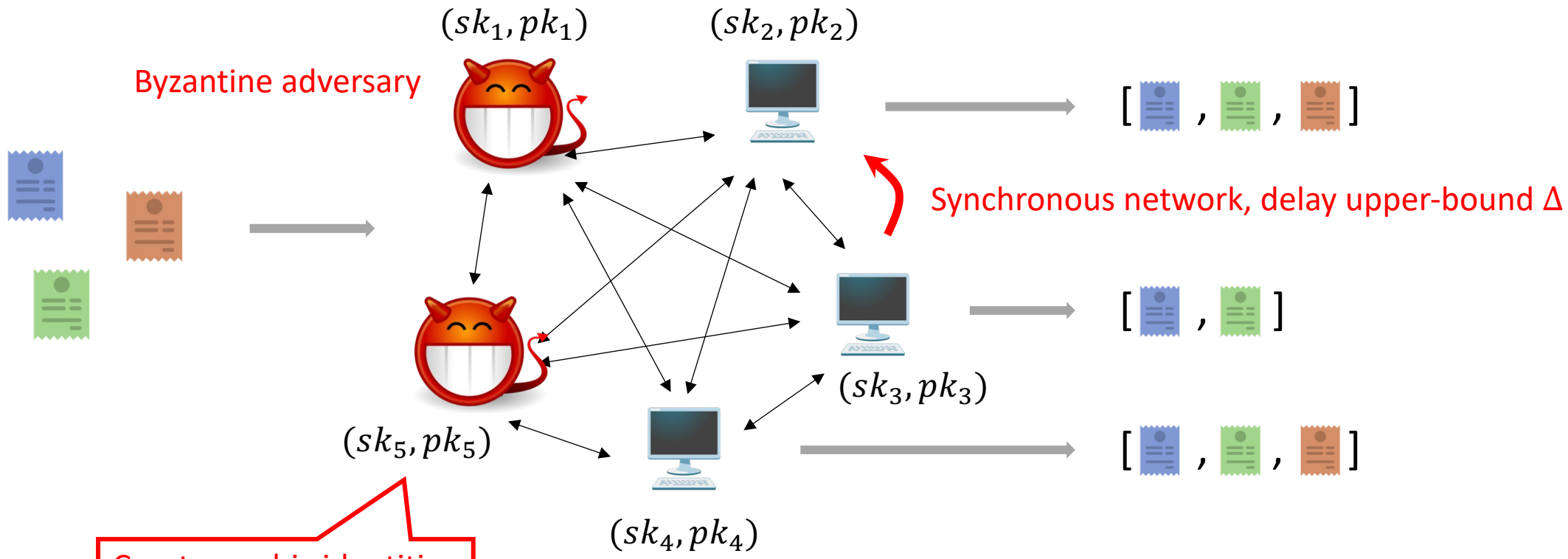

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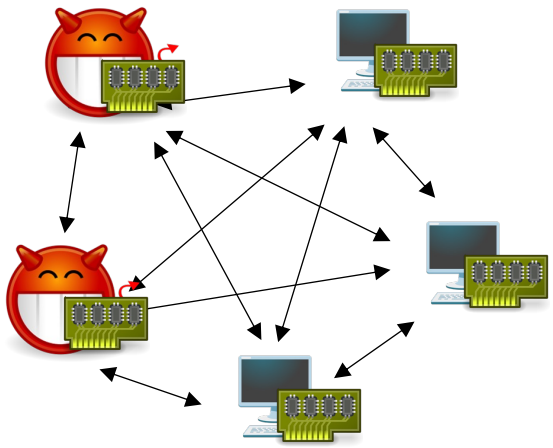

Nakamoto Consensus

Params: difficulty D, confirmation depth k

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if $Hash(b_{\text{new}}) \leq 2^{256} \cdot D$:

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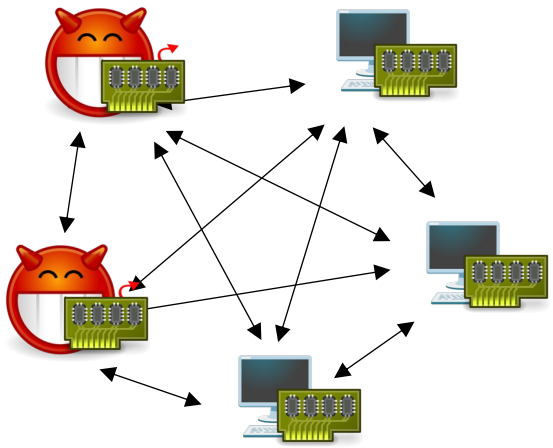

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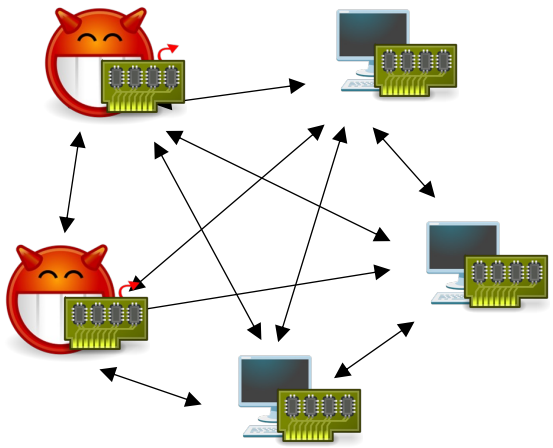

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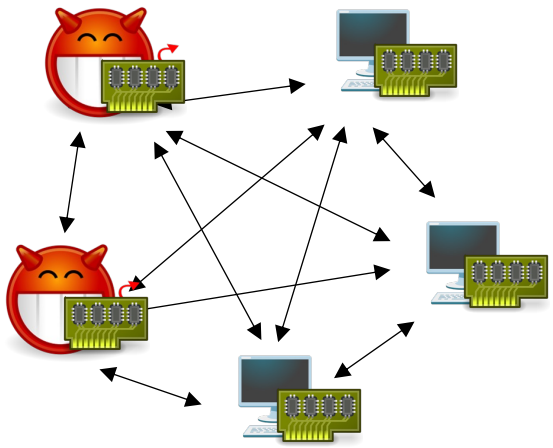

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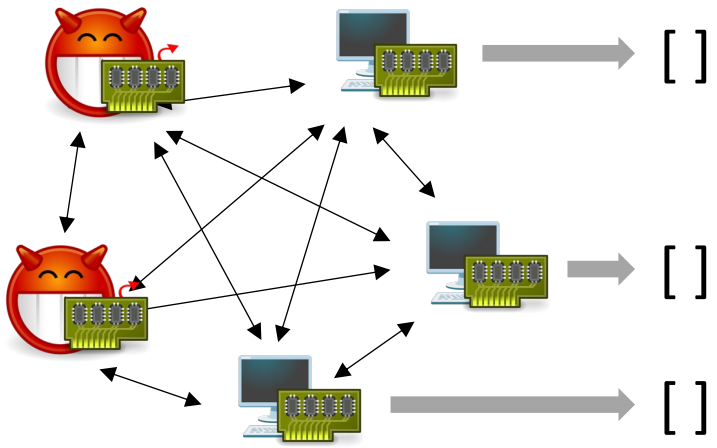

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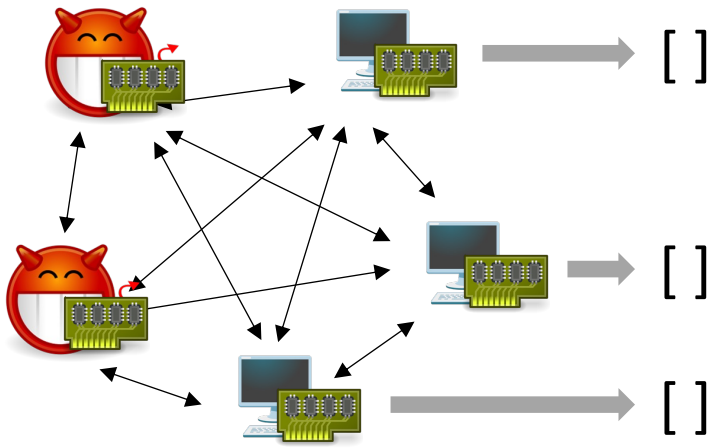

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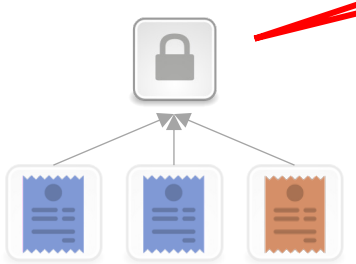

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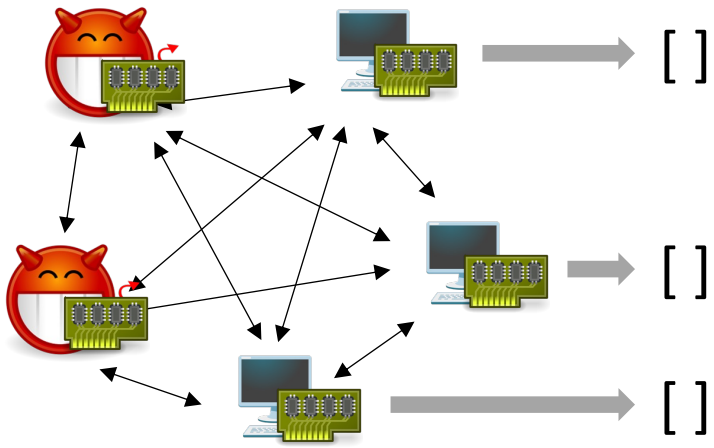

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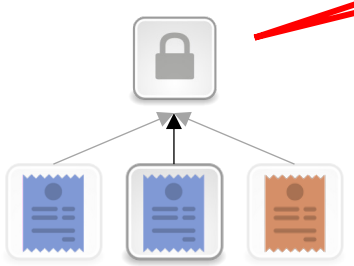

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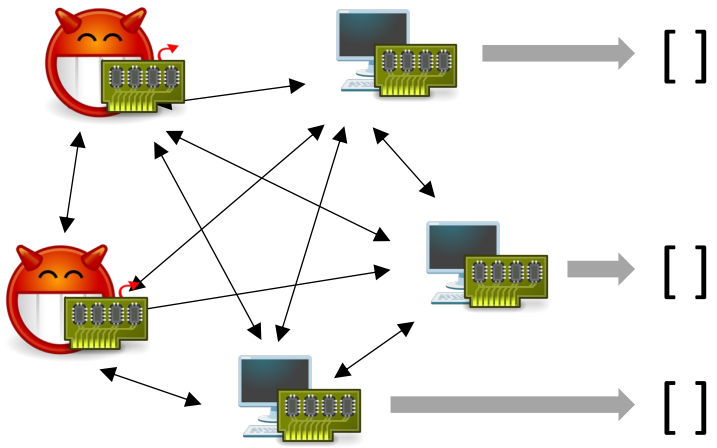


$Hash: \{0,1\}^* \rightarrow [1, 2^{256}]$

Output of $Hash$ assumed to be random

→ $\lambda_{\text{a}} = Q_{\text{a}} \cdot D$: adversary block production rate

→ $\lambda_{\text{h}} = Q_{\text{h}} \cdot D$: honest block production rate

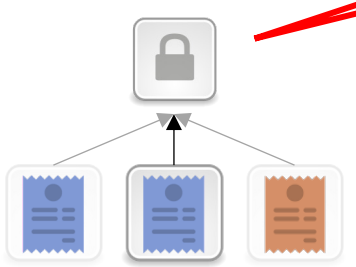
Q_{a}: adversary hash rate

Q_{h}: honest hash rate

Nakamoto Consensus

Assume $\Delta = 0$.
→ Honest nodes see the same blocks

Genesis block



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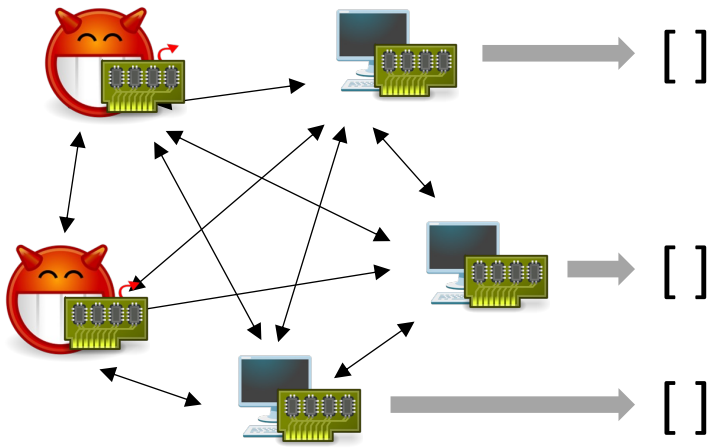

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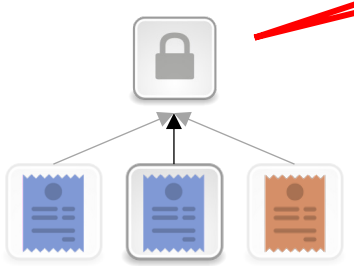

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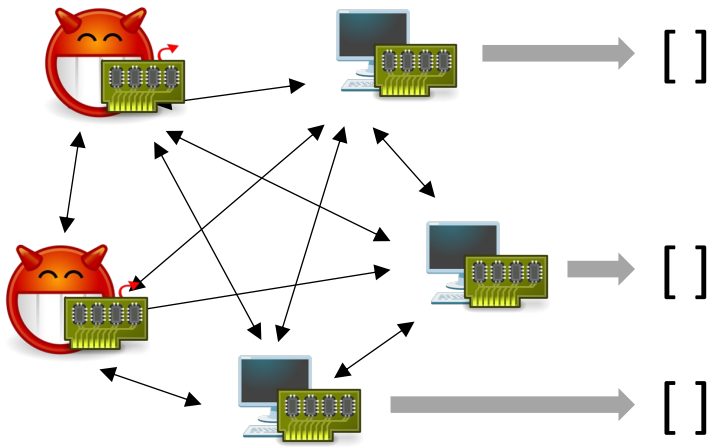

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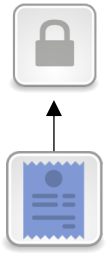

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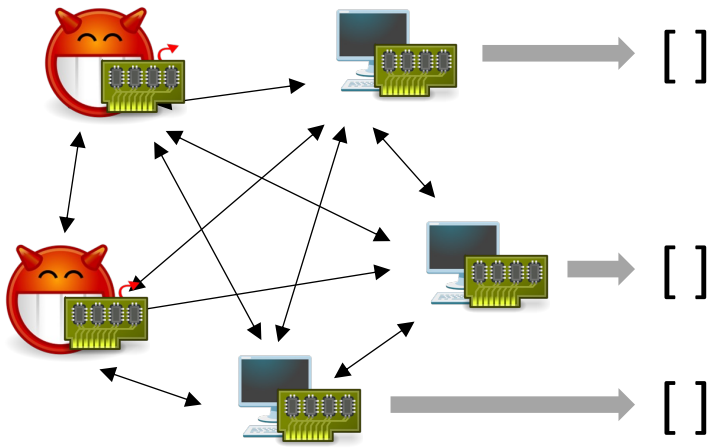

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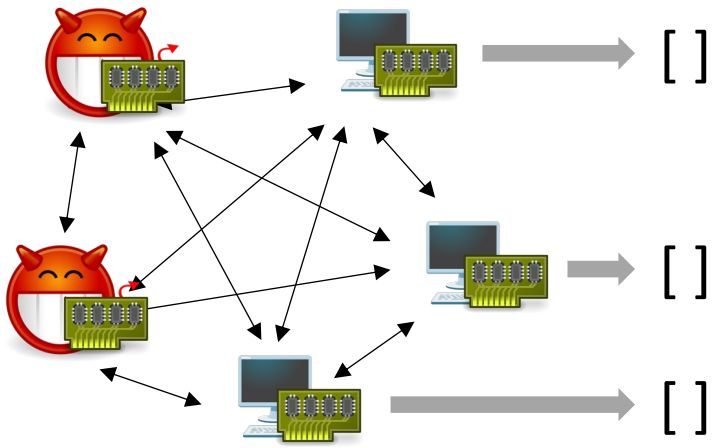

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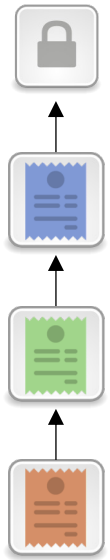

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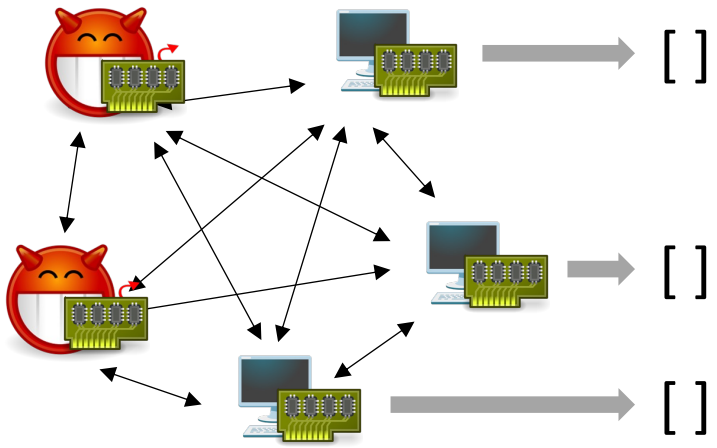

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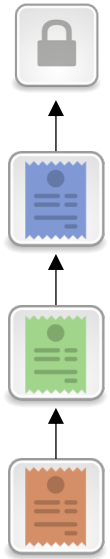

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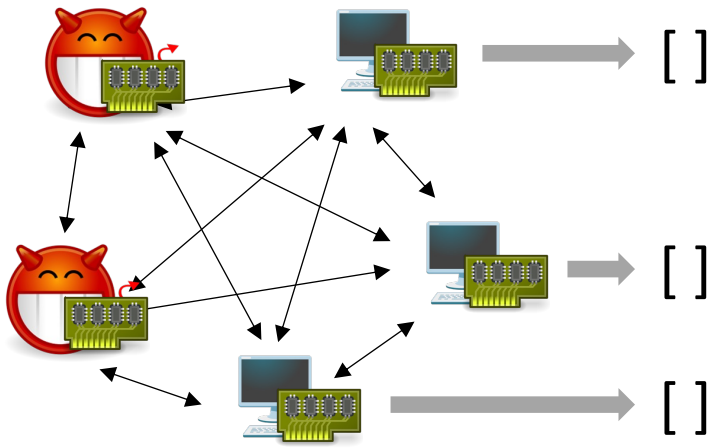

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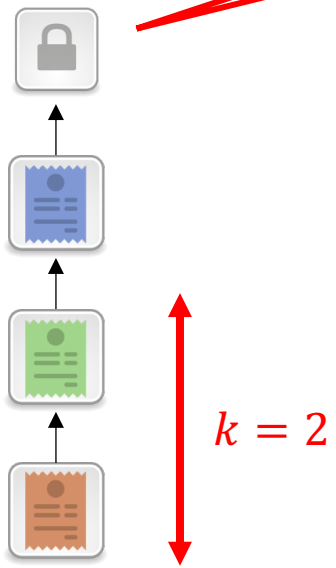

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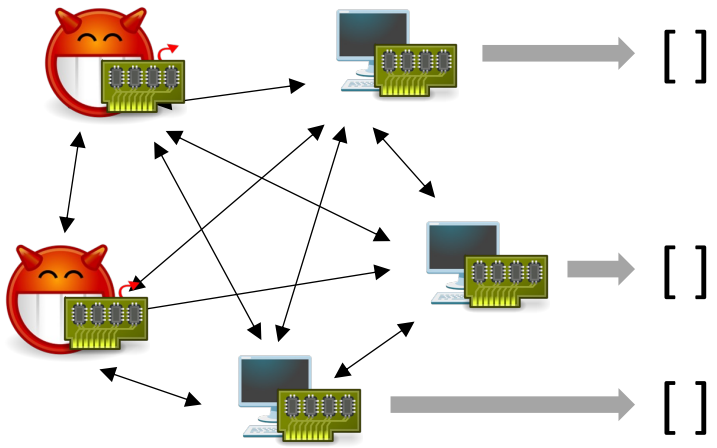
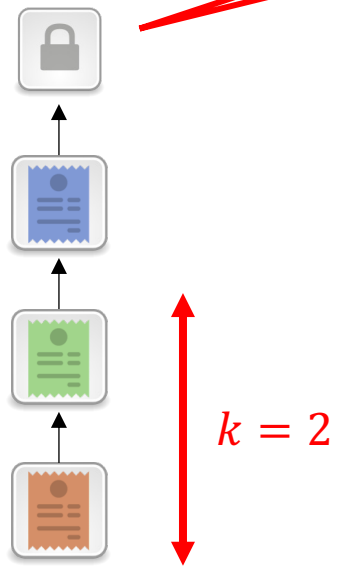


Nakamoto Consensus

Assume $\Delta = 0$.
→ Honest nodes see the same blocks

Genesis block



Params: difficulty D, confirmation depth k
forever:
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  $LOG_p^t \leftarrow GetDeepTxs(b^*, k)$
  $txs \leftarrow GetPendingTxs()$
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    if $Hash(b_{\text{new}}) \leq 2^{256} \cdot D$:
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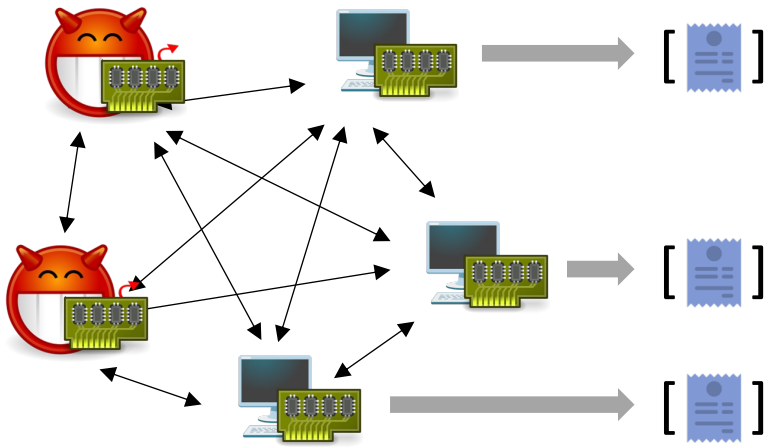

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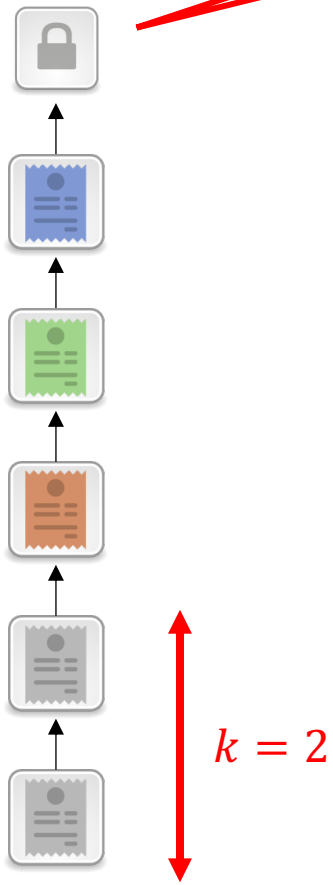

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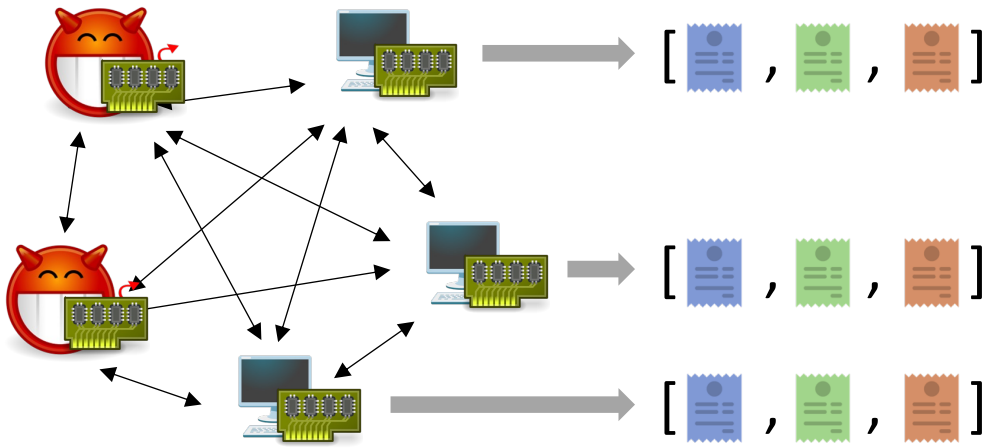

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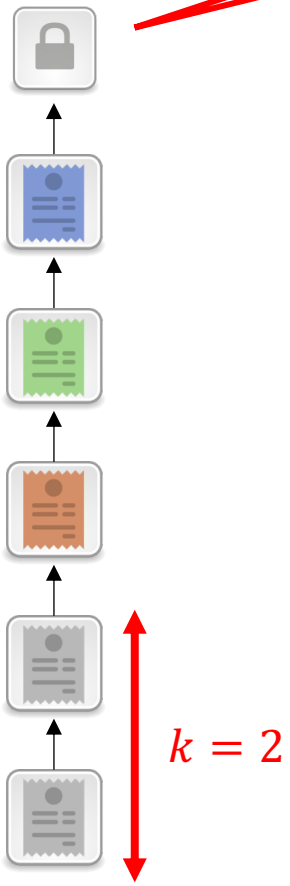
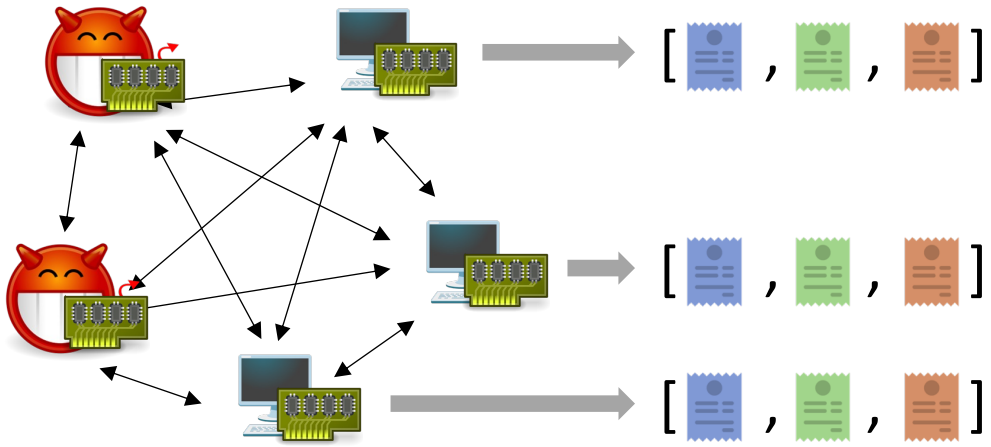
Genesis block





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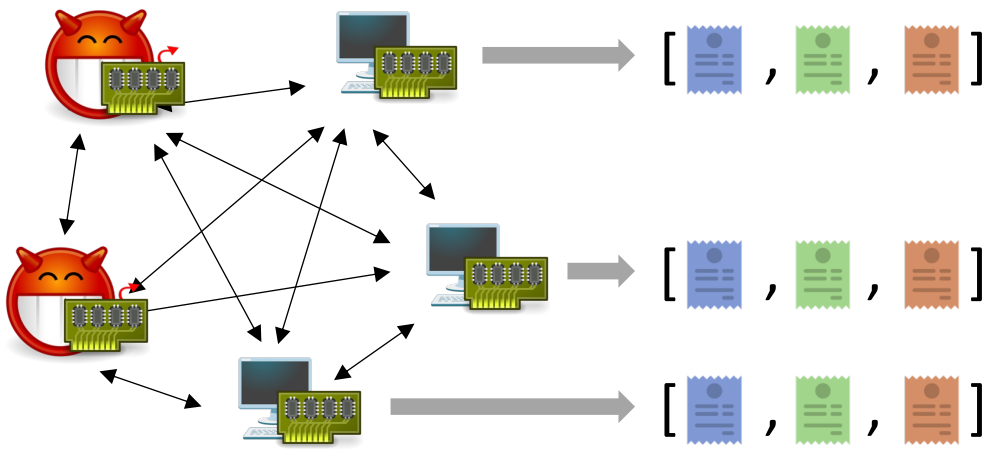

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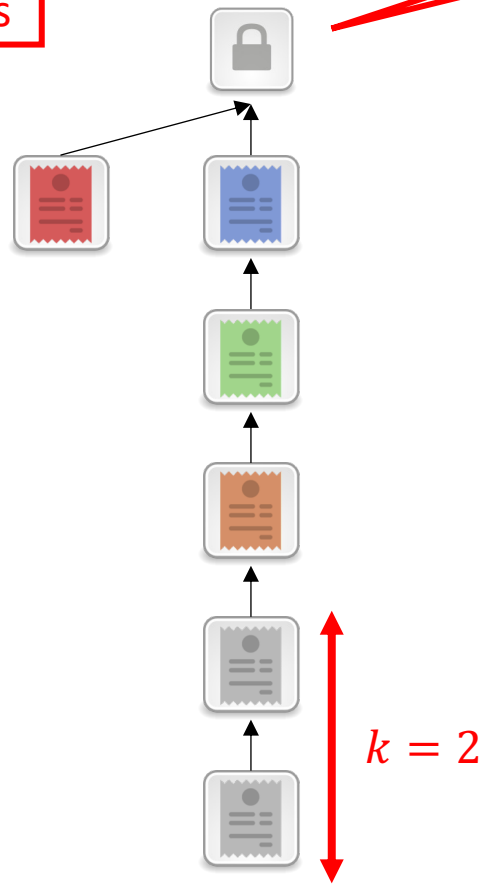
If $Q_a > Q_h$, then $\lambda_a > \lambda_h$ …

Genesis block



$k = 2$

Nakamoto Consensus

Params: difficulty D, confirmation depth k

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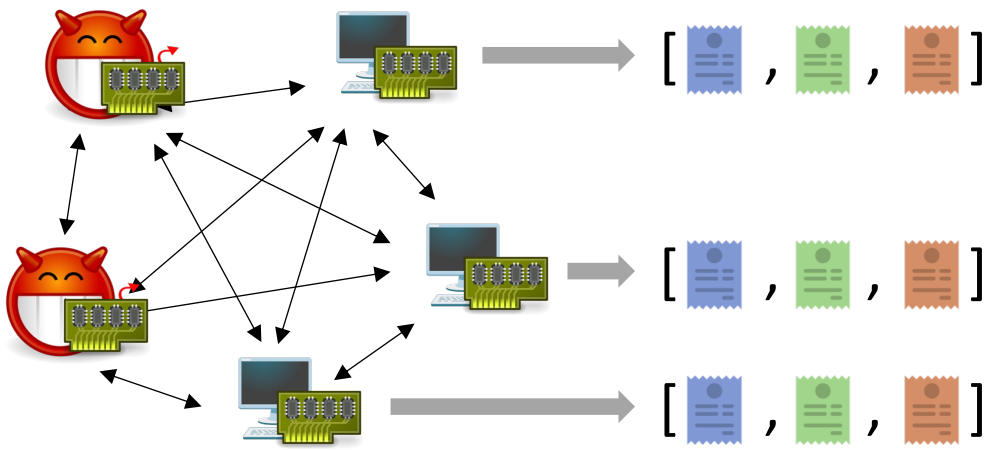

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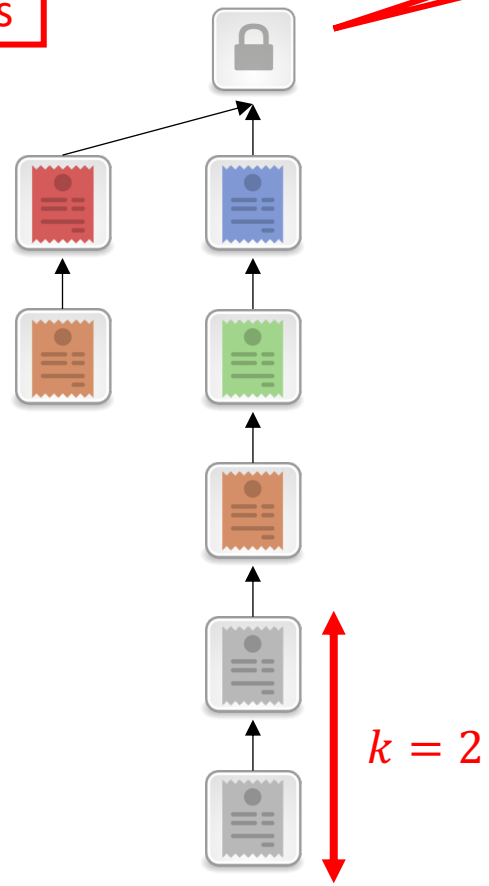

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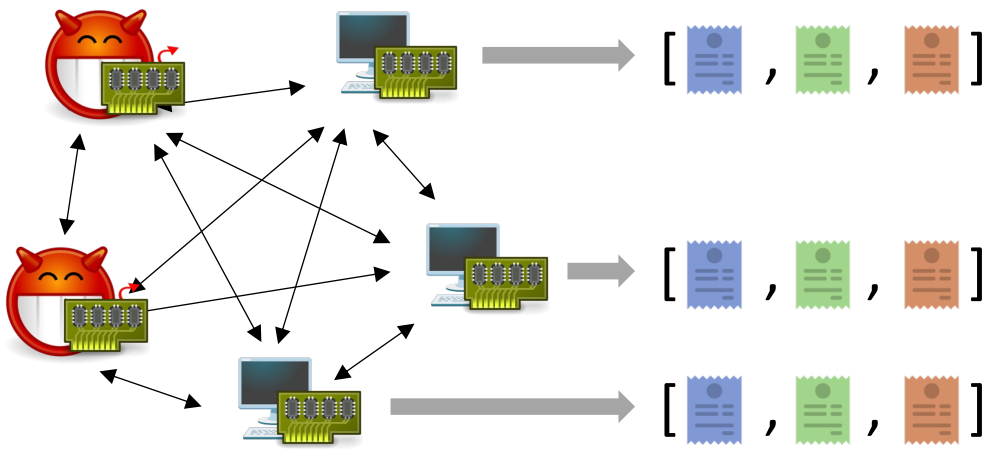

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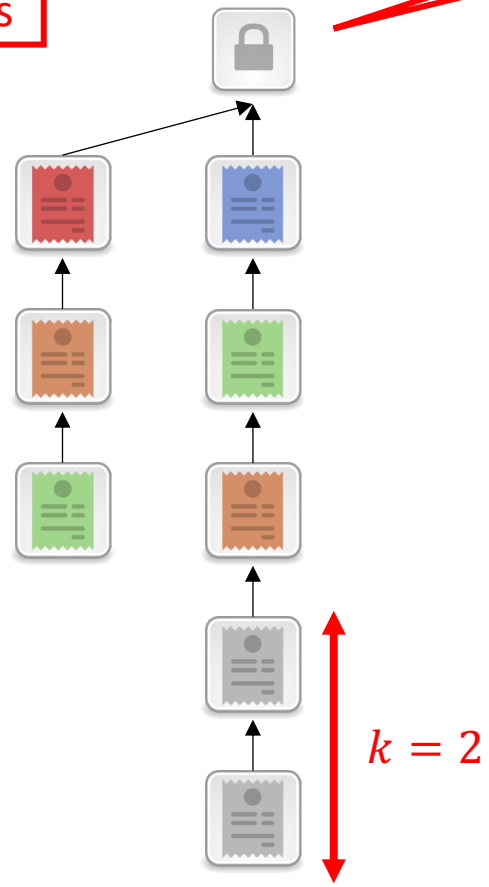

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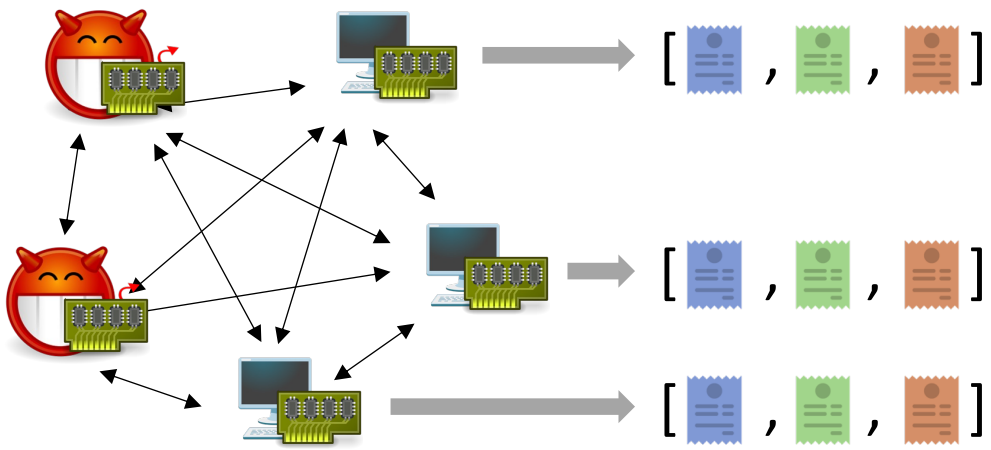

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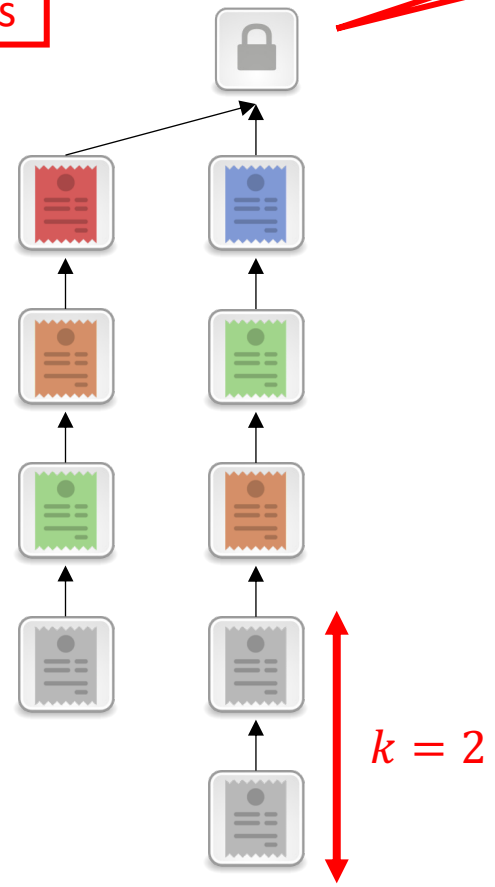

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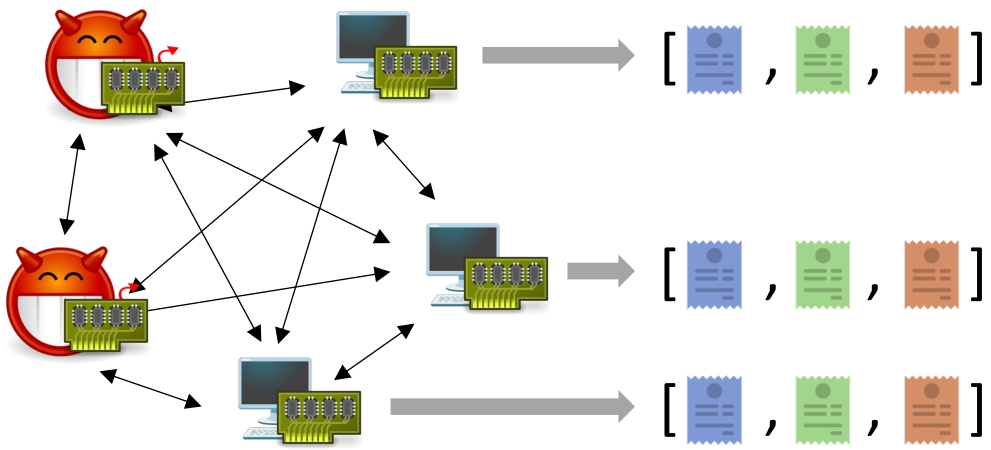

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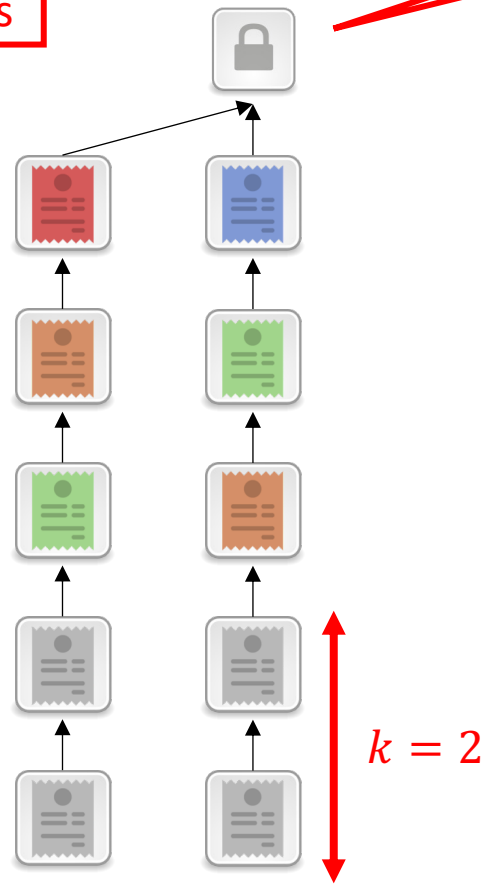

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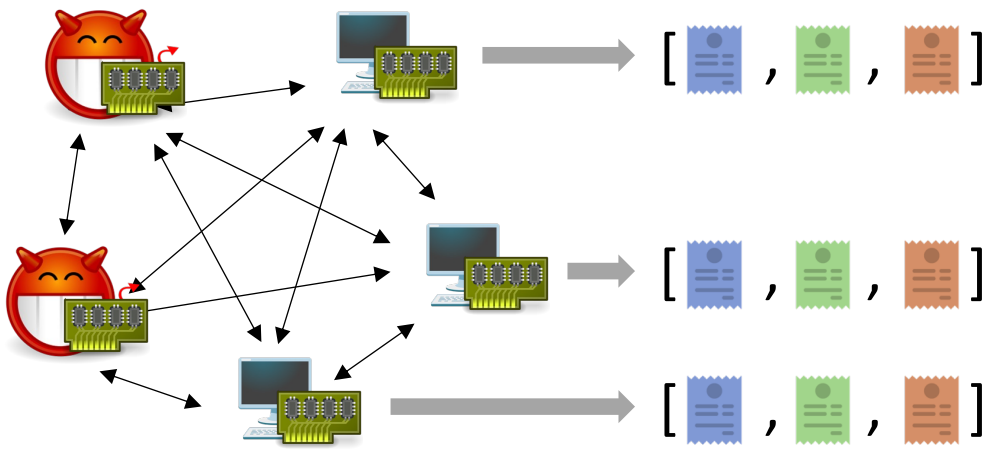

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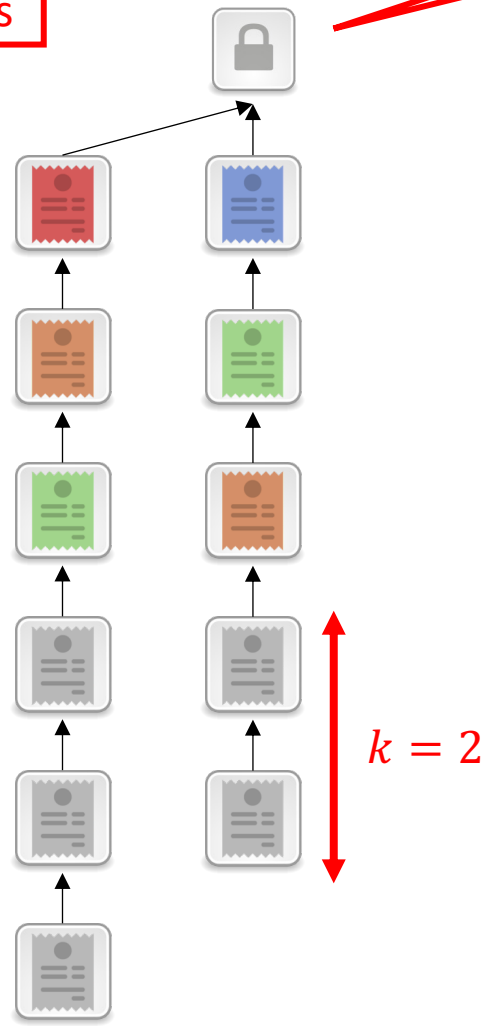

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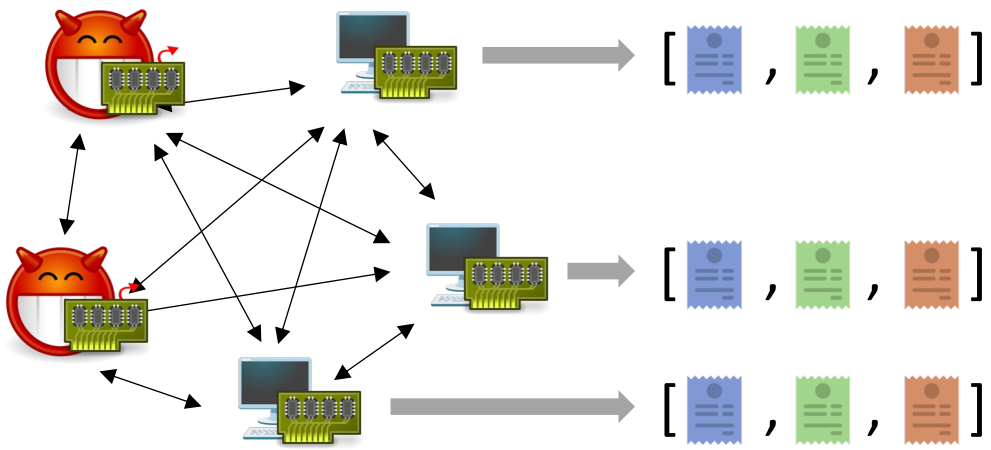

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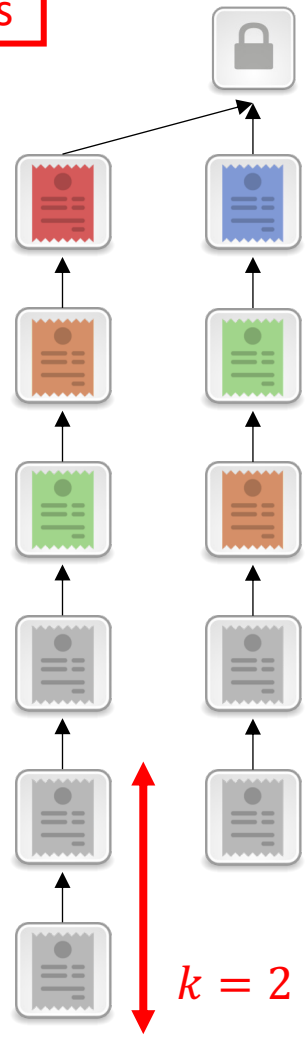

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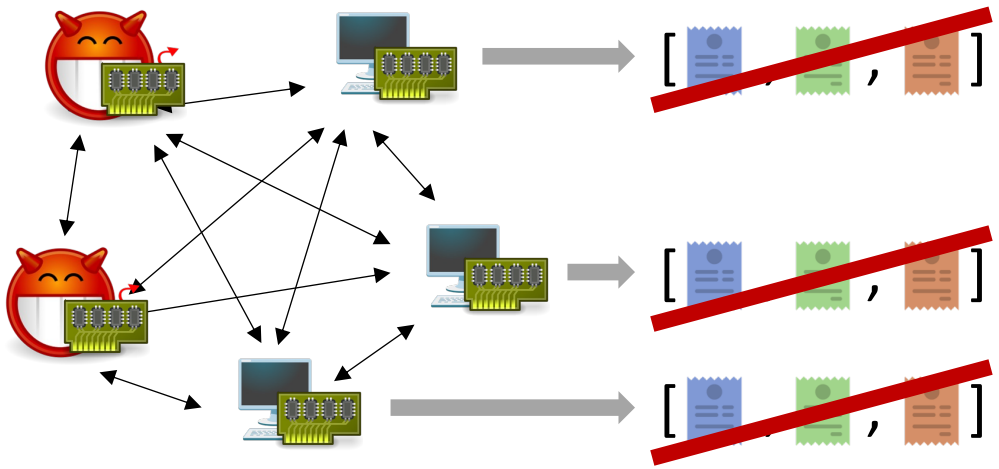

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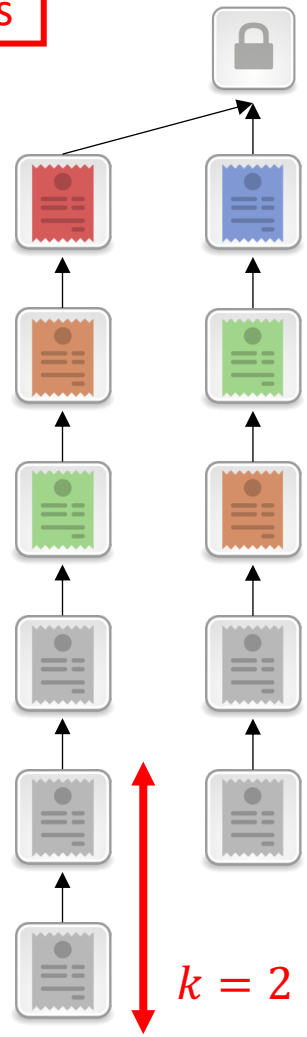

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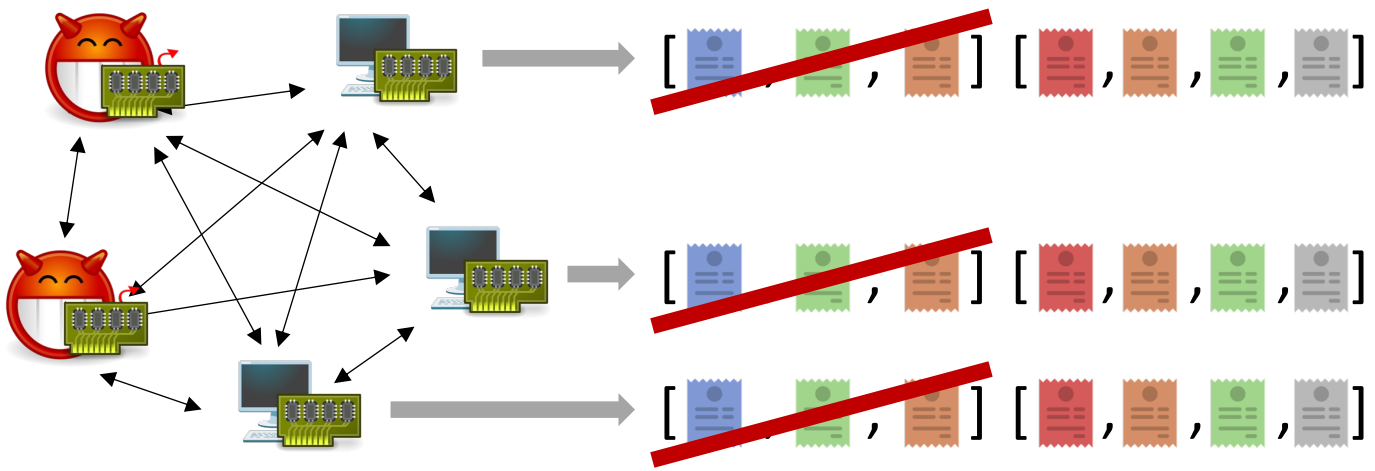

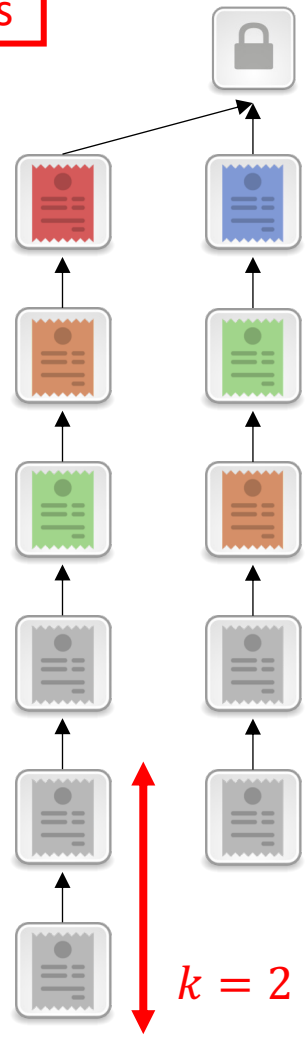

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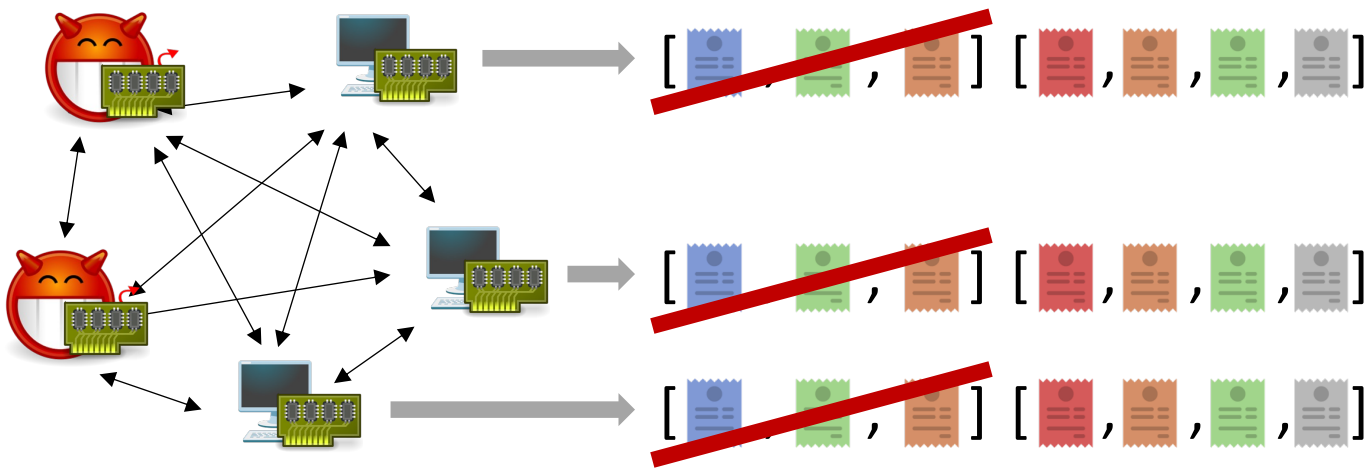
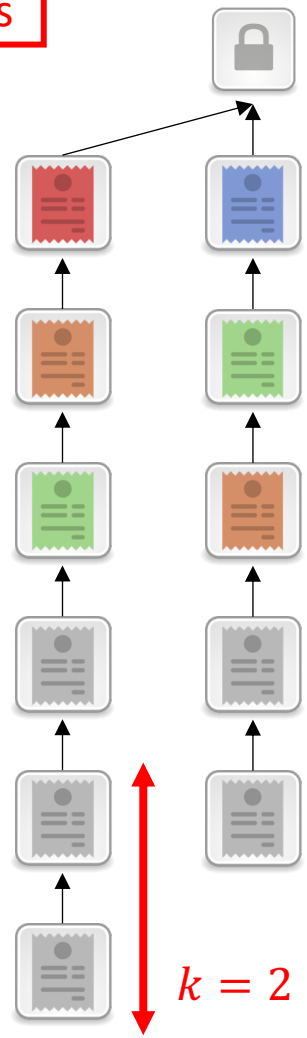
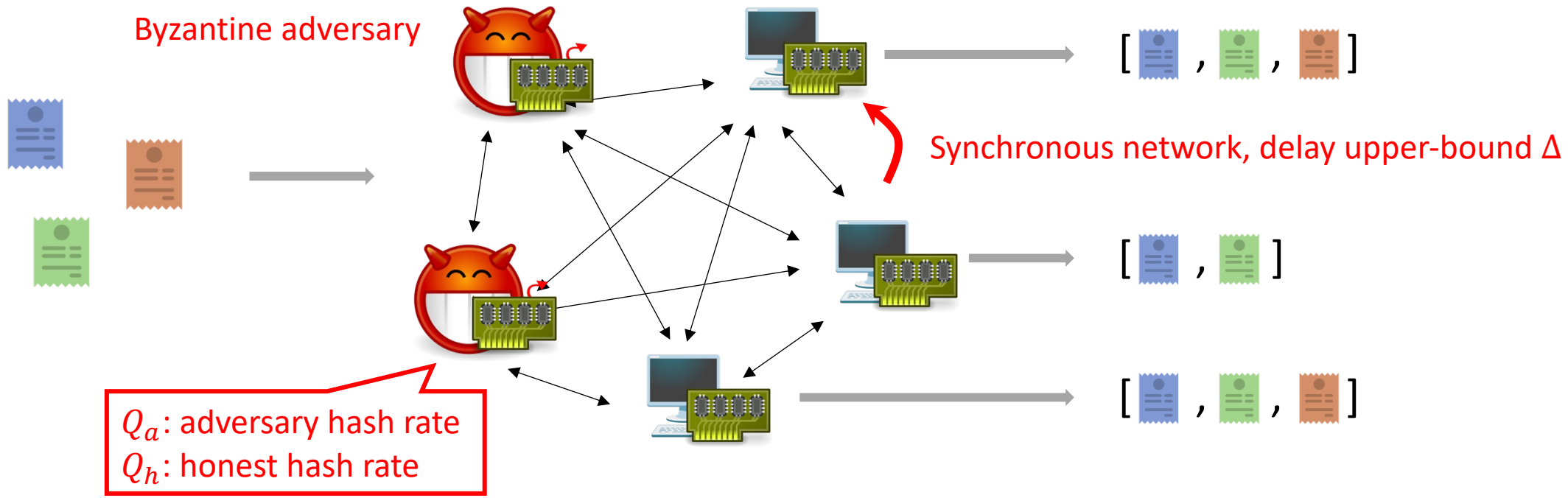
"Private attack"

Genesis block





SMR Example 1: Proof-of-Work Nakamoto Consensus

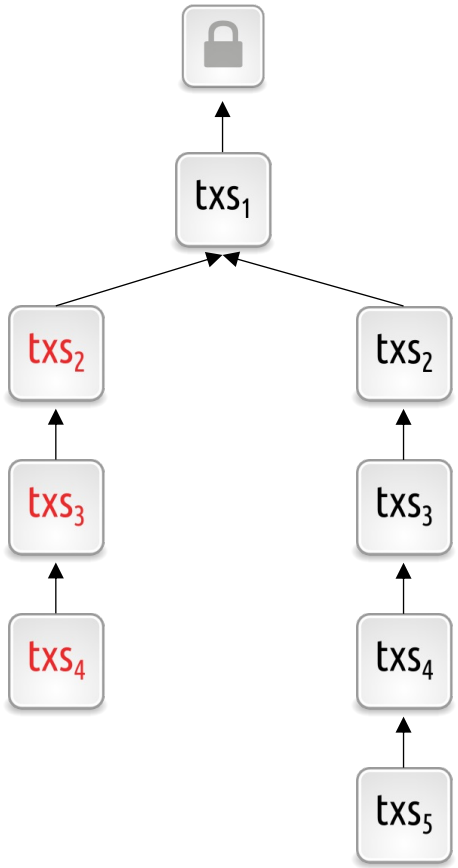


Theorem

For $\Delta = 0$, proof-of-work Nakamoto consensus is safe and live iff $Q_{\mathrm{a}} < Q_{\mathrm{h}}$, under synchrony, except with probability decaying exponentially in k.

"The Sleepy Model of Consensus", Pass, Shi 2017; "Everything is a Race and Nakamoto Always Wins", Dembo et al. 2020

Security for $\Delta = 0$



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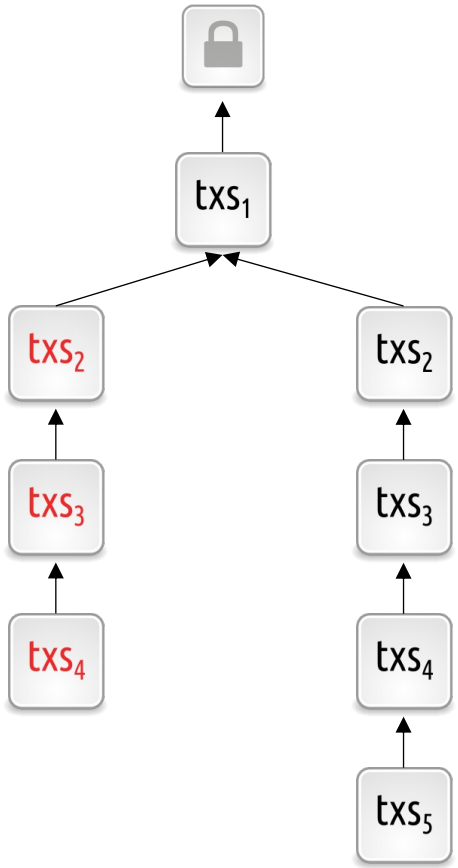
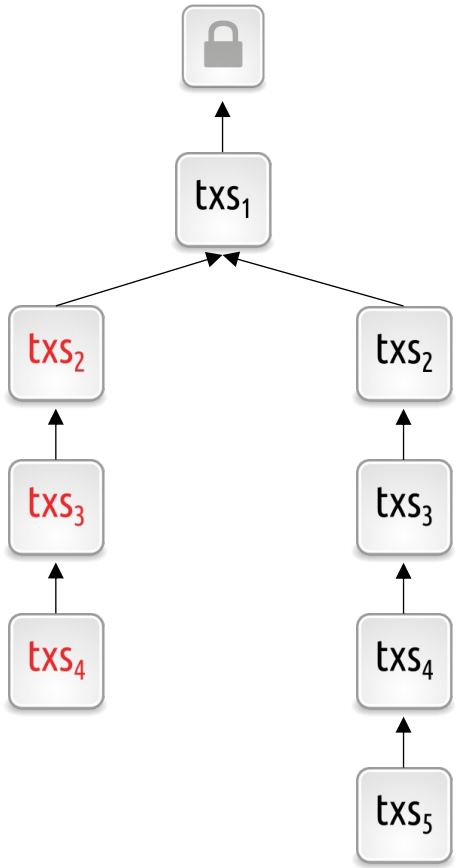


$$\lambda_{\text{growth}} = \lambda_{\text{h}} = Q_{\text{h}} \cdot D$$

Security for $\Delta = 0$

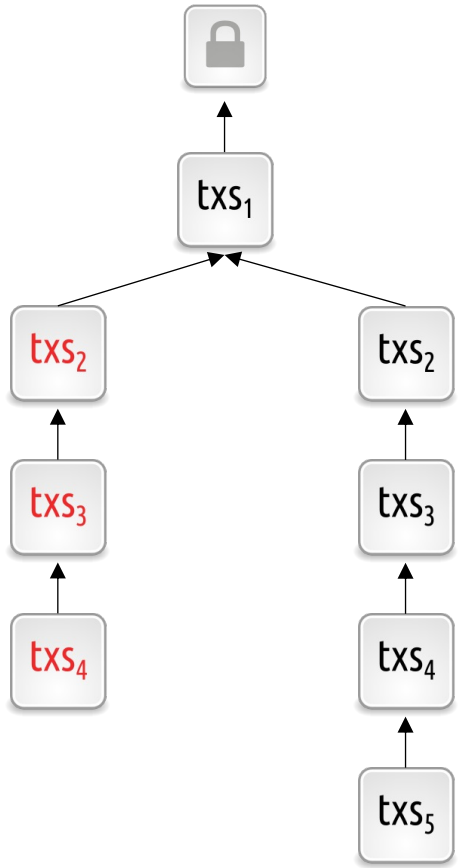


$\lambda_{\mathrm{a}} = Q_{\mathrm{a}} \cdot D$

$\lambda_{\mathrm{growth}} = \lambda_{\mathrm{h}} = Q_{\mathrm{h}} \cdot D$

Security for $\Delta = 0$

Under $\Delta = 0, Q_{\mathrm{a}} < Q_{\mathrm{h}}$:



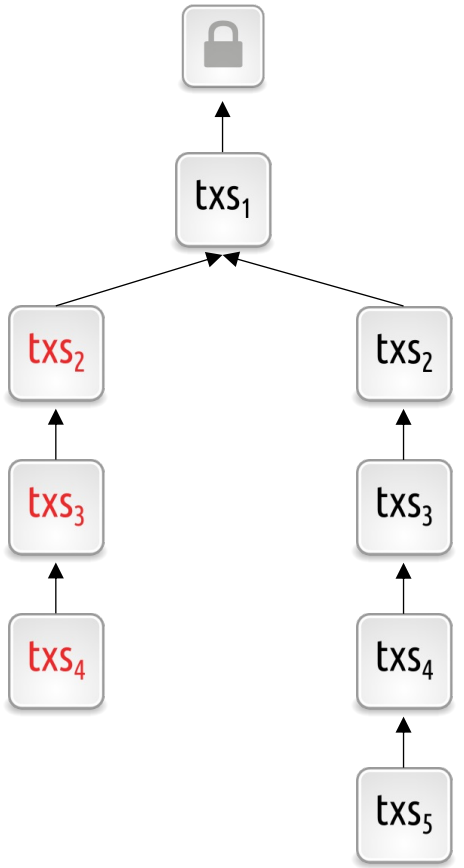
$$\lambda_{\mathrm{a}} = Q_{\mathrm{a}} \cdot D \quad < \quad \lambda_{\mathrm{growth}} = \lambda_{\mathrm{h}} = Q_{\mathrm{h}} \cdot D$$

Security for $\Delta = 0$

Under $\Delta = 0, Q_{\mathrm{a}} < Q_{\mathrm{h}}$:

Safety:

- Longest chain grows faster than adversary chain.
- Safety violation requires that adversary chain catches up with longest chain at length k, or length $k + 1$, or length $k + 2$, etc.
- → Probability decays exponentially in k.



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Safety:

- Longest chain grows faster than adversary chain.
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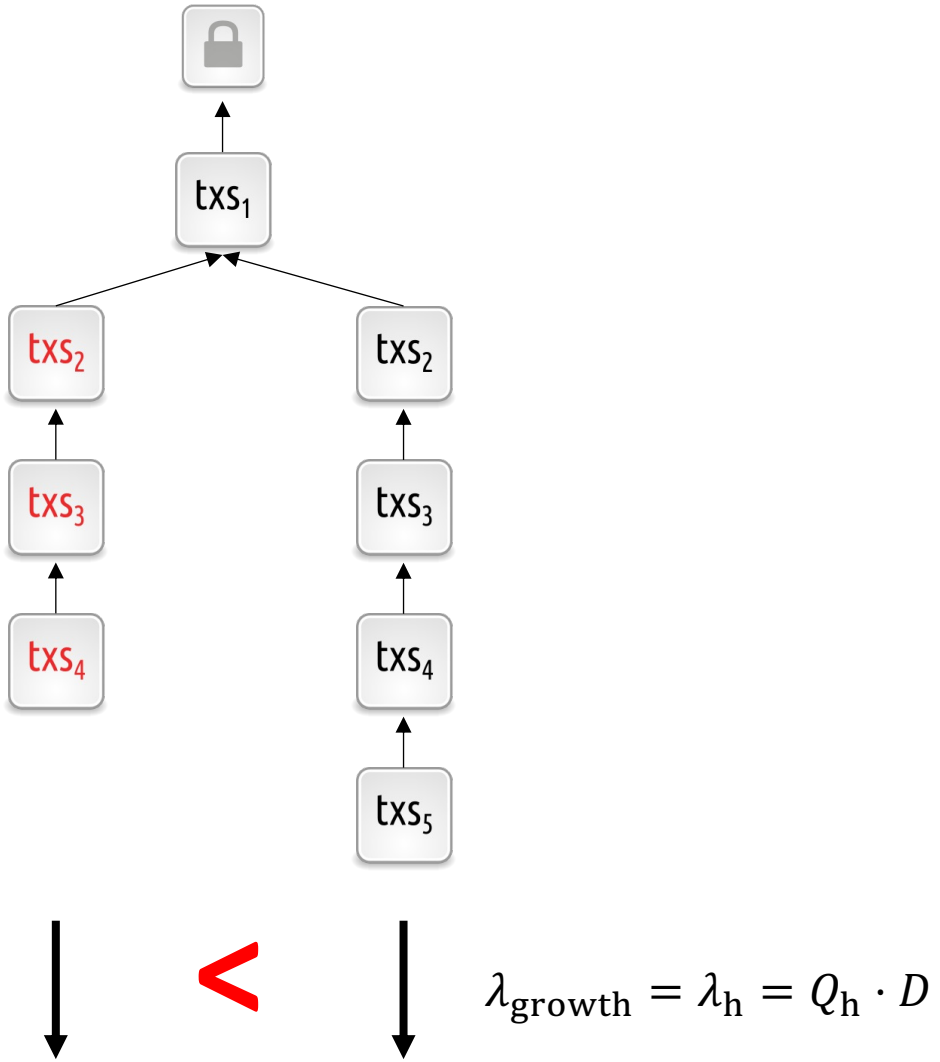
- → Probability decays exponentially in k.

Liveness:

- Longest chain grows at rate $\lambda_{\mathrm{growth}} = \lambda_{\mathrm{h}} > \lambda_{\mathrm{a}}$.
- By pigeonhole principle, there must be honestly produced blocks on the longest chain.
- → Transactions get confirmed eventually.



Security for $\Delta > 0$

Params: difficulty D, confirmation depth k

forever:

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until new block arrives:

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$b_{\text{new}} \leftarrow NewBlock(b^*, txs, \pi)$

if $Hash(b_{\text{new}}) \leq 2^{256} \cdot D$:

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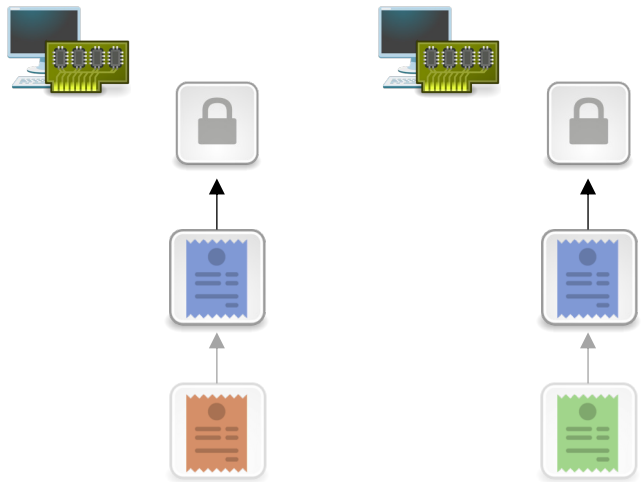

Time

Security for $\Delta > 0$

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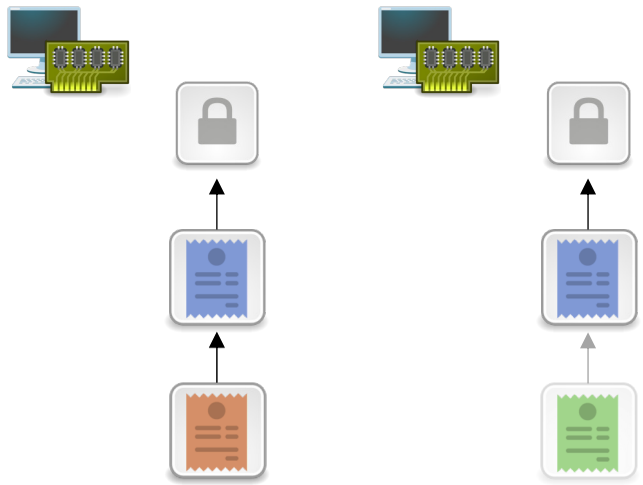

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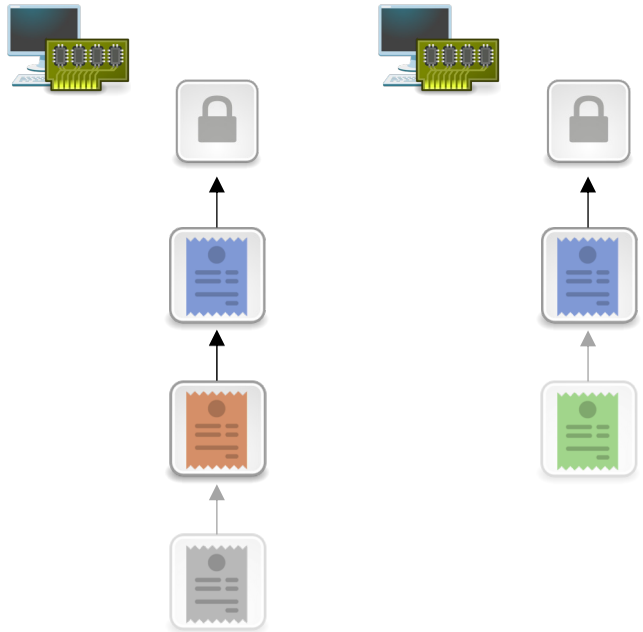

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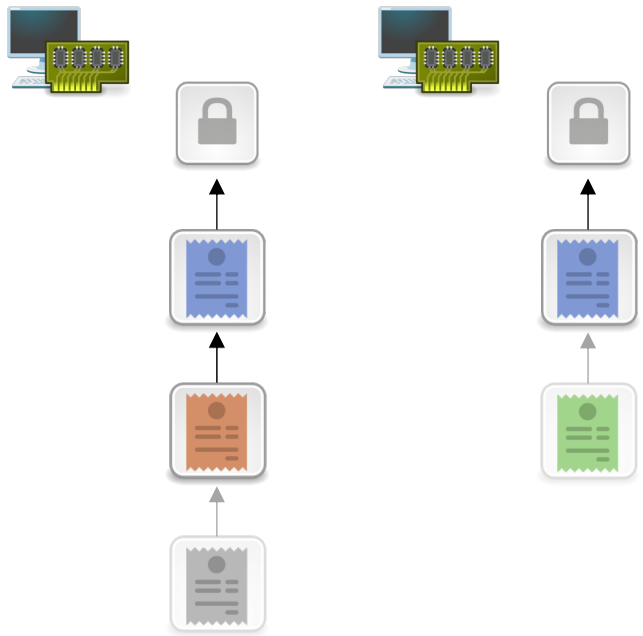

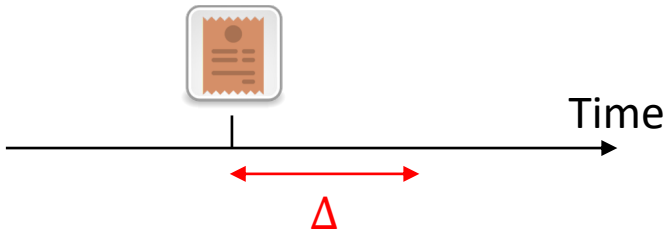

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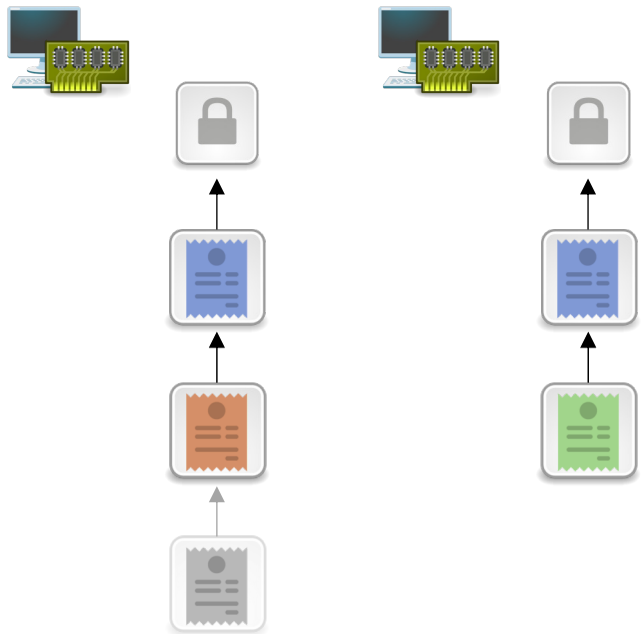

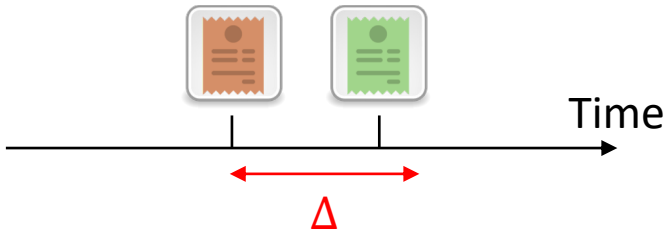

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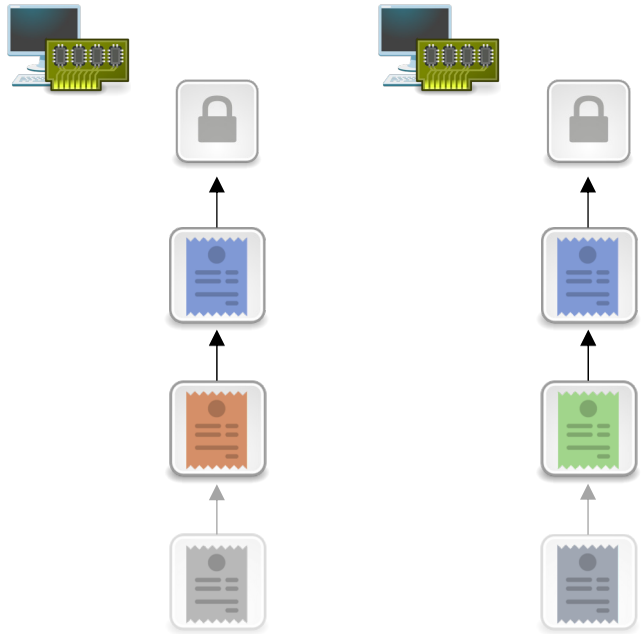

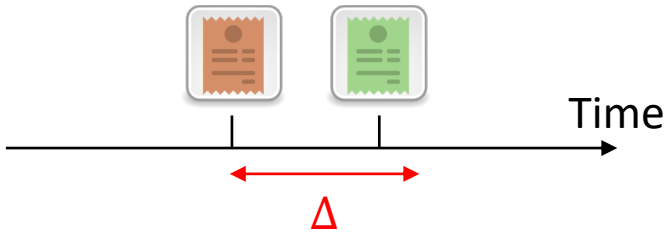

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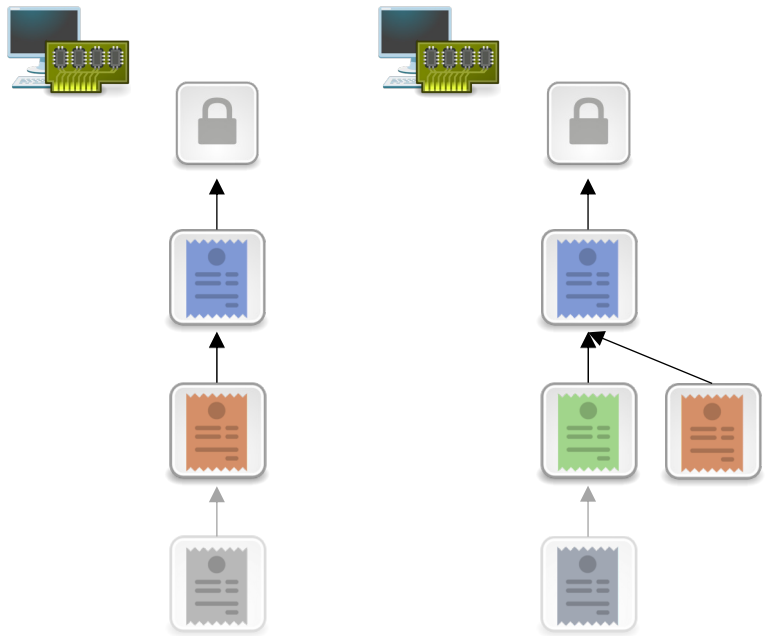

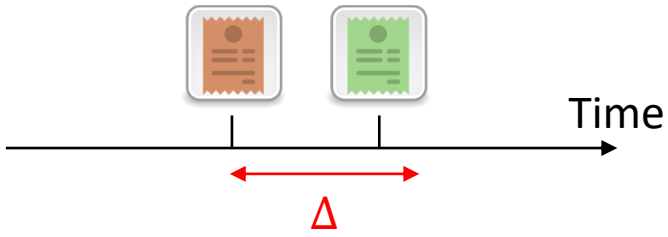

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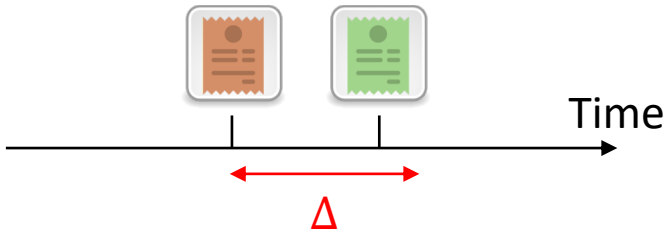

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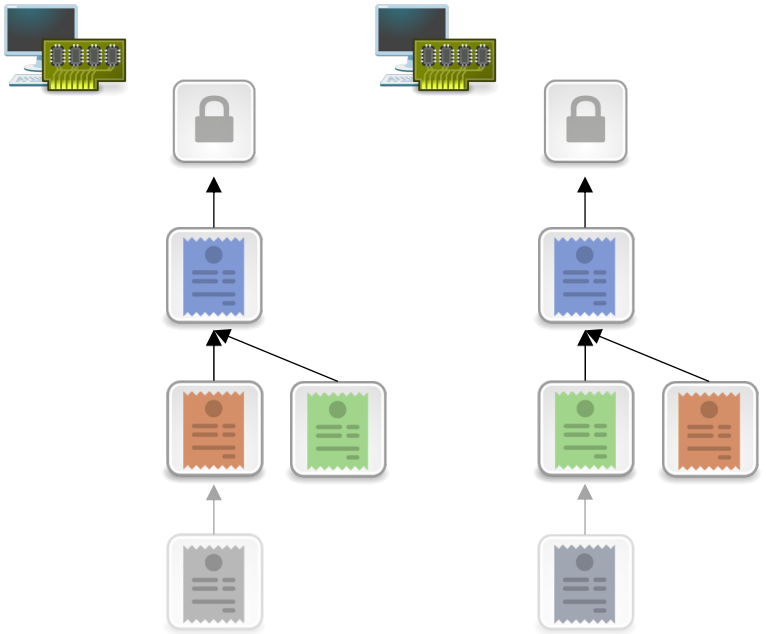

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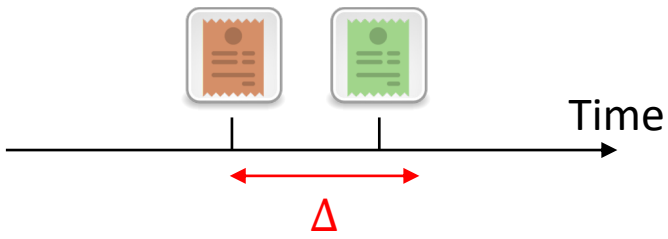

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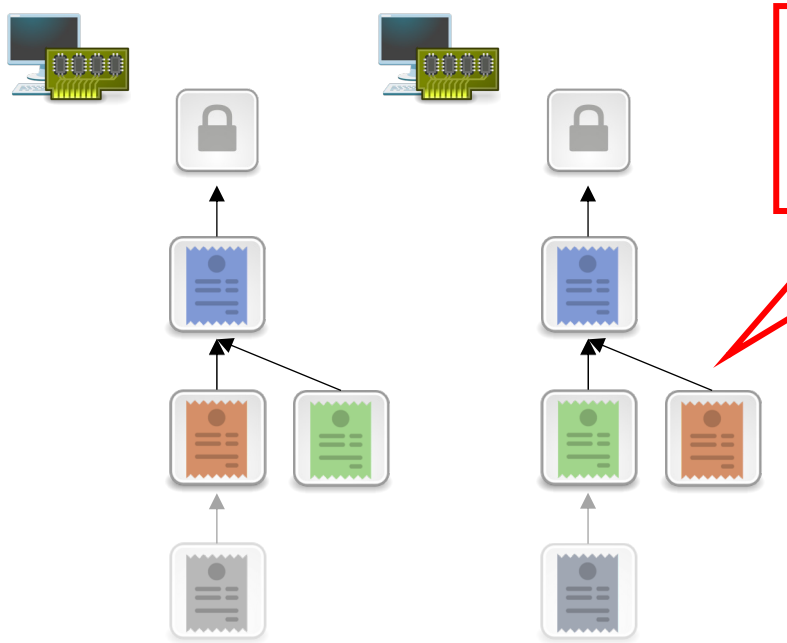

Forking! Multiple honest blocks on the same height!

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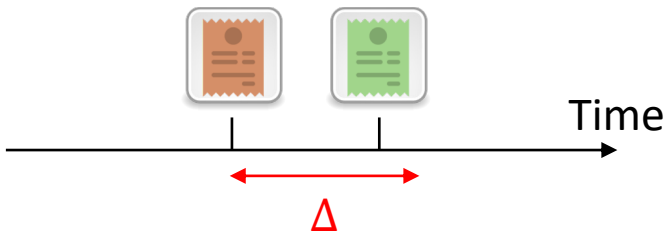

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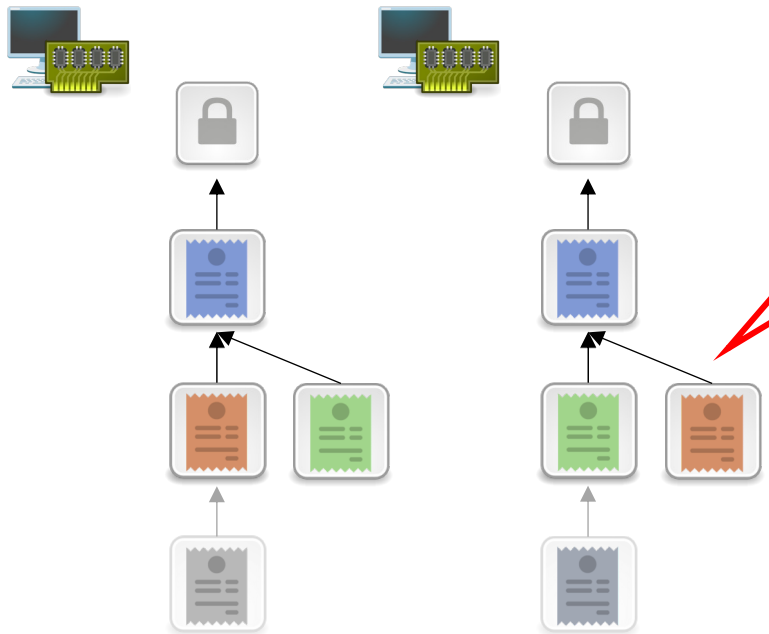

Forking! Multiple honest blocks on the same height!

Bad, because it lowers the chain growth rate of the longest chain!

Security for $\Delta > 0$

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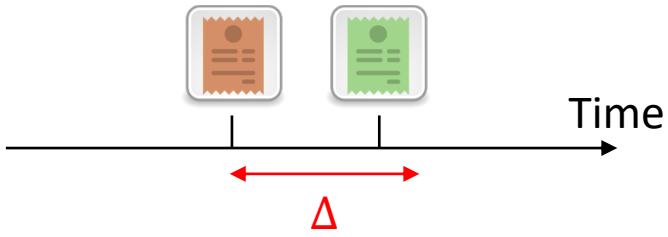

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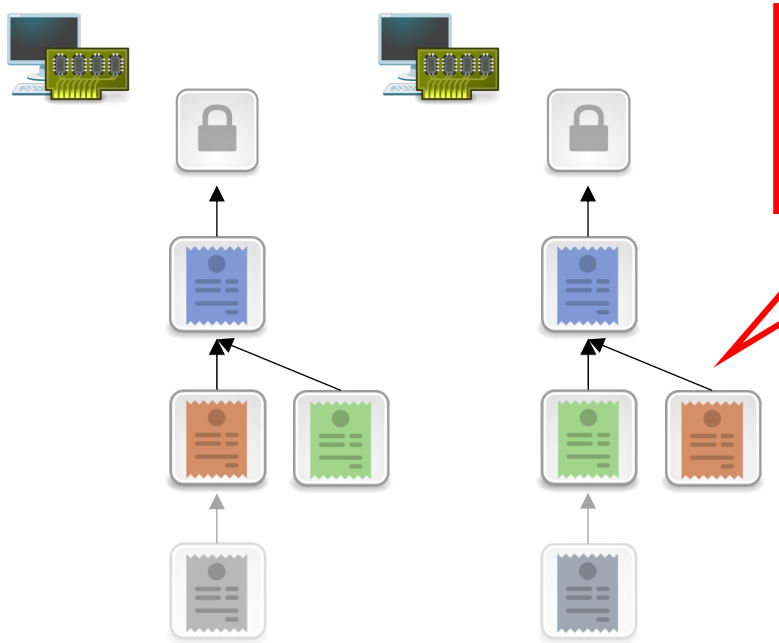

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$$\lambda_{\text{growth}}^{\Delta=0} = \lambda_{\text{h}}$$

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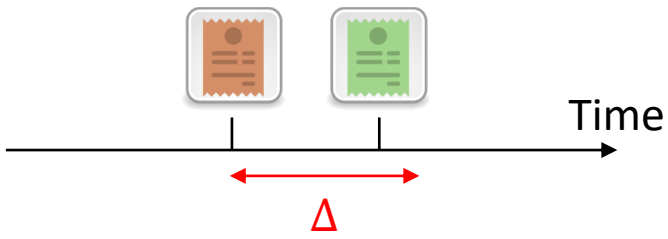

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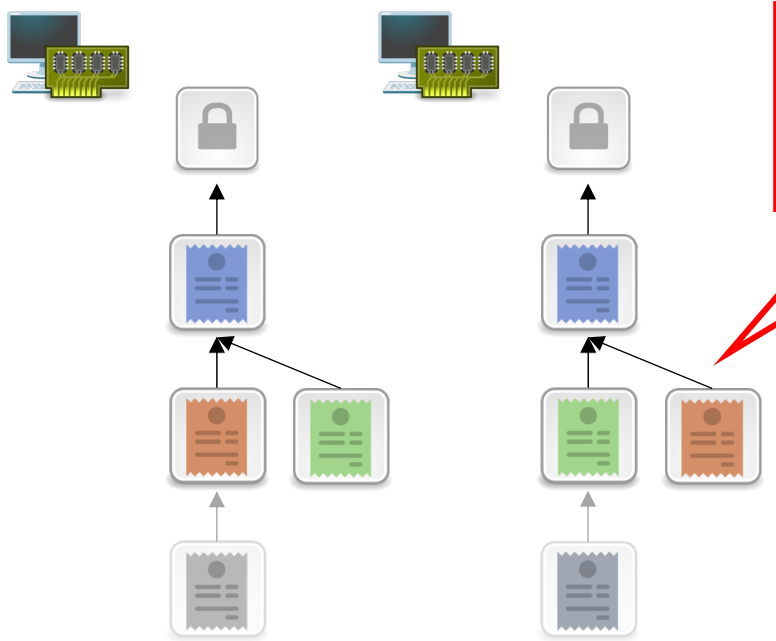

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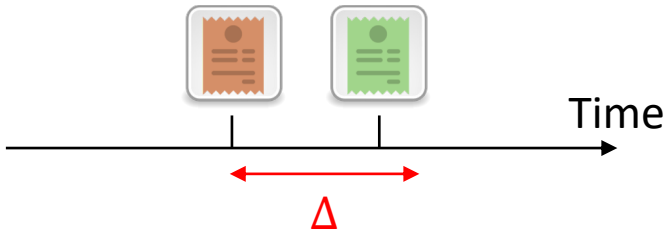

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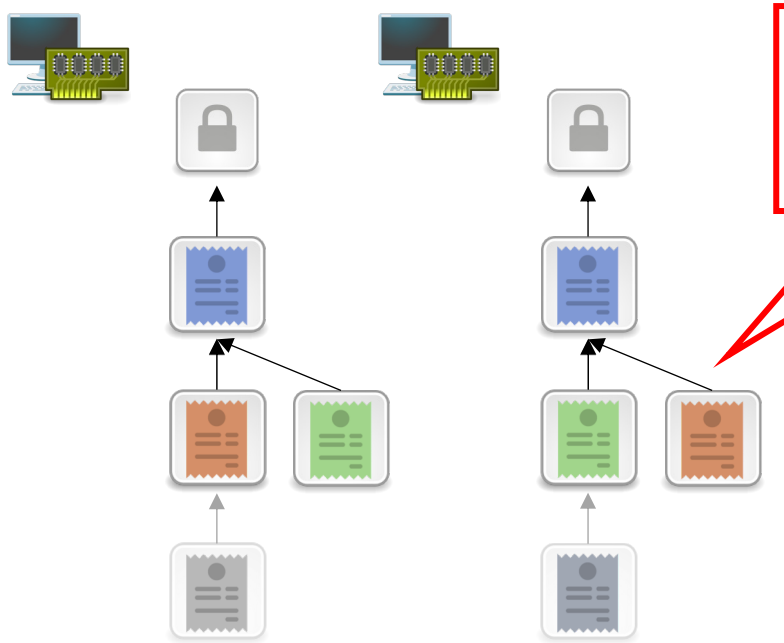

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$$\lambda_{\text{growth}}^{\Delta=0} = \lambda_{\text{h}} \quad \Rightarrow \quad \lambda_{\text{growth}}^{\Delta>0} = \lambda_{\text{h}} \cdot \frac{1}{1 + \lambda_{\text{h}} \cdot \Delta}$$

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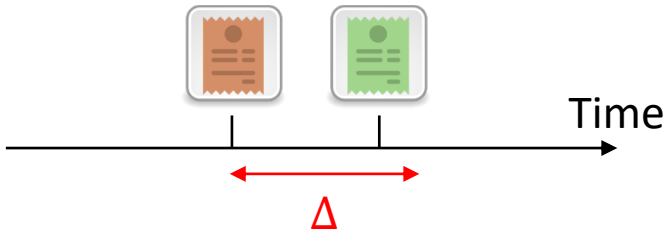

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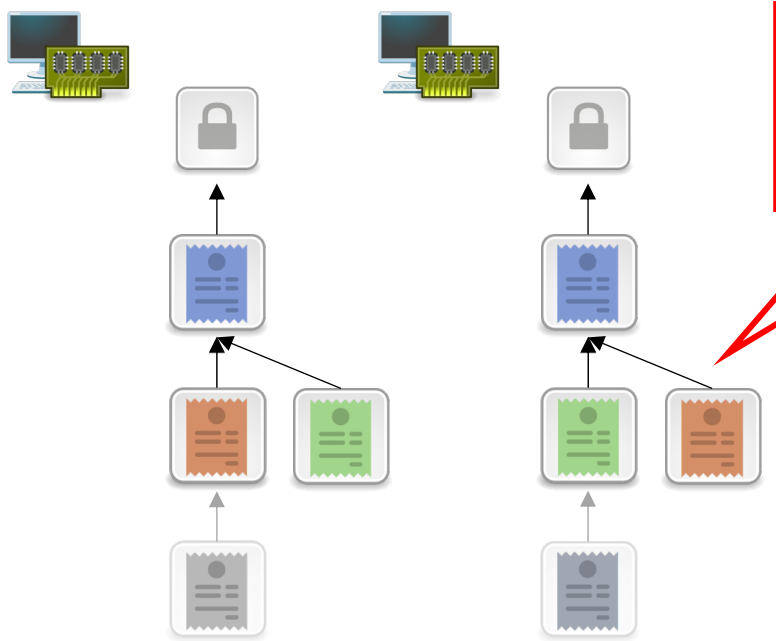

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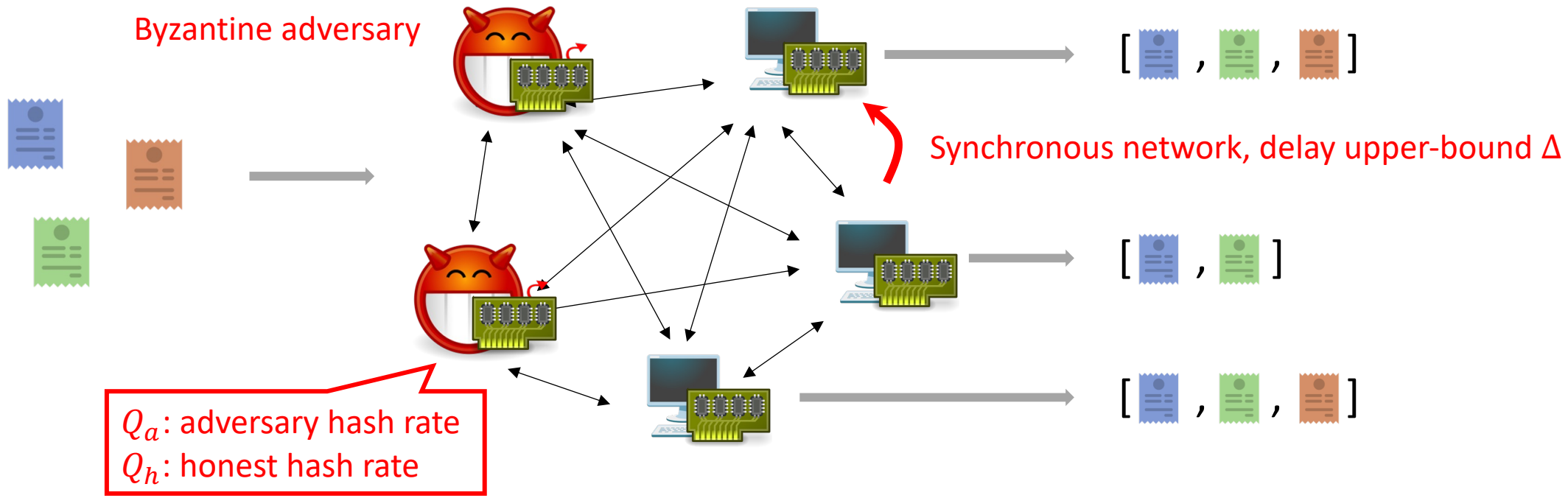
Bad, because it lowers the chain growth rate of the longest chain!

Fraction of honest blocks not produced within Δ after an honest block

$$\lambda_{\text{growth}}^{\Delta=0} = \lambda_{\text{h}} \quad \Rightarrow \quad \lambda_{\text{growth}}^{\Delta>0} = \lambda_{\text{h}} \cdot \frac{1}{1 + \lambda_{\text{h}} \cdot \Delta}$$

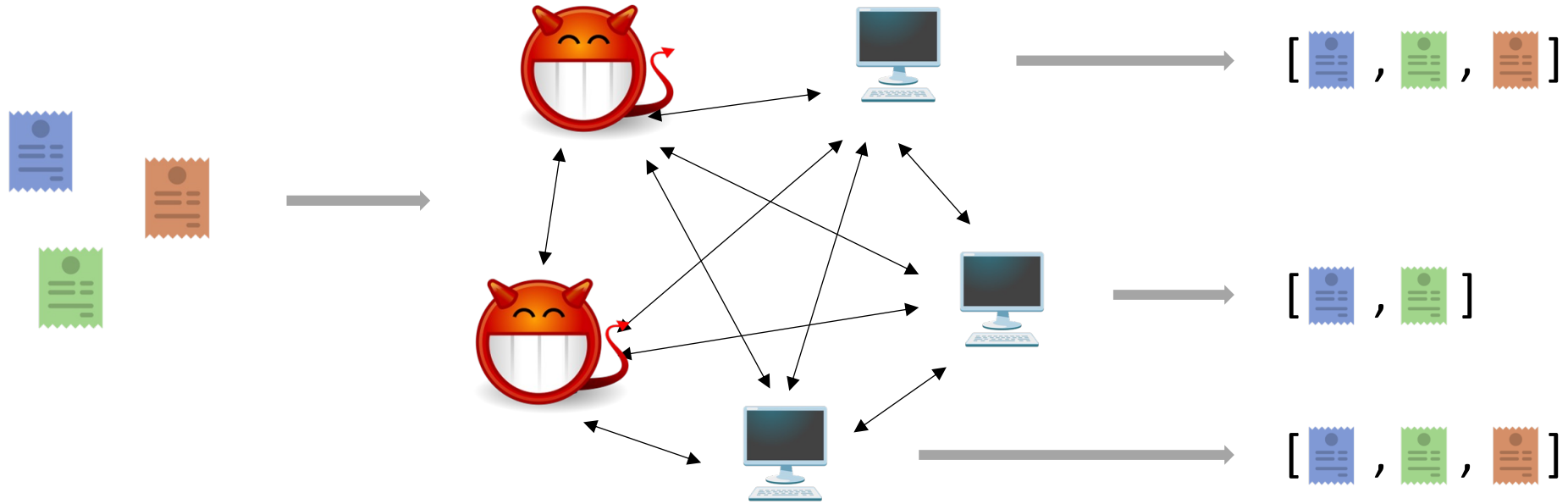
SMR Example 1: Proof-of-Work Nakamoto Consensus



Theorem

Proof-of-work Nakamoto consensus with difficulty D is safe and live iff $Q_{\mathrm{a}} < Q_{\mathrm{h}} \cdot \frac{1}{1+Q_{\mathrm{h}} \cdot D \cdot \Delta}$, under synchrony, except with probability decaying exponentially in k.

SMR Example 2: Permissioned PBFT-Style Consensus



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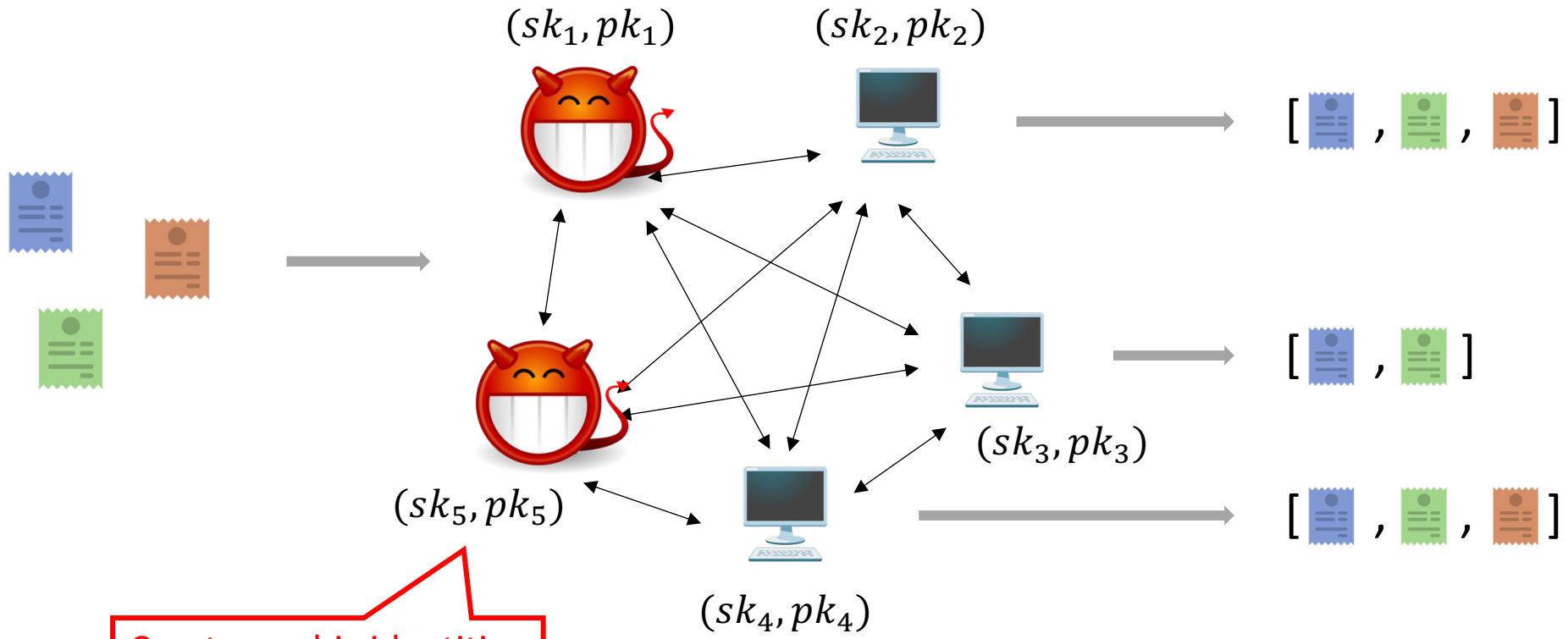

Cryptographic identities
n: nodes
f: adversary nodes
$n - f$: honest nodes

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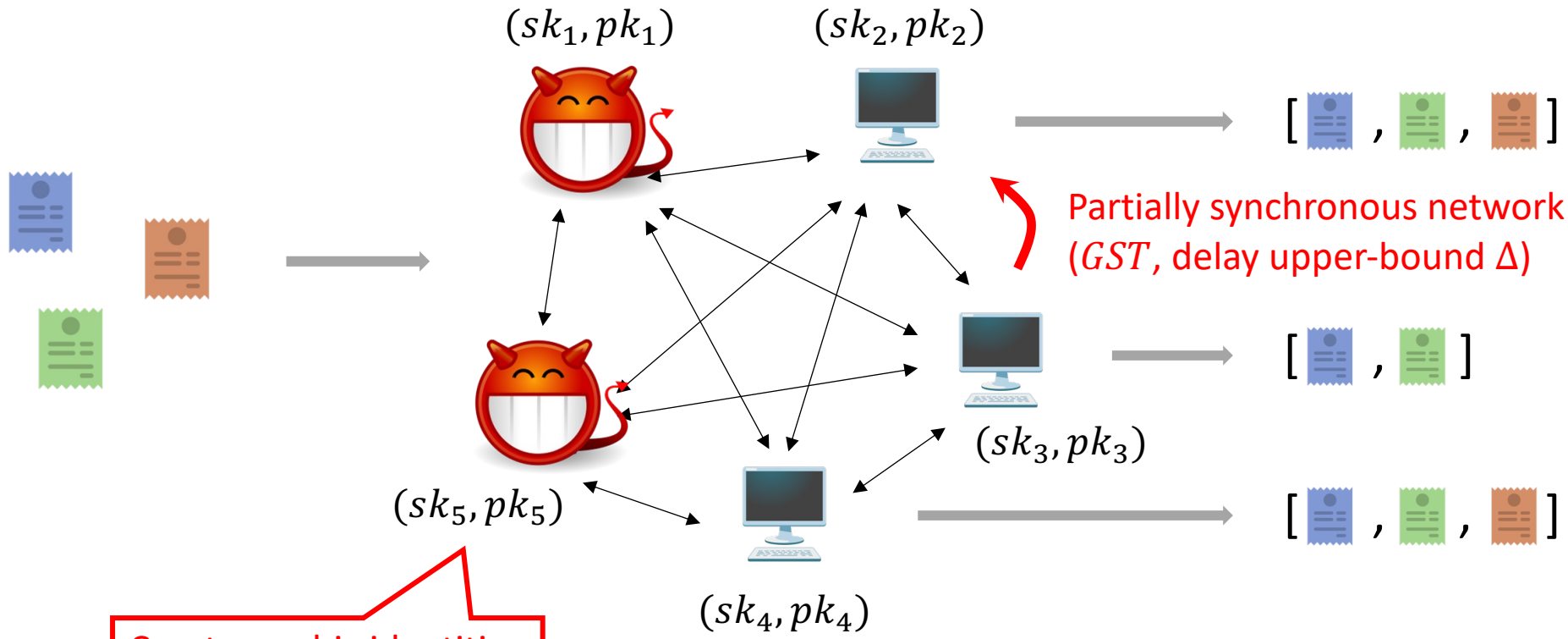

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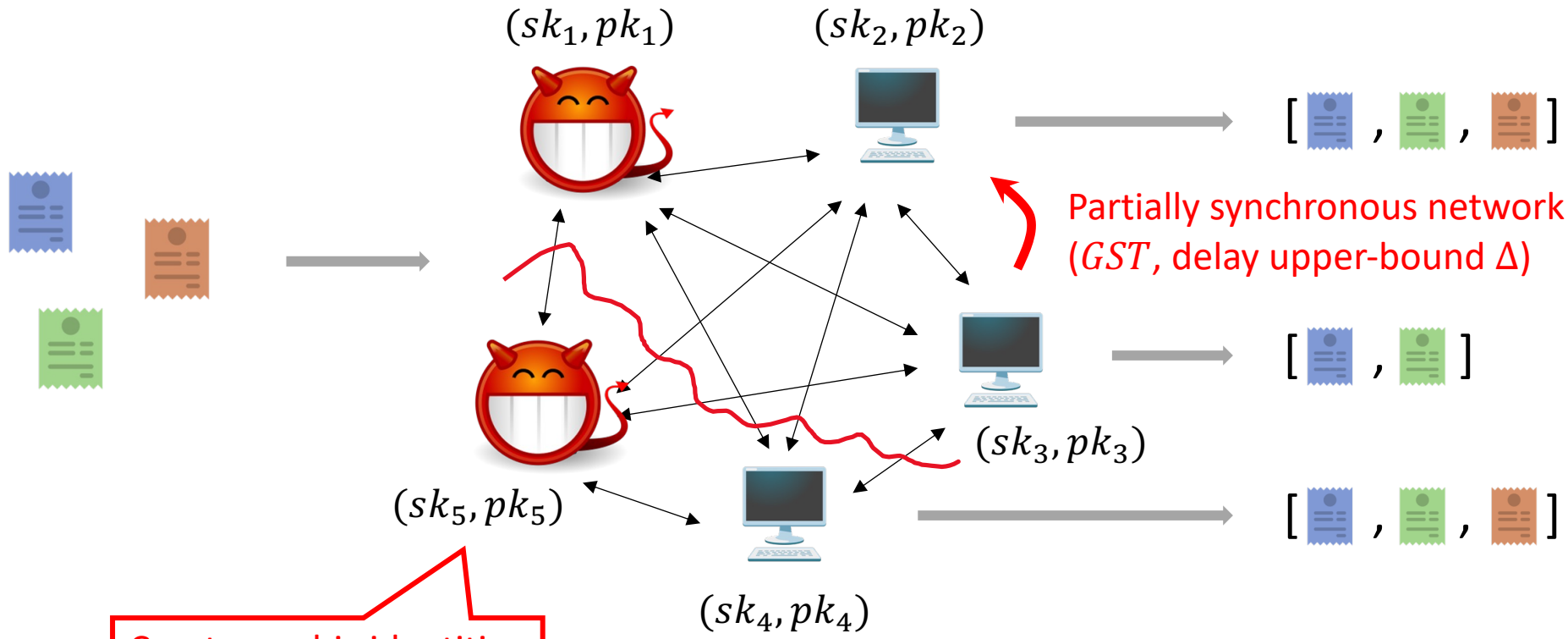

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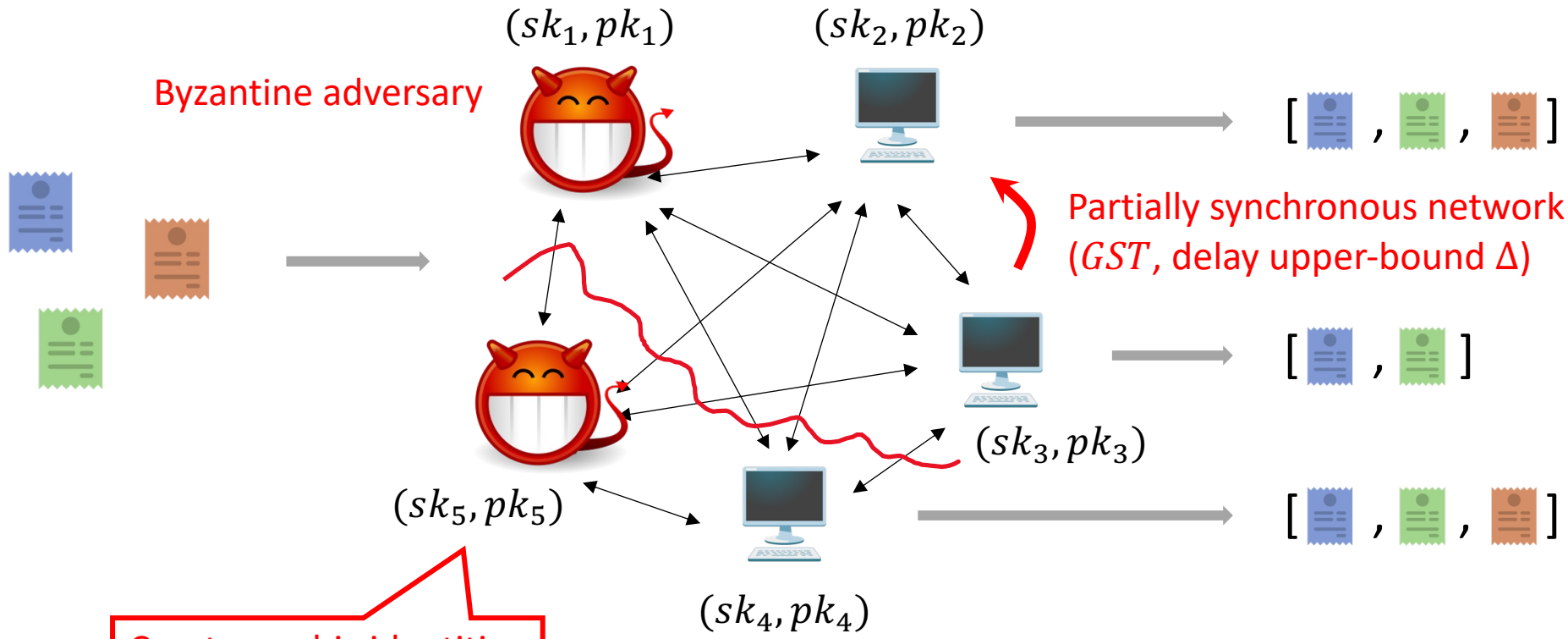
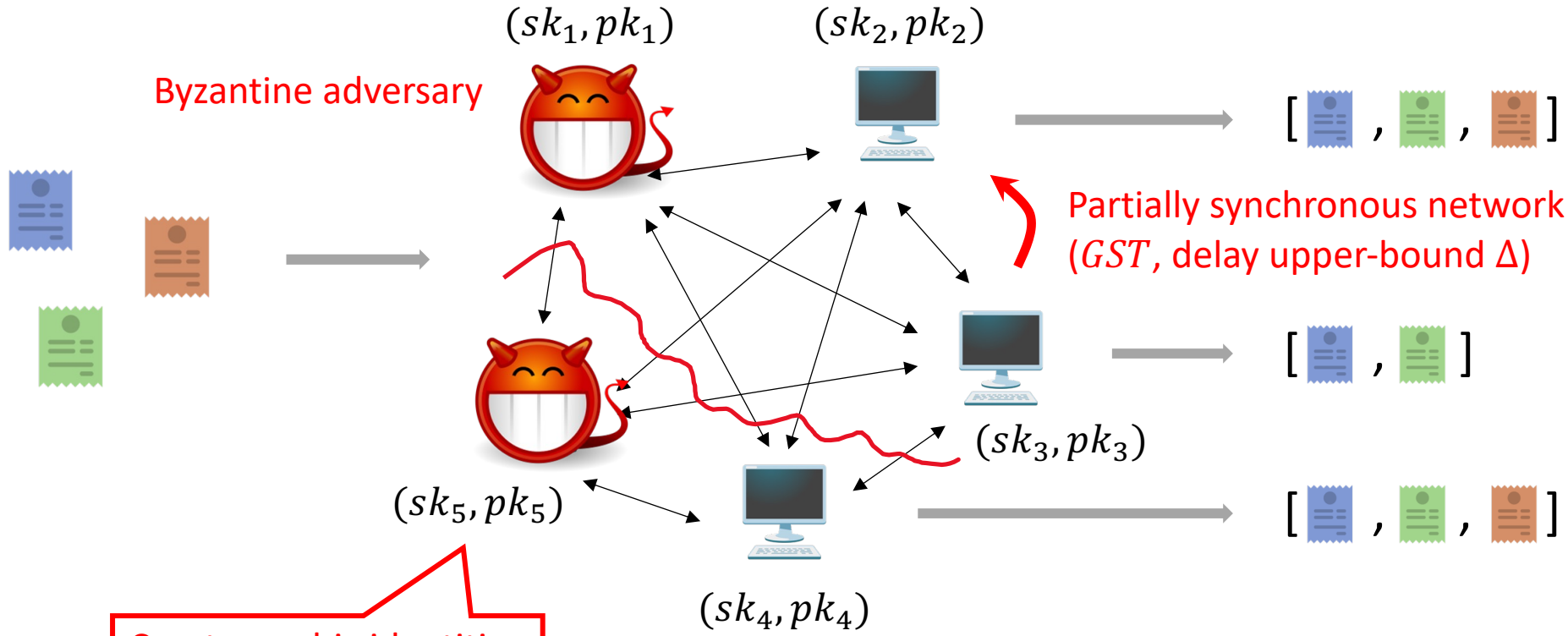


SMR Example 2: Permissioned PBFT-Style Consensus

Pre-dates blockchains by 10+ years



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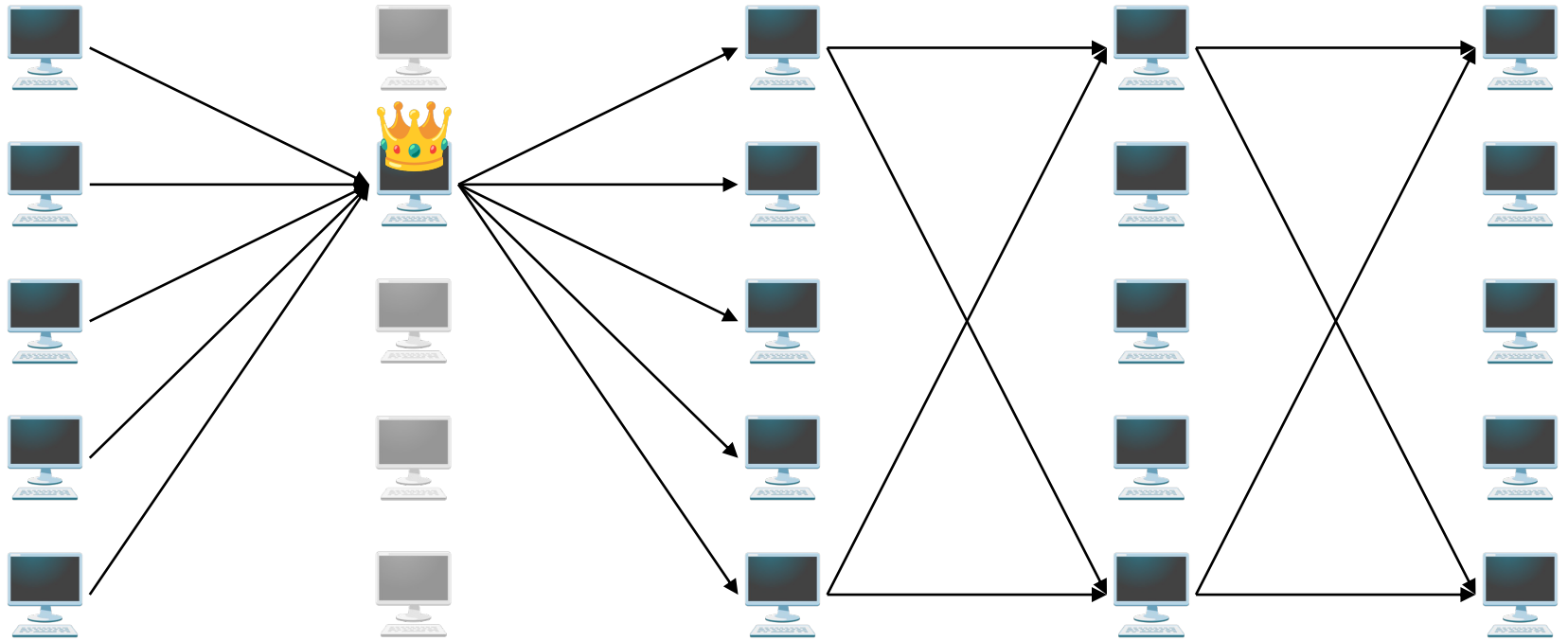
f: adversary nodes
$n - f$: honest nodes

PBFT-Style Consensus

Proceeds in views, each with a proposal by a designated leader followed by two rounds of votes (with a quorum of $n - f$).



PBFT-Style Consensus

Example: $n = 7, f = 2$ → quorum 5

Genesis block

$Q_{\text{lock}} \leftarrow \{\}$
for view $v = 1,2,3, \ldots$:
  at time $t = 3\Delta v + 0\Delta$: // only leader of view v
    $(b, Q) \leftarrow$ block with vote-1 quorum for highest view
    broadcast $NewBlock(v, b, Q, GetPendingTxs())$
  at time $t = 3\Delta v + 1\Delta$: // all nodes
    for first proposal b with $view(Q_{\text{lock}}) \leq view(b.Q)$:
      broadcast $NewVote(b, 1)$
  at time $t = 3\Delta v + 2\Delta$: // all nodes
    for vote-1 quorum Q for proposal b:
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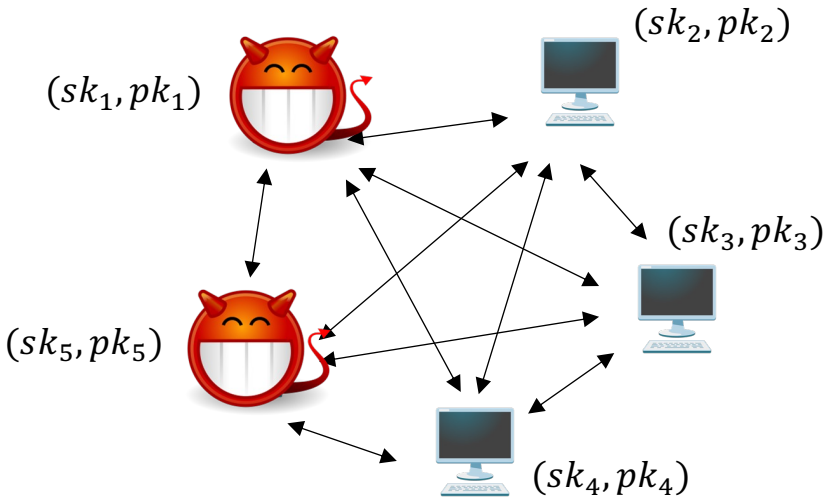
      broadcast $NewVote(b, 2)$, broadcast Q_{lock}



PBFT-Style Consensus

Example: $n = 7, f = 2$ → quorum 5

Genesis block

$Q_{\text{lock}} \leftarrow \{\}$
for view $v = 1,2,3, \ldots$:
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    $(b, Q) \leftarrow$ block with vote-1 quorum for highest view
    broadcast $NewBlock(v, b, Q, GetPendingTxs())$
  at time $t = 3\Delta v + 1\Delta$: // all nodes
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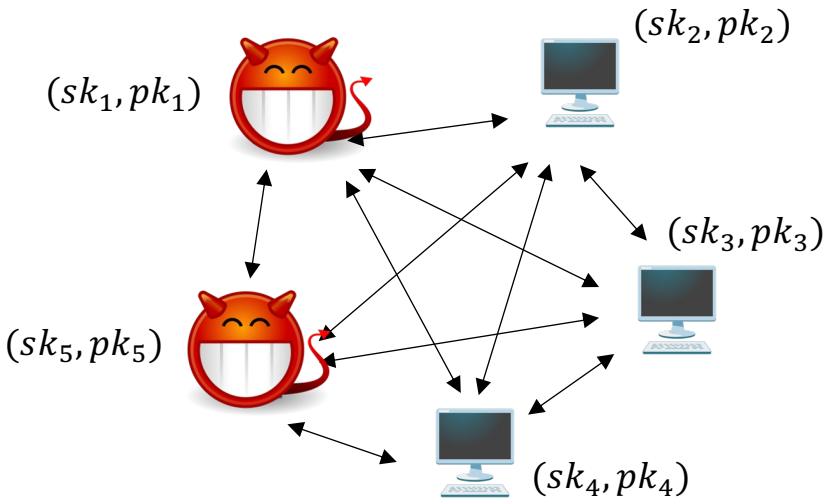
"Catch-up", view change



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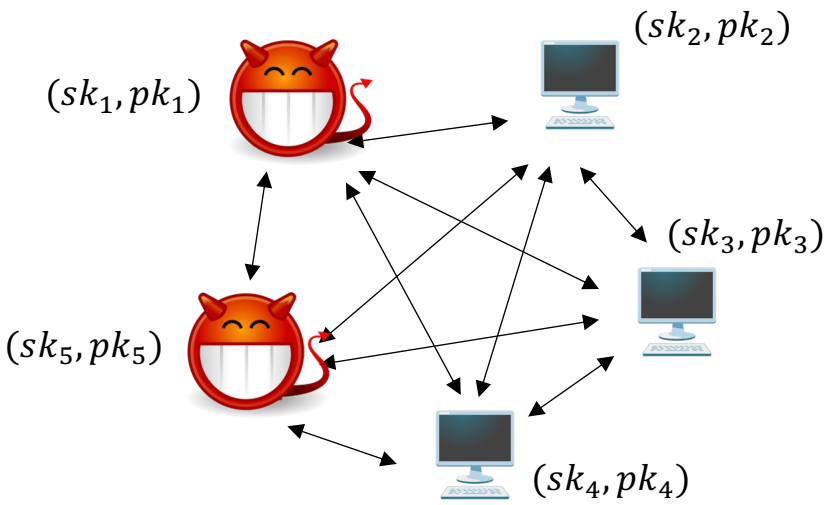
Example: $n = 7, f = 2 \rightarrow$ quorum 5

Genesis block

Leader proposal

"Catch-up", view change



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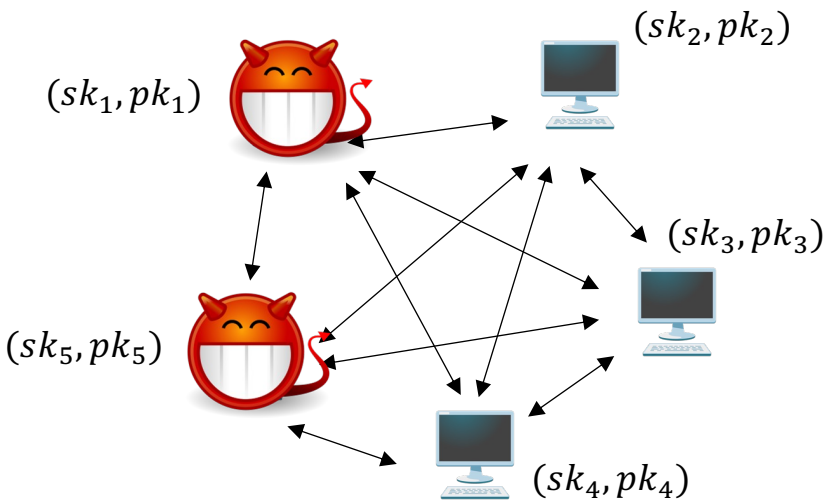
Example: $n = 7, f = 2 \rightarrow$ quorum 5

Genesis block

Leader proposal

"Works for me", vote 1

"Catch-up", view change



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Example: $n = 7, f = 2 \rightarrow$ quorum 5

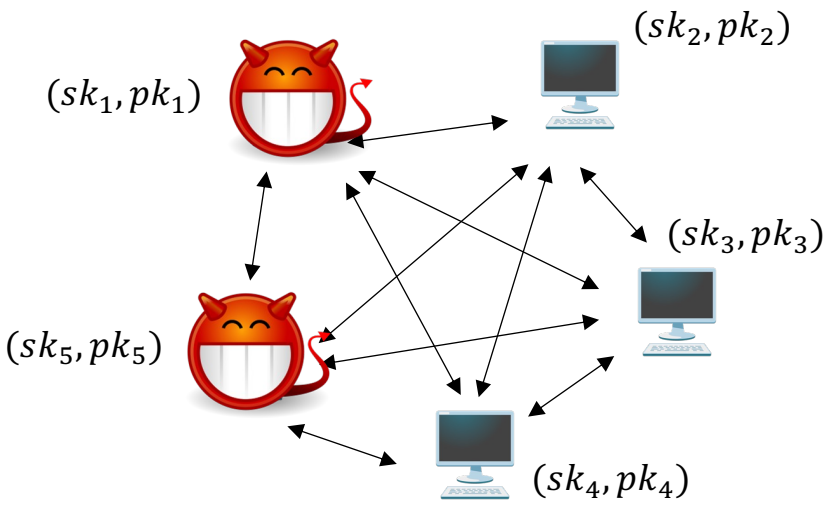
Genesis block

Leader proposal

"Works for me", vote 1

"Let's do it", vote 2

"Catch-up", view change



PBFT-Style Consensus

Example: $n = 7, f = 2$ → quorum 5

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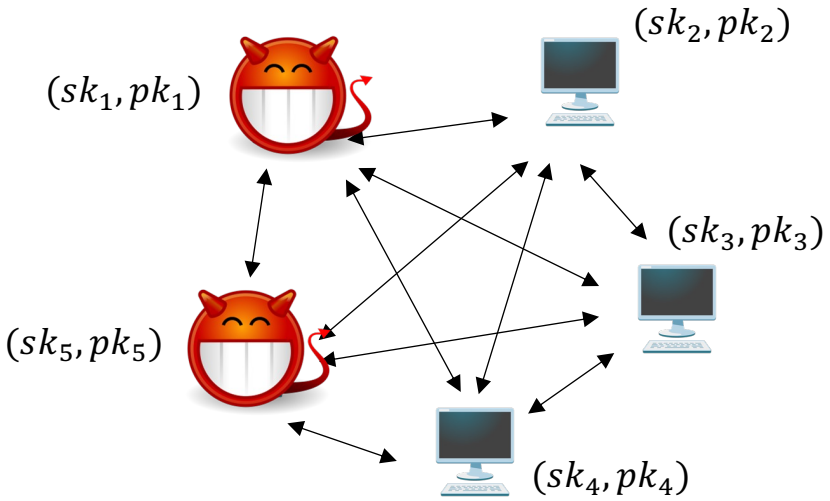

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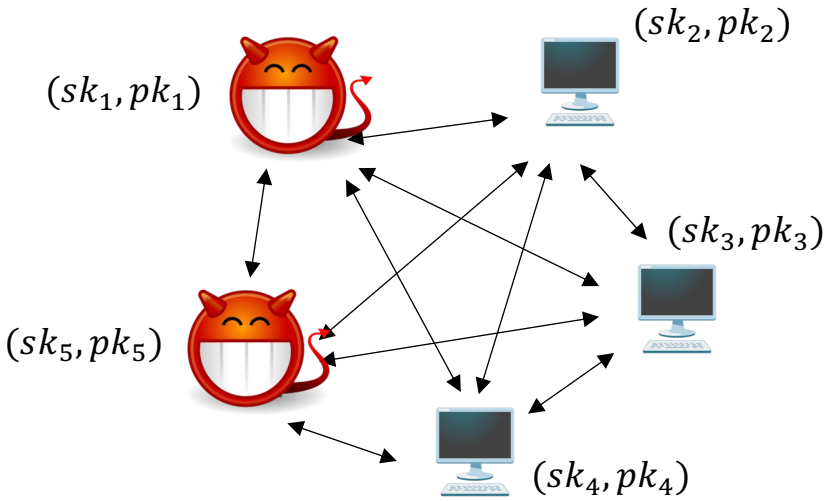

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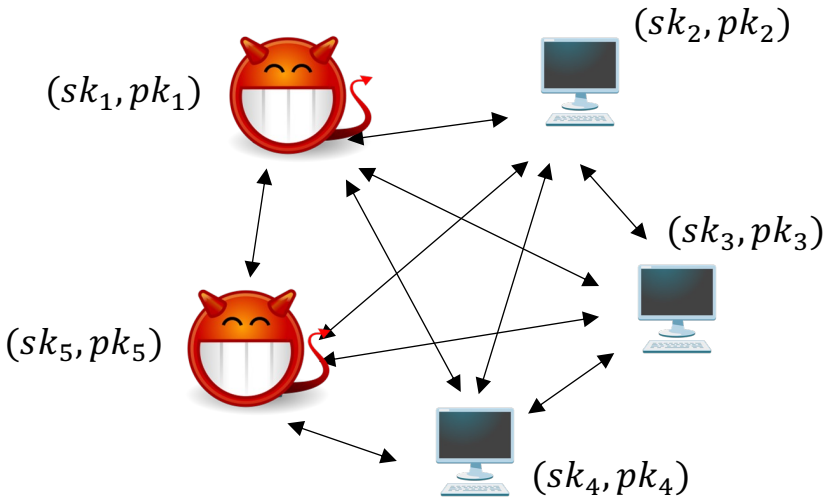

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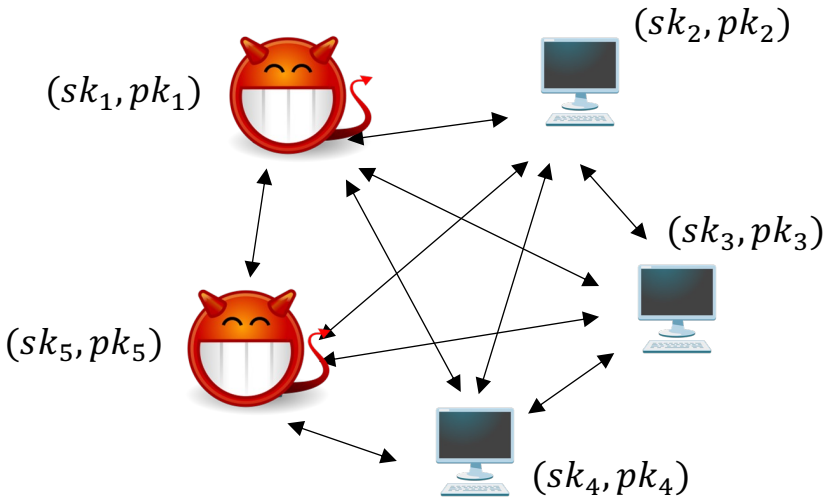

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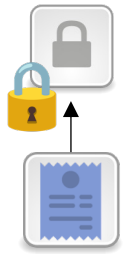

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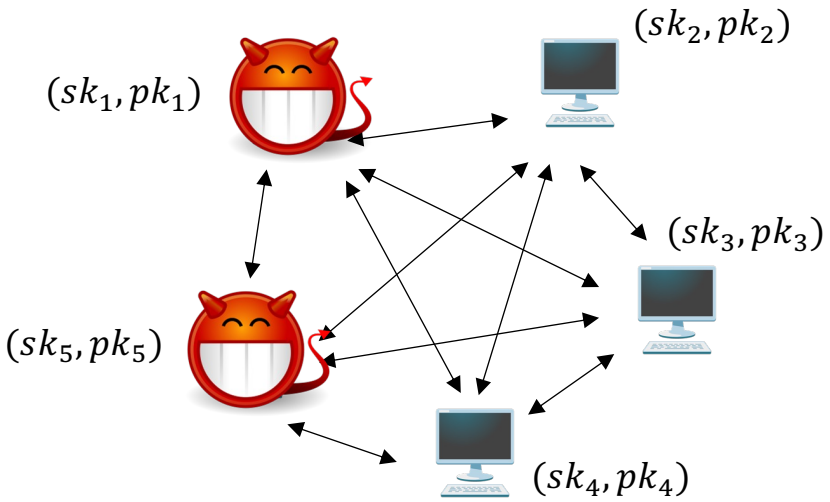

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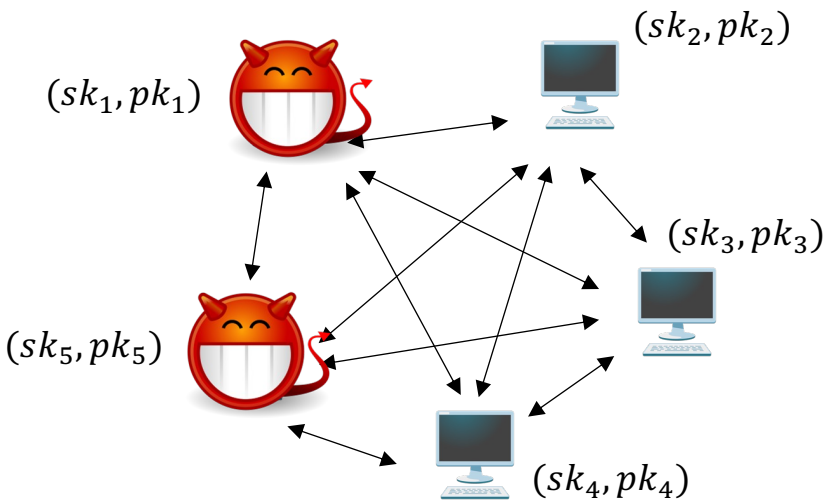
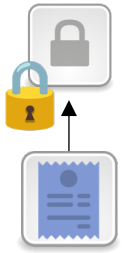


Example: $n = 7, f = 2 \rightarrow$ quorum 5

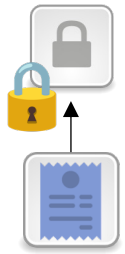
Genesis block



PBFT-Style Consensus

Example: $n = 7, f = 2 \rightarrow$ quorum 5

Genesis block



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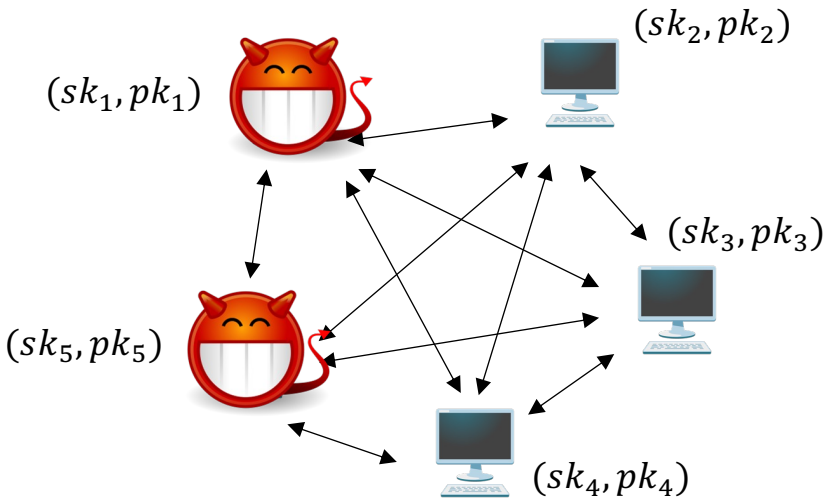

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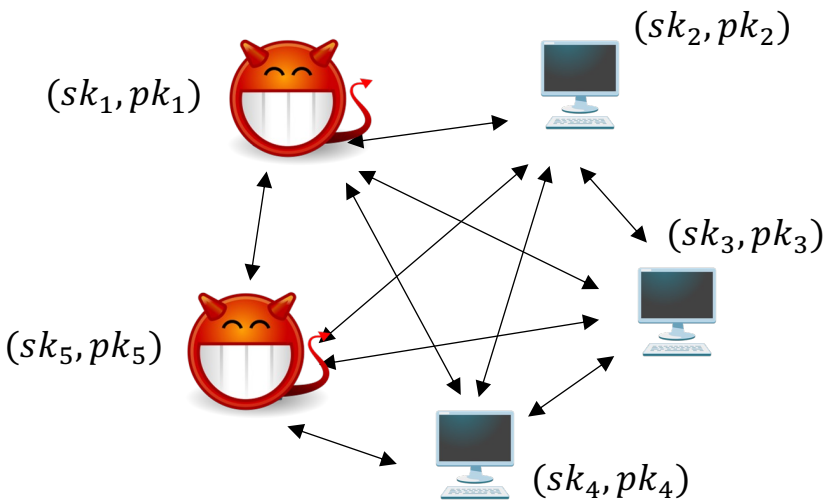

Example: $n = 7, f = 2 \rightarrow$ quorum 5

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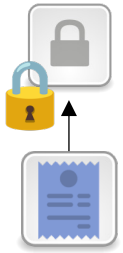

PBFT-Style Consensus

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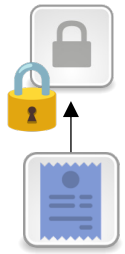
Genesis block



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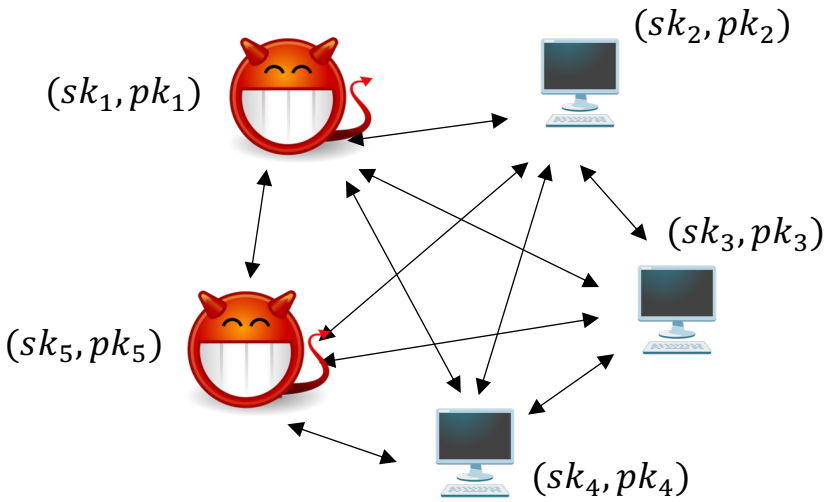

PBFT-Style Consensus

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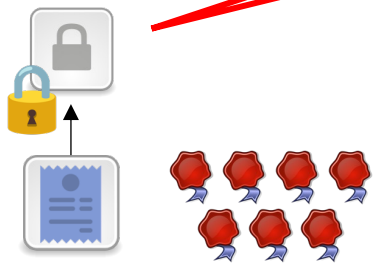

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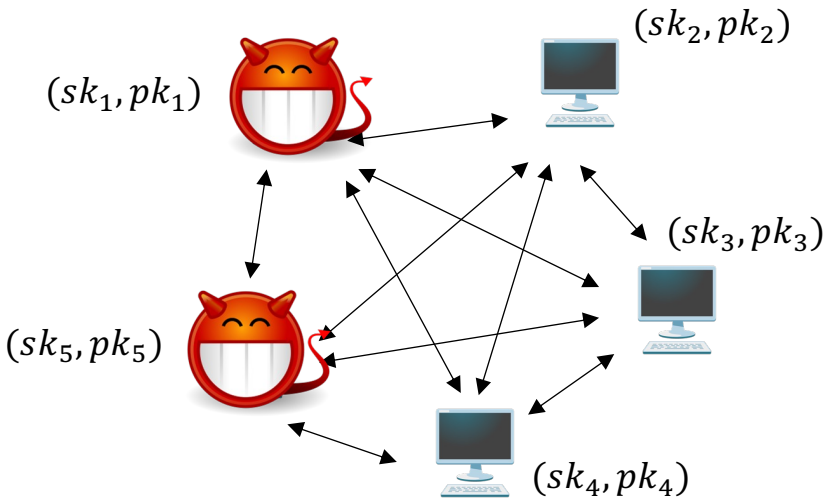

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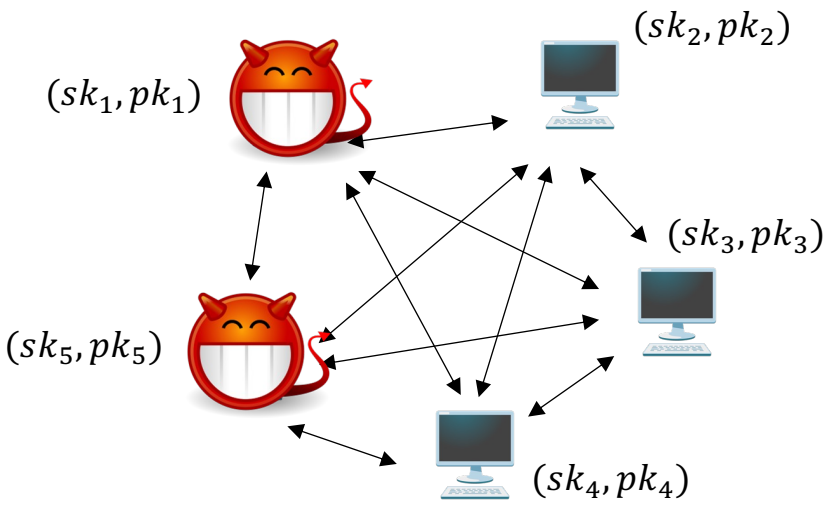

Example: $n = 7, f = 2 \rightarrow$ quorum 5

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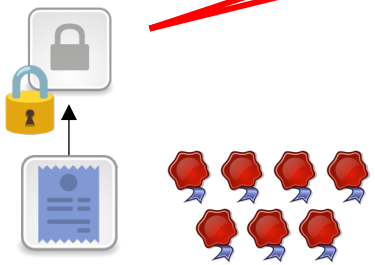

PBFT-Style Consensus

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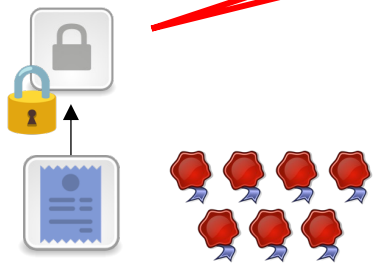

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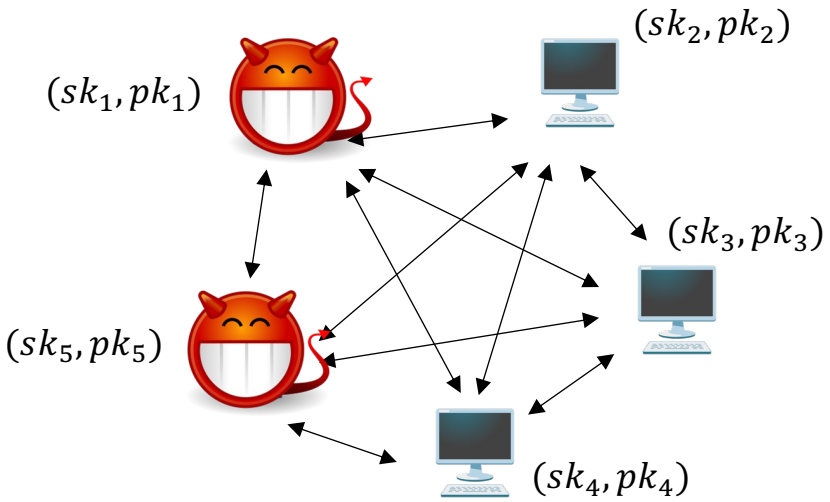

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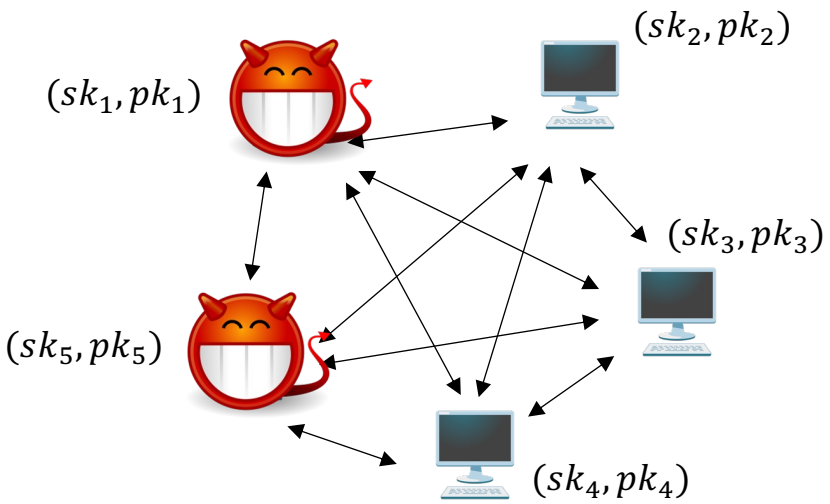
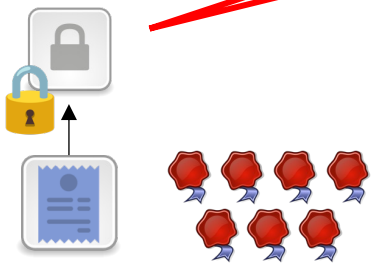
    for vote-1 quorum Q for proposal b:
      $Q_{\text{lock}} \leftarrow Q$
      broadcast $NewVote(b, 2)$, broadcast Q_{lock}



Example: $n = 7, f = 2 \rightarrow$ quorum 5

Genesis block



PBFT-Style Consensus

$Q_{\text{lock}} \leftarrow \{\}$
for view $v = 1,2,3, \ldots$:
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    $(b, Q) \leftarrow$ block with vote-1 quorum for highest view
    broadcast $NewBlock(v, b, Q, GetPendingTxs())$
  at time $t = 3\Delta v + 1\Delta$: // all nodes
    for first proposal b with $view(Q_{\text{lock}}) \leq view(b.Q)$:
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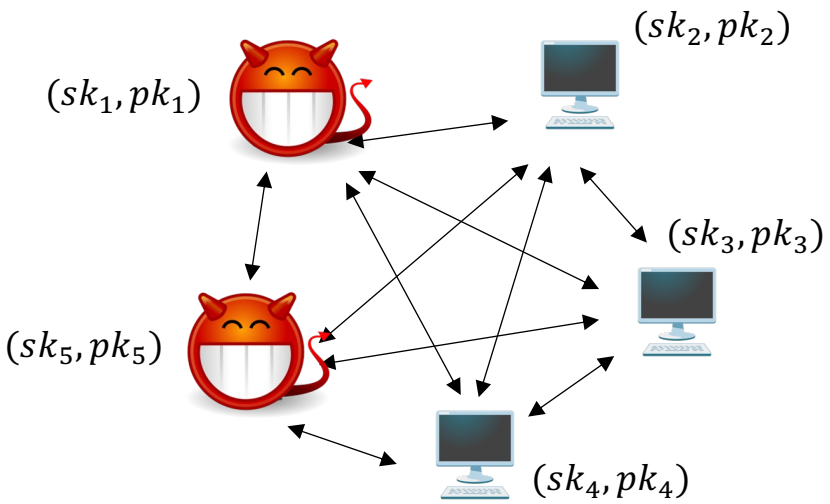

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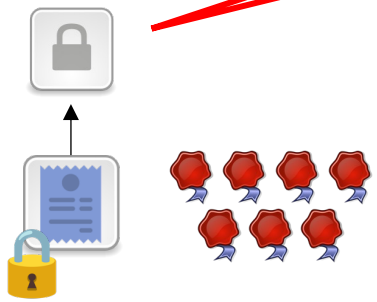

PBFT-Style Consensus

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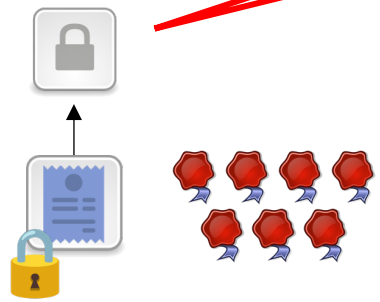
Genesis block



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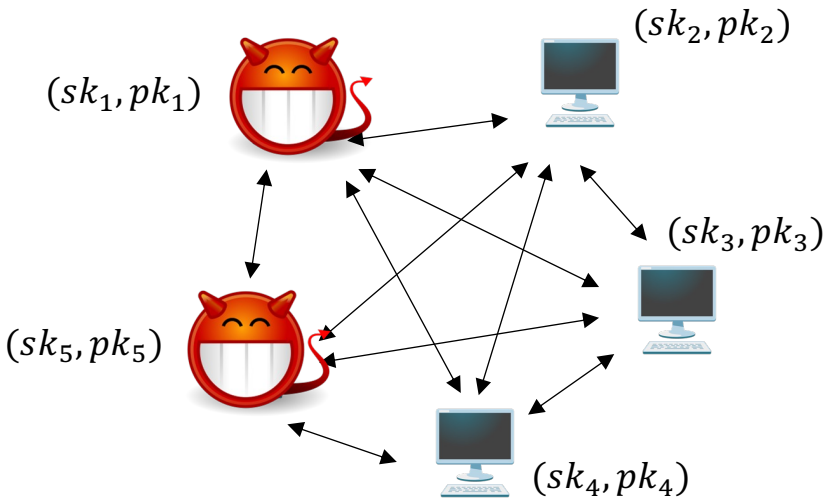

PBFT-Style Consensus

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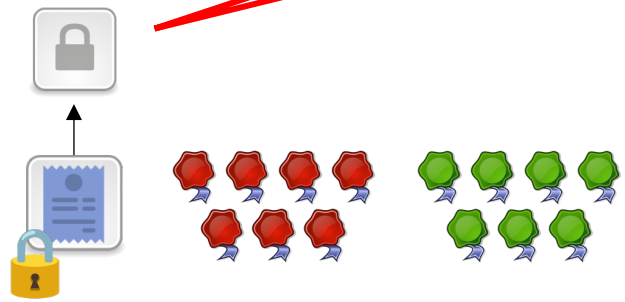

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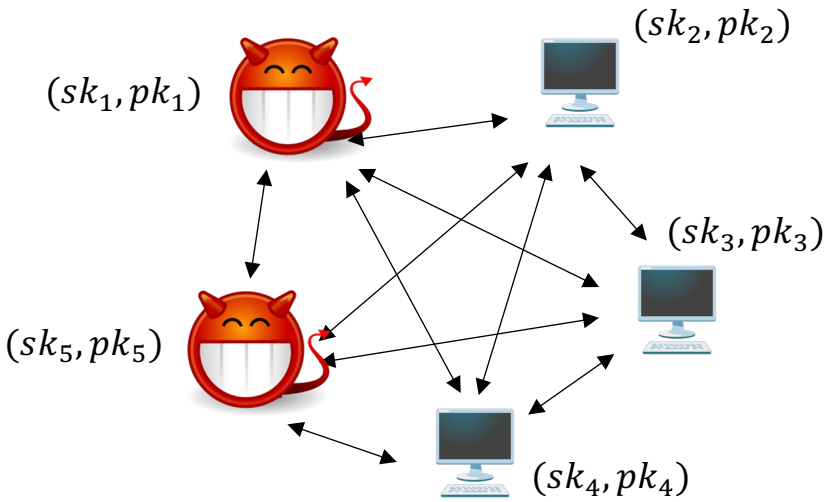

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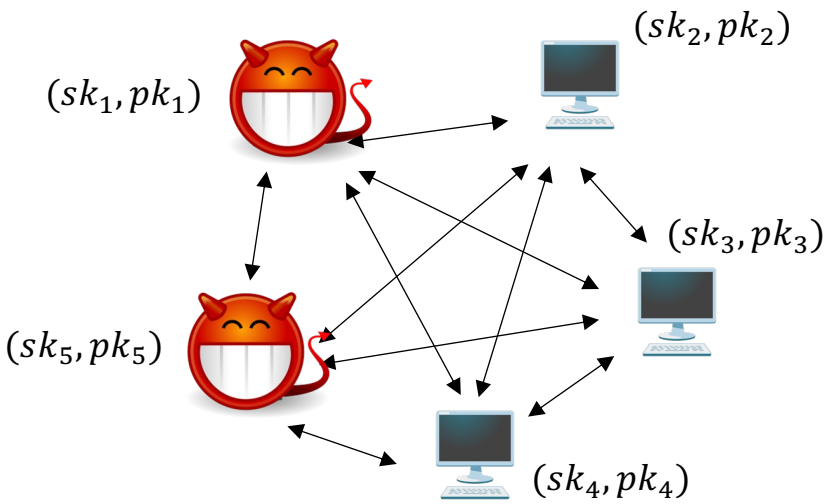

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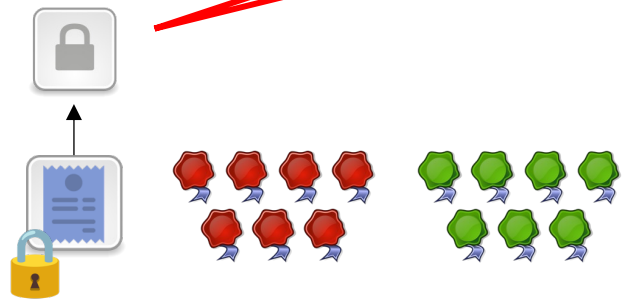
Genesis block



PBFT-Style Consensus

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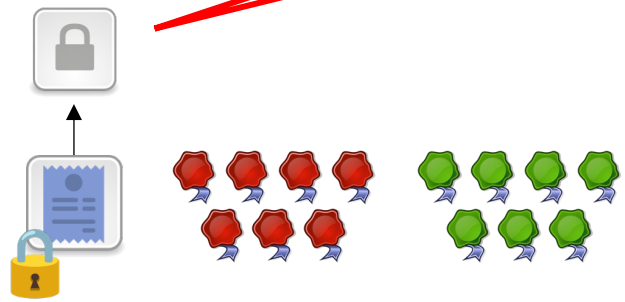

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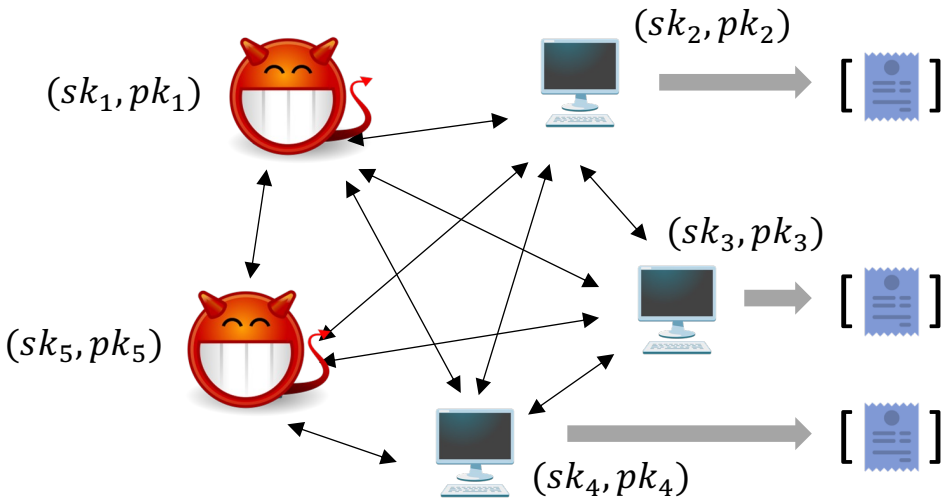

PBFT-Style Consensus

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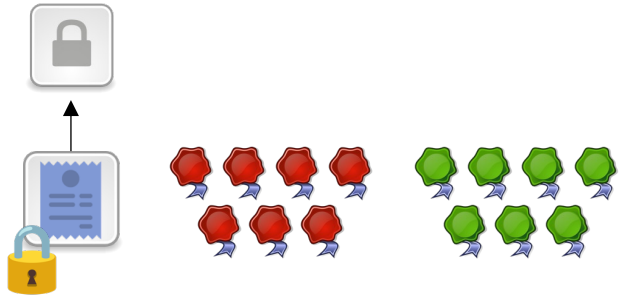

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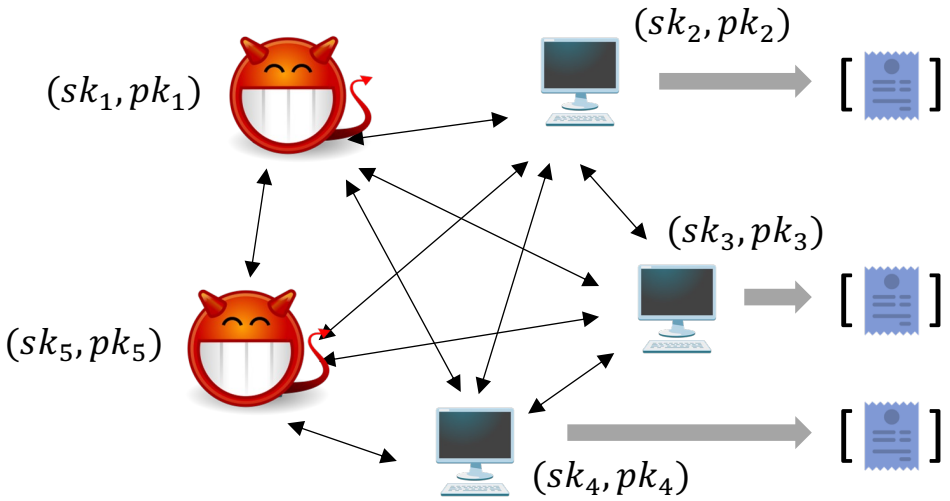

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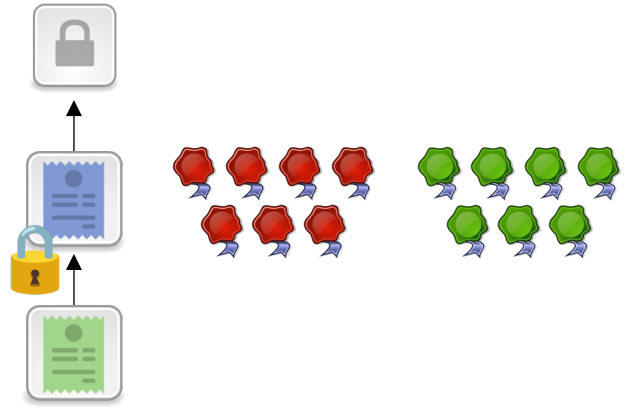

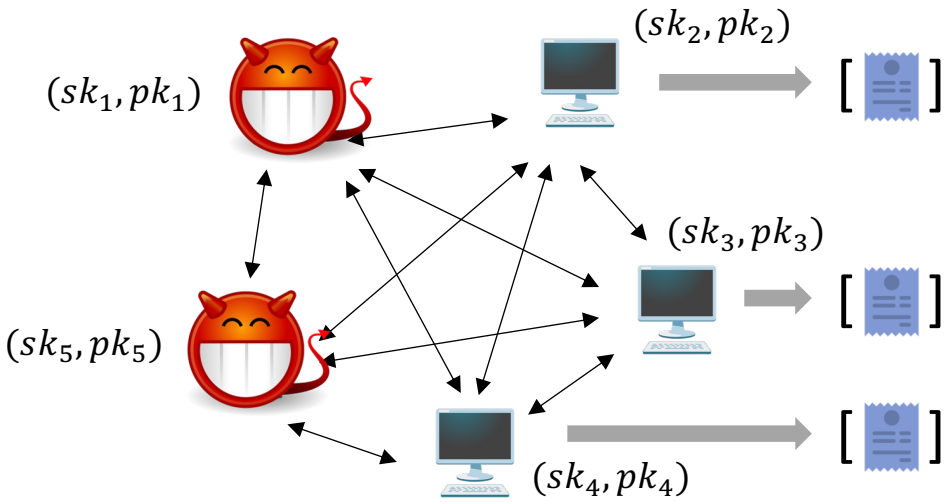

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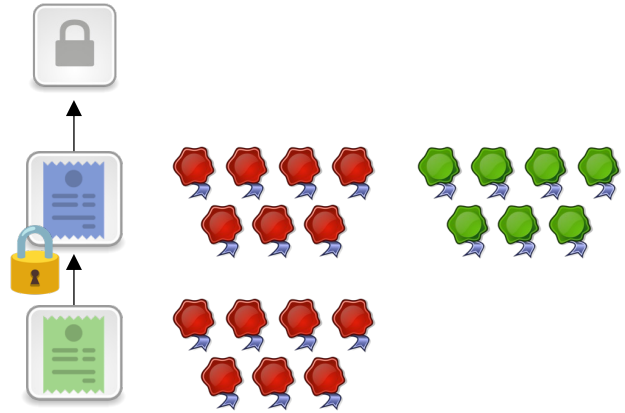

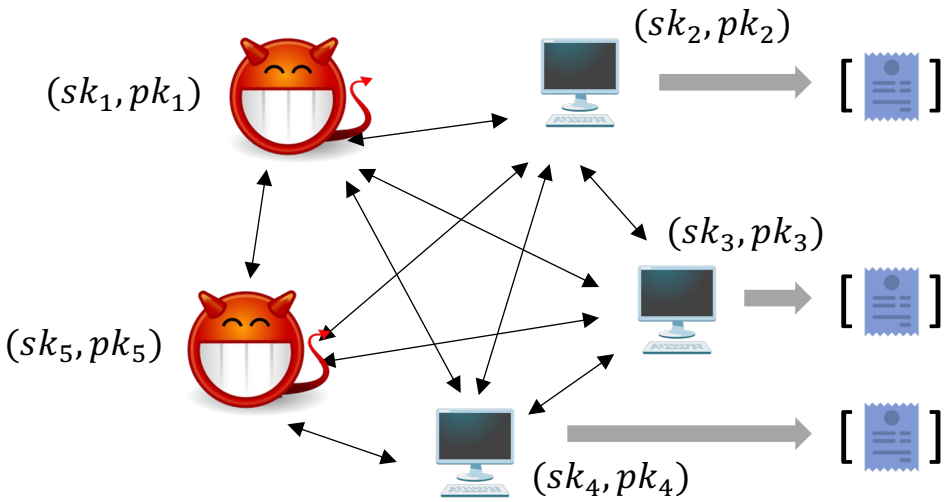

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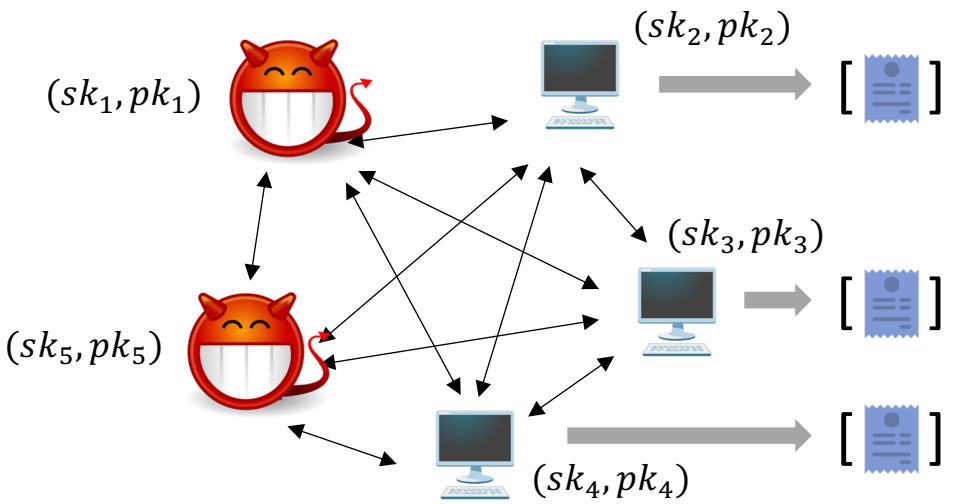

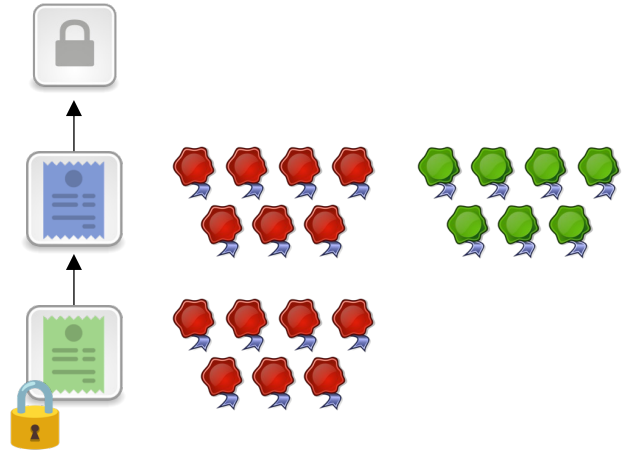

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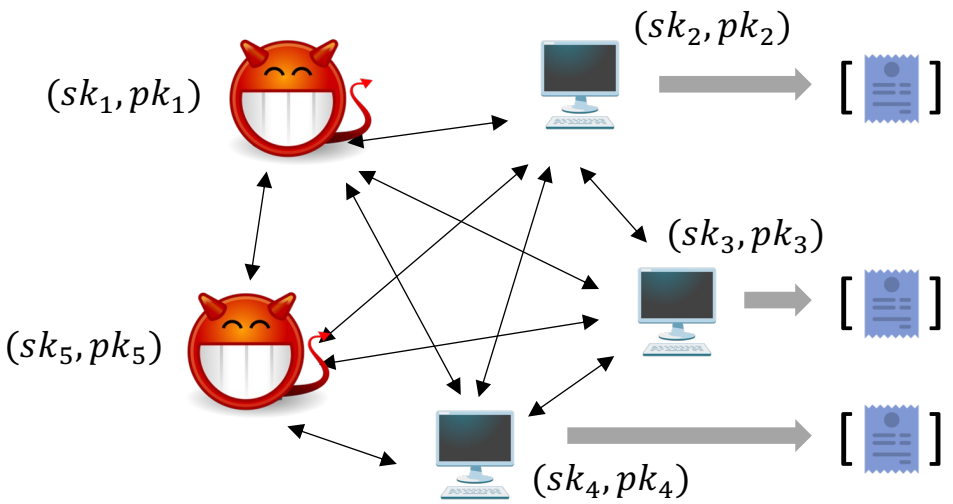

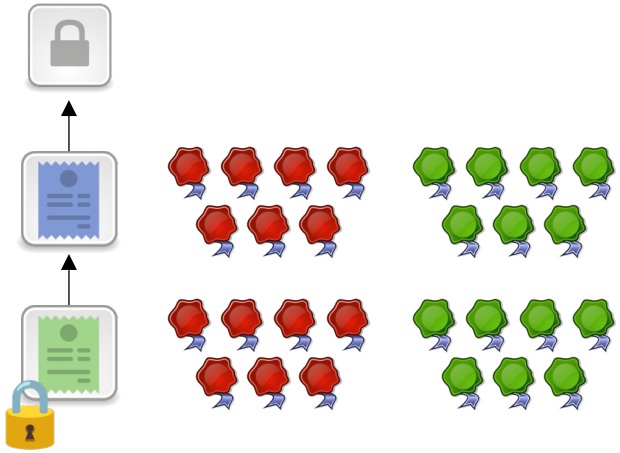

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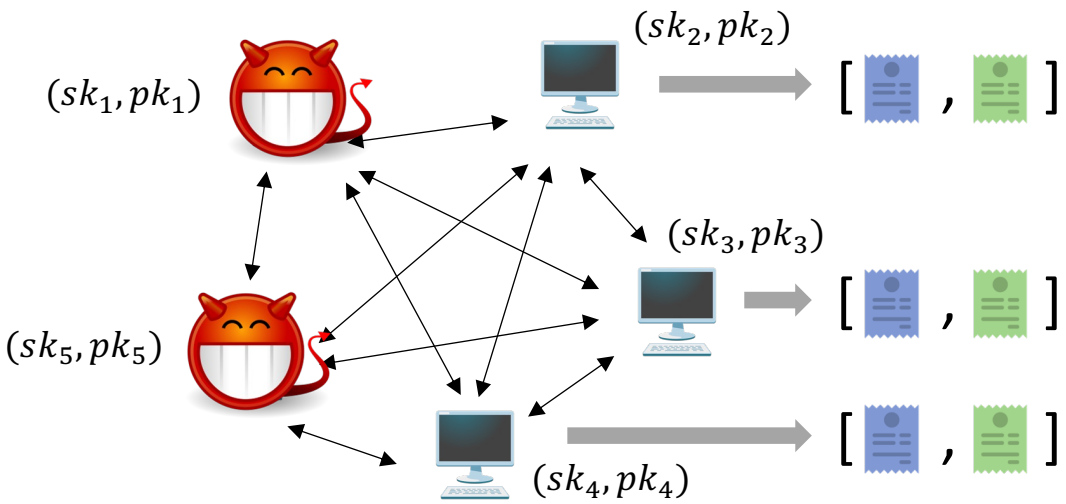

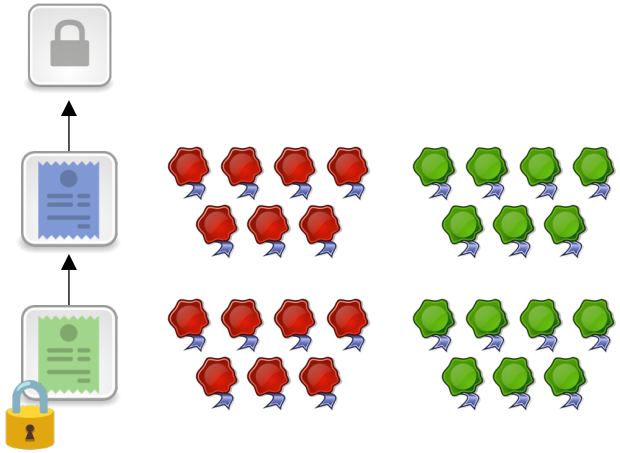

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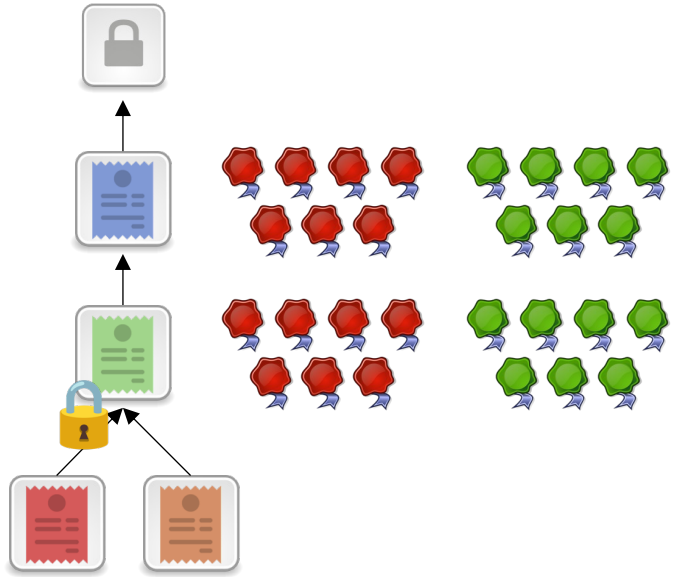

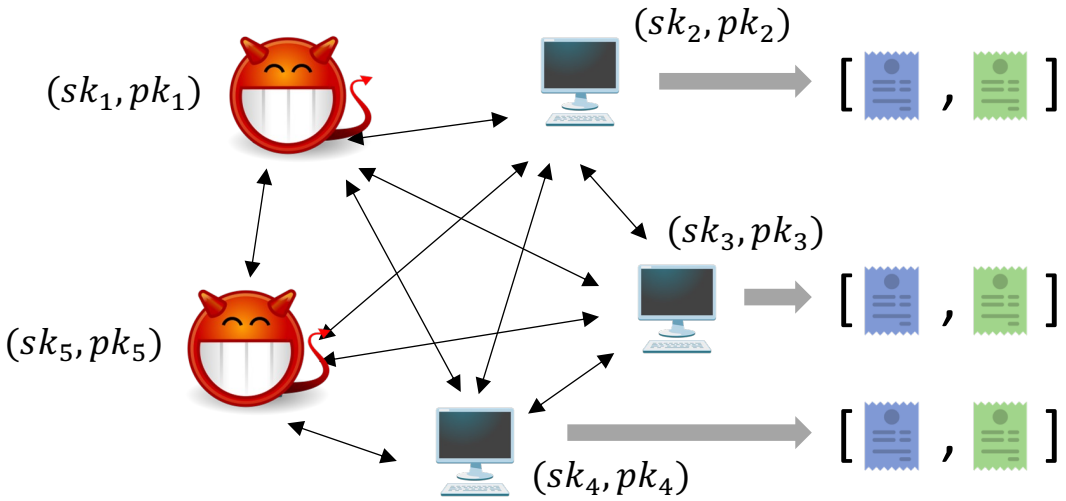

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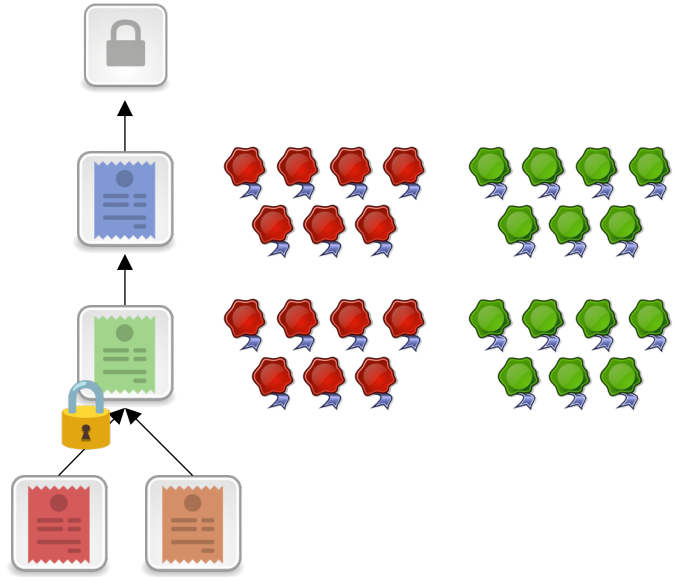

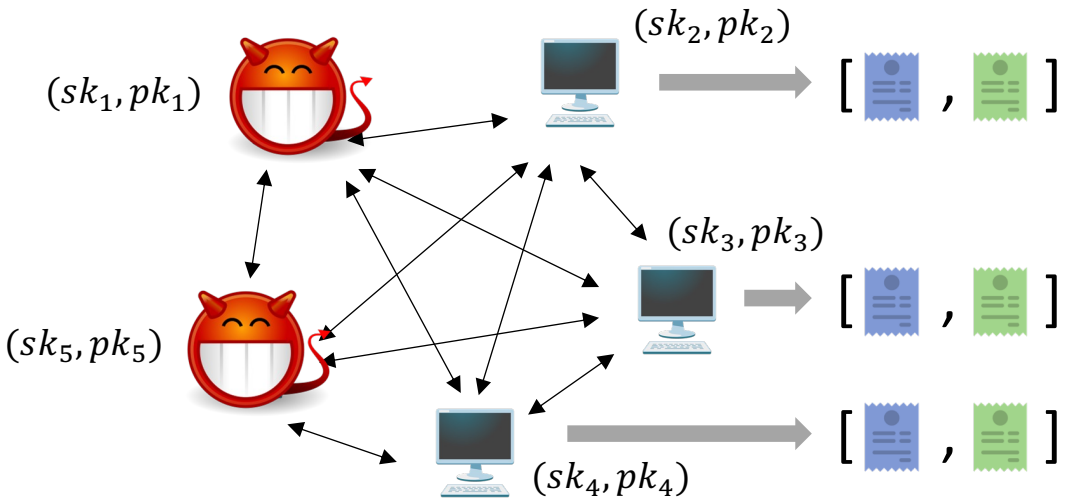

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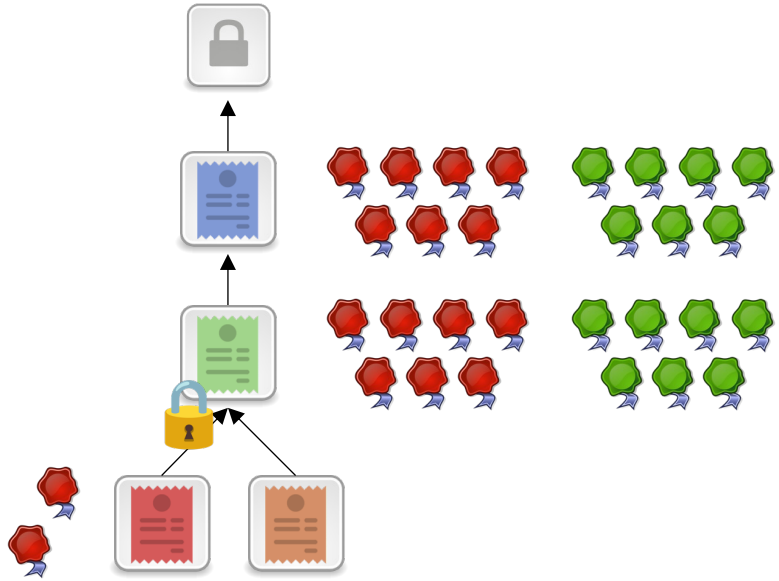

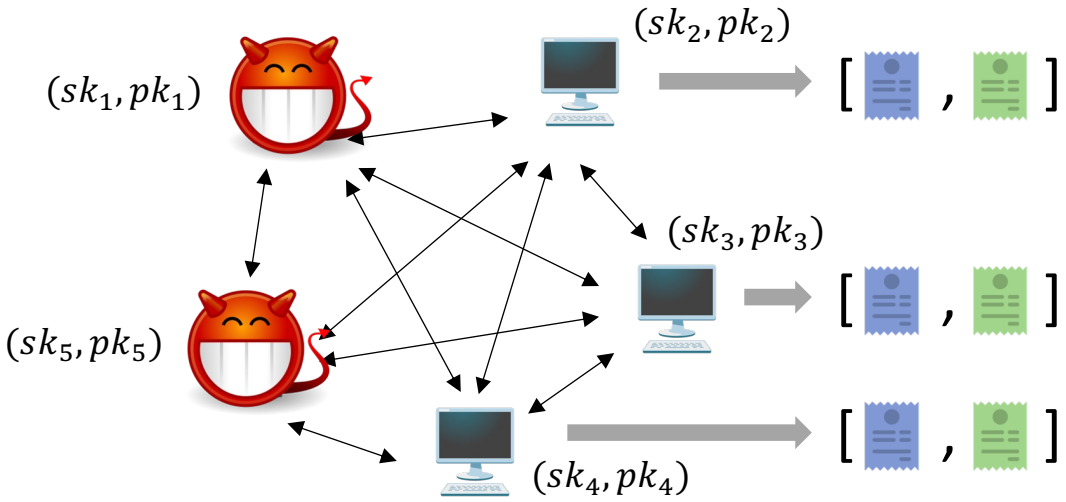

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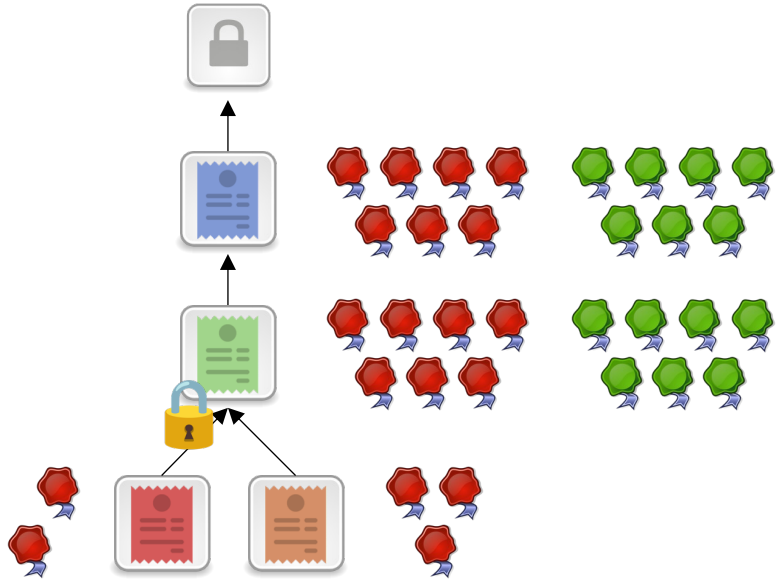

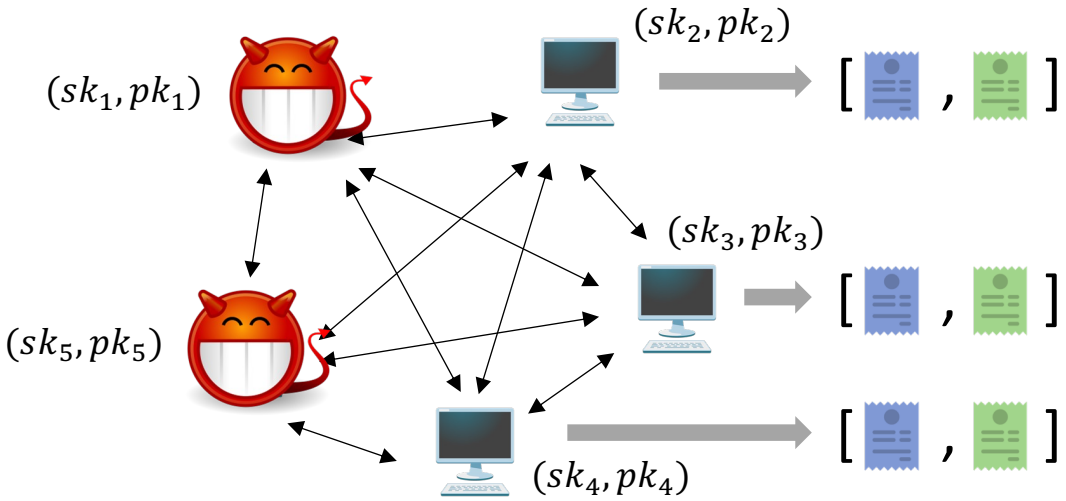

PBFT-Style Consensus

Example: $n = 7, f = 2$ → quorum 5

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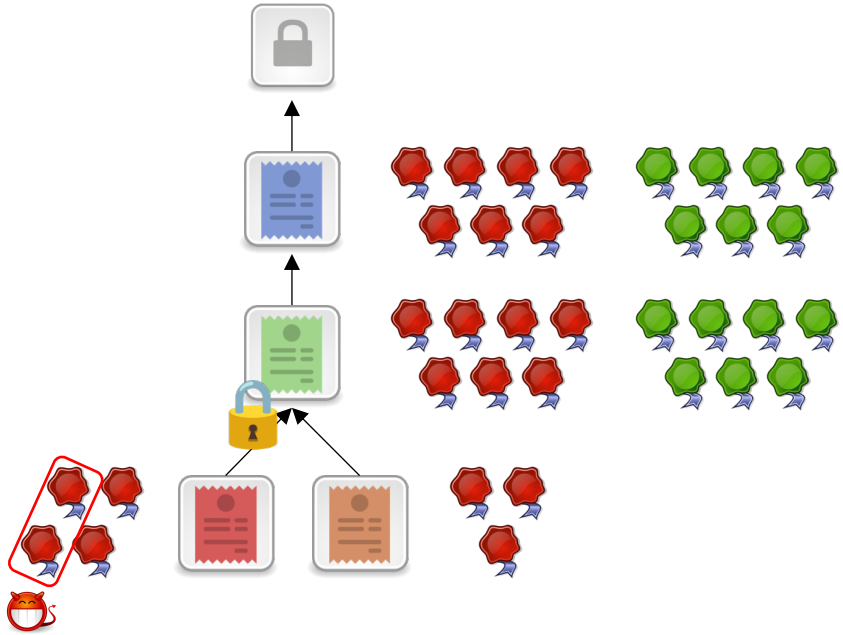

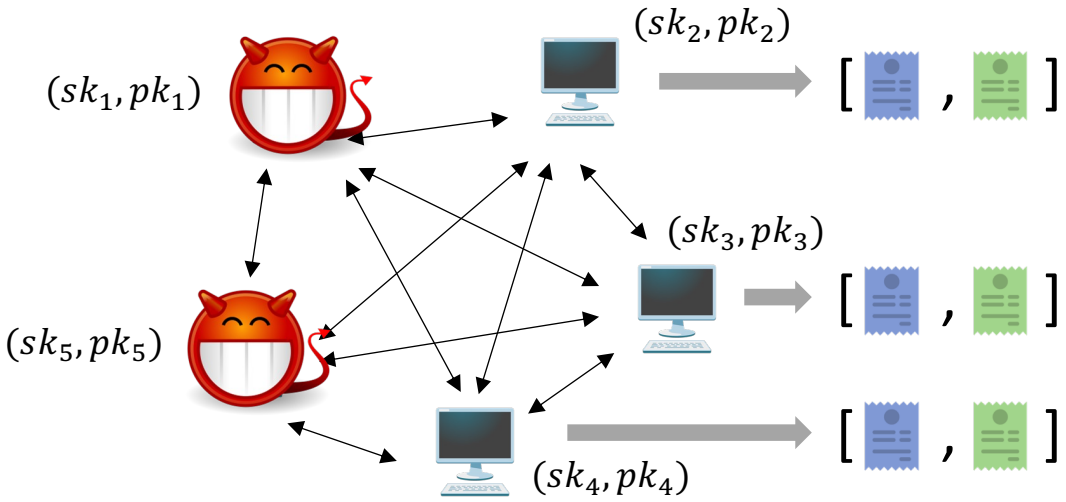

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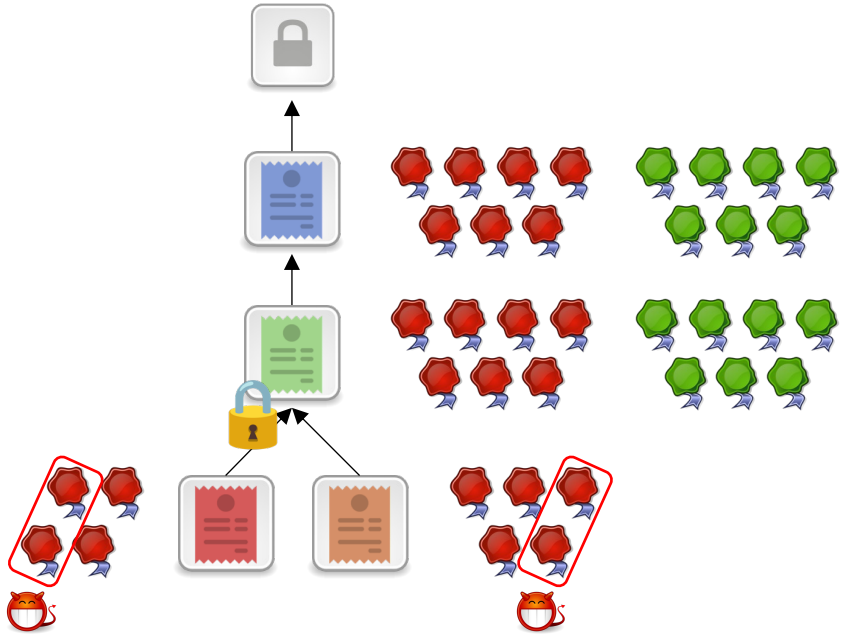

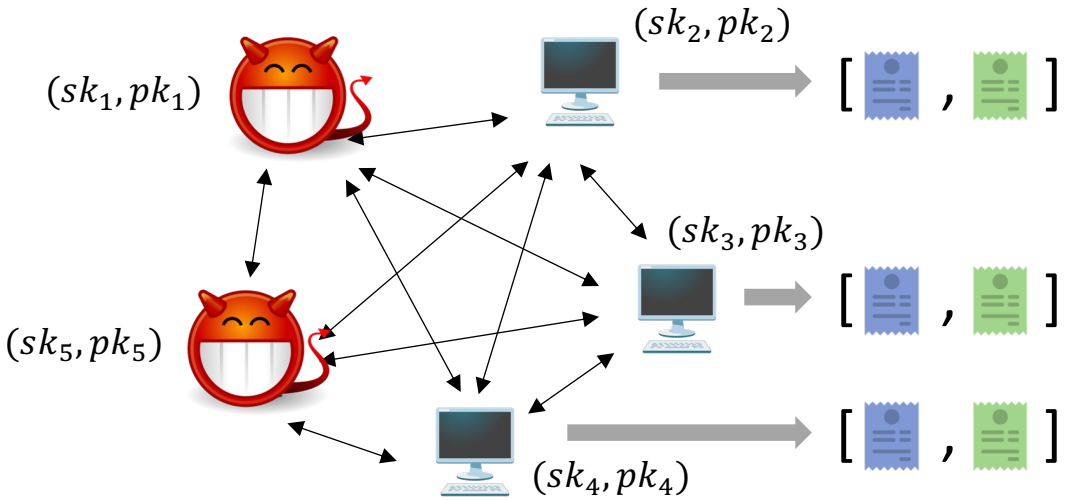

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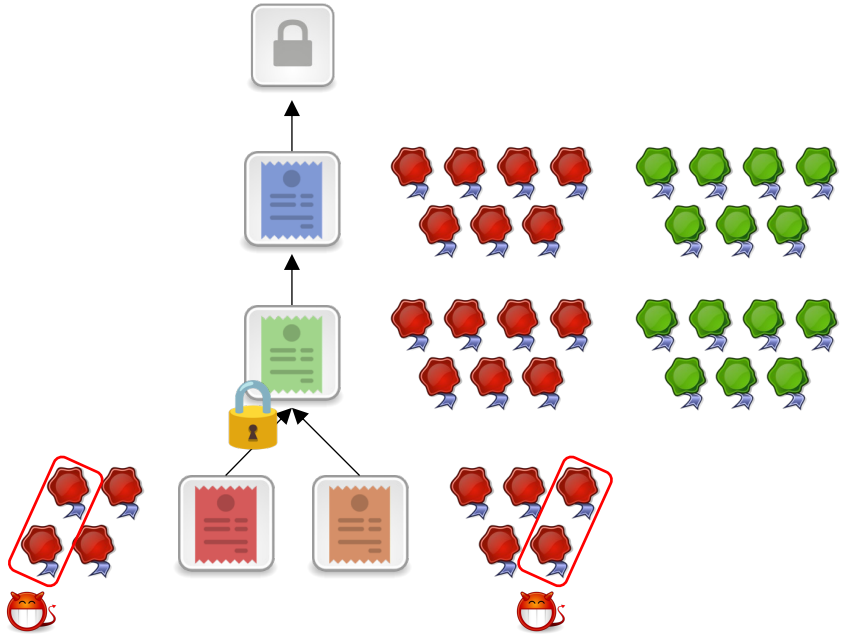

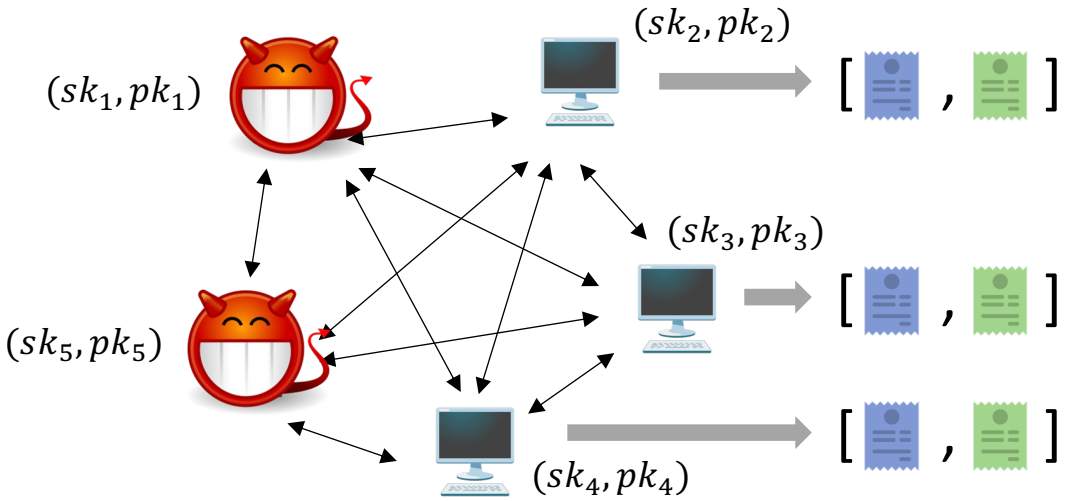

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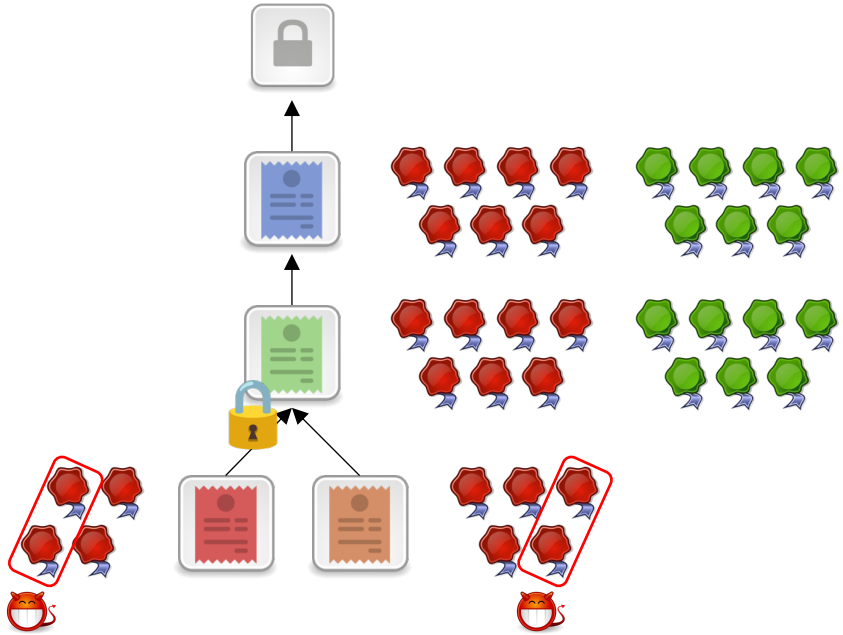

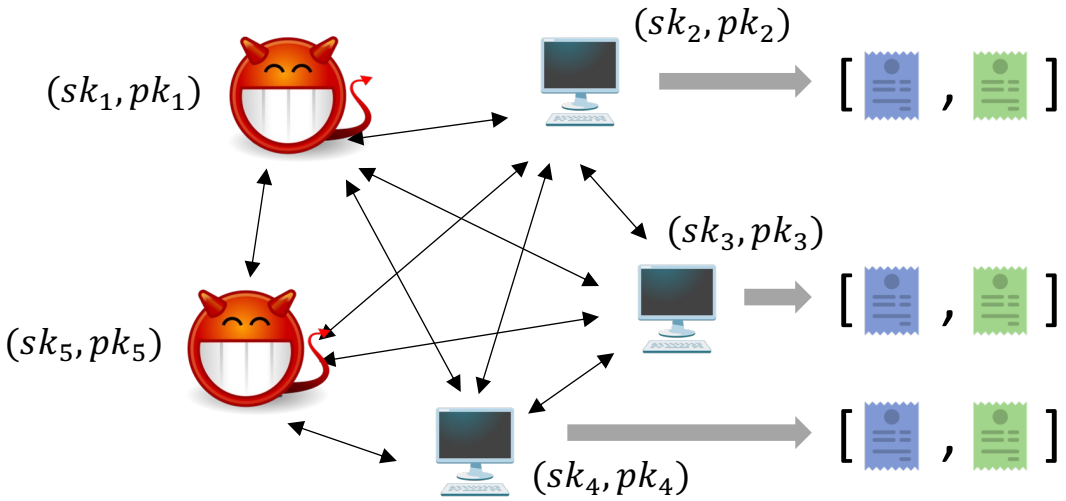

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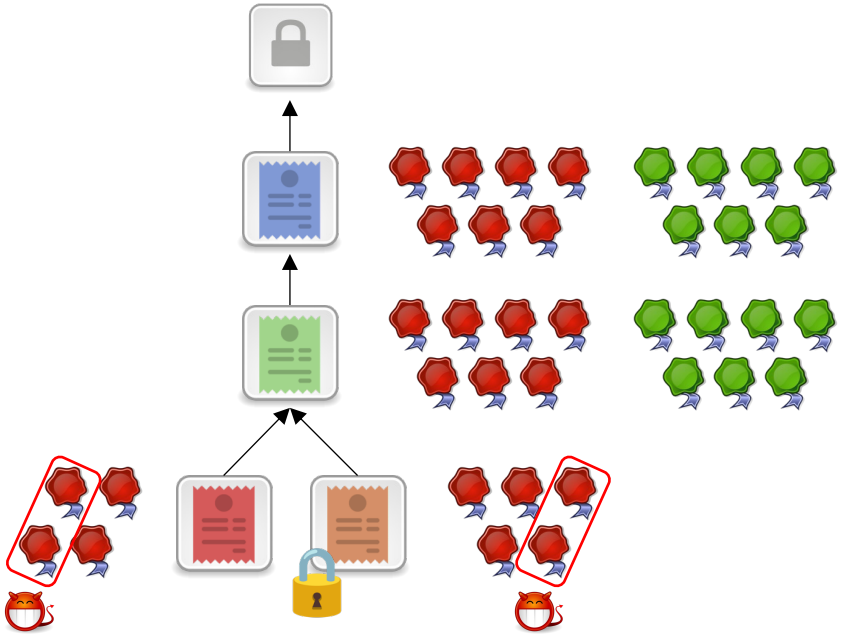

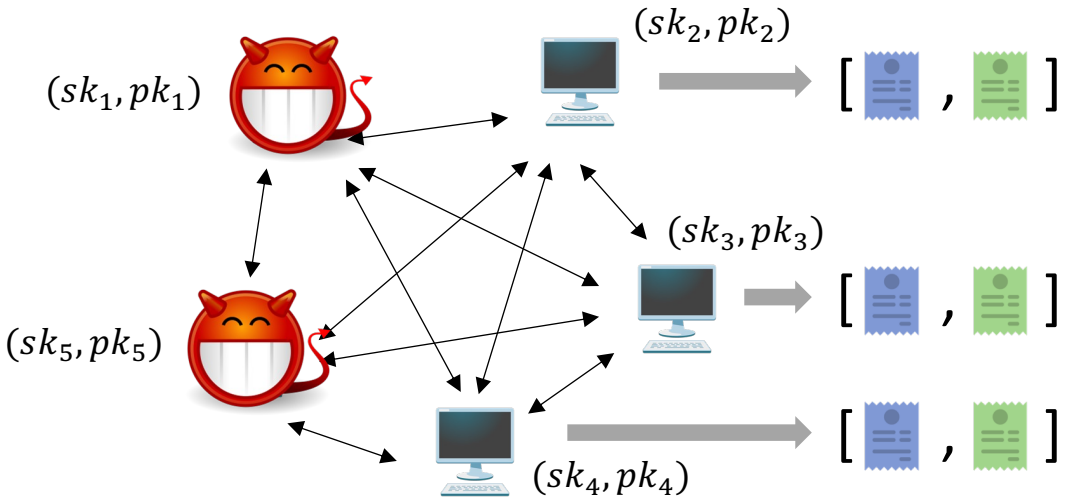

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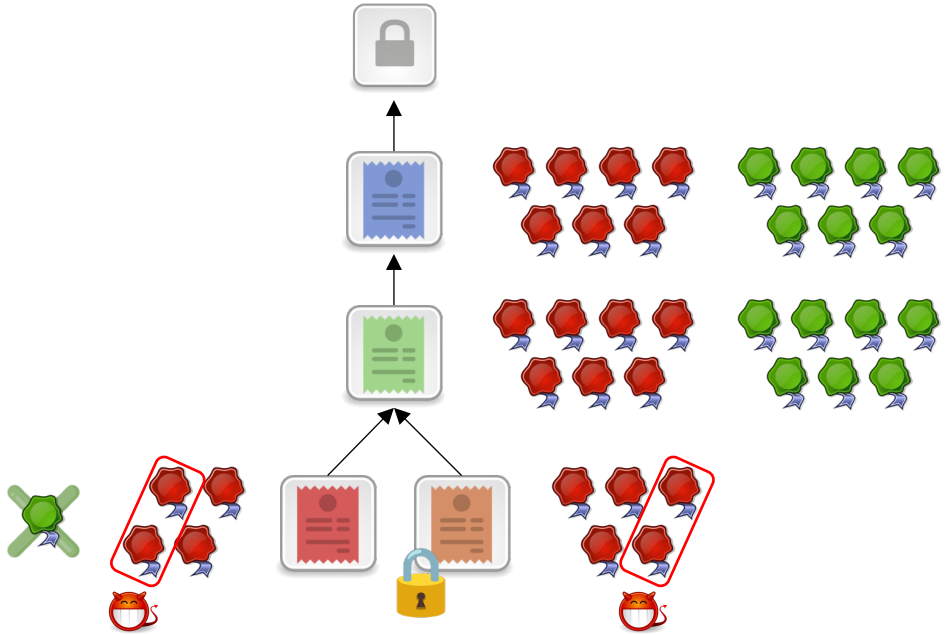

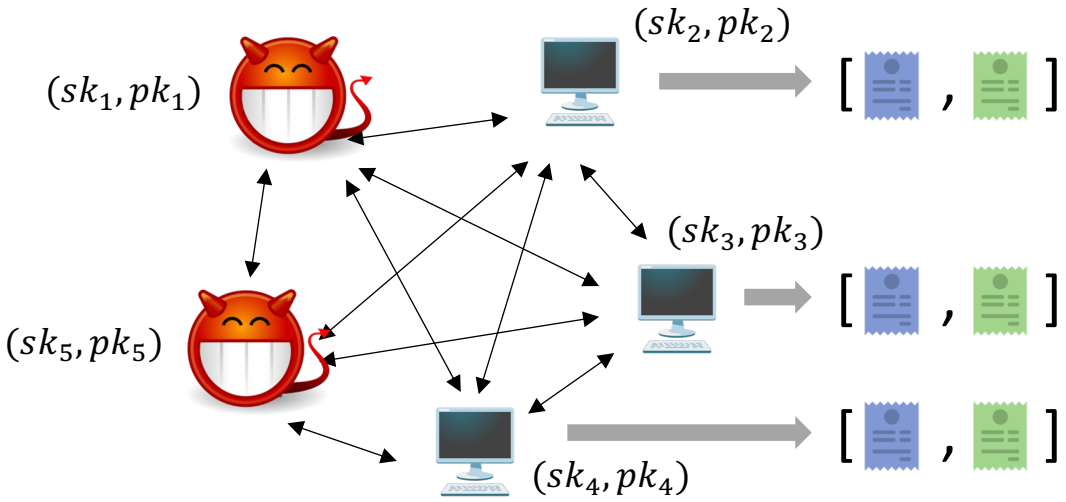

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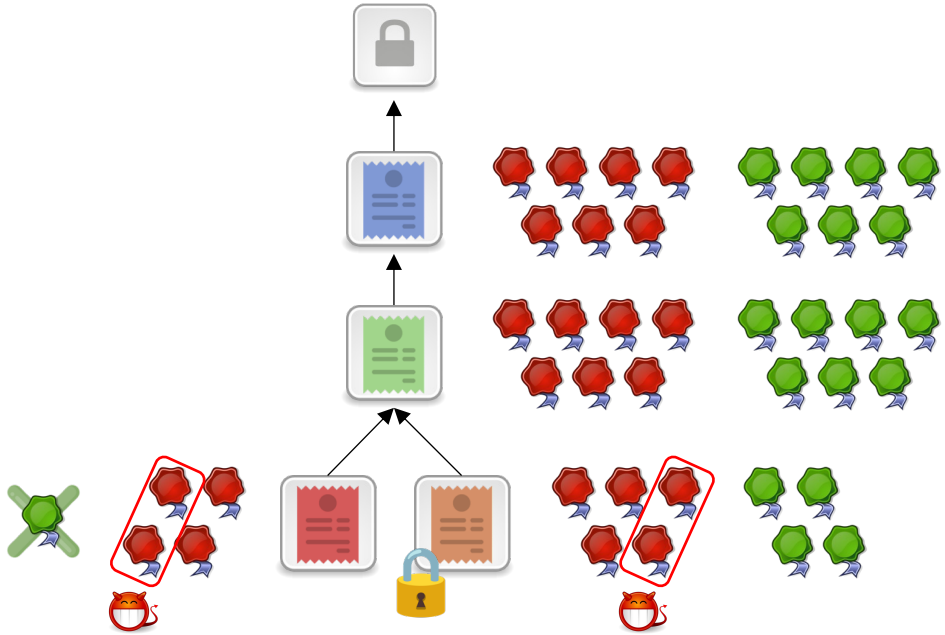

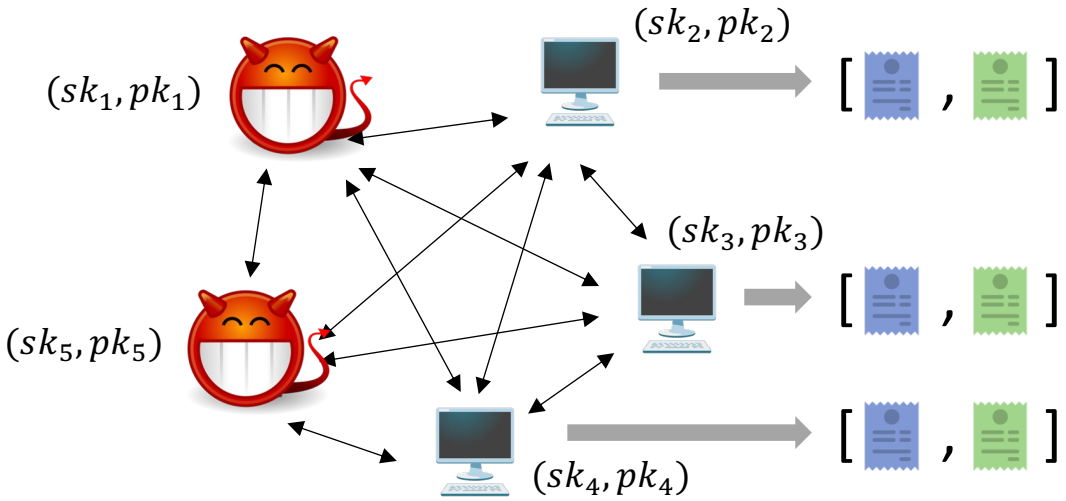

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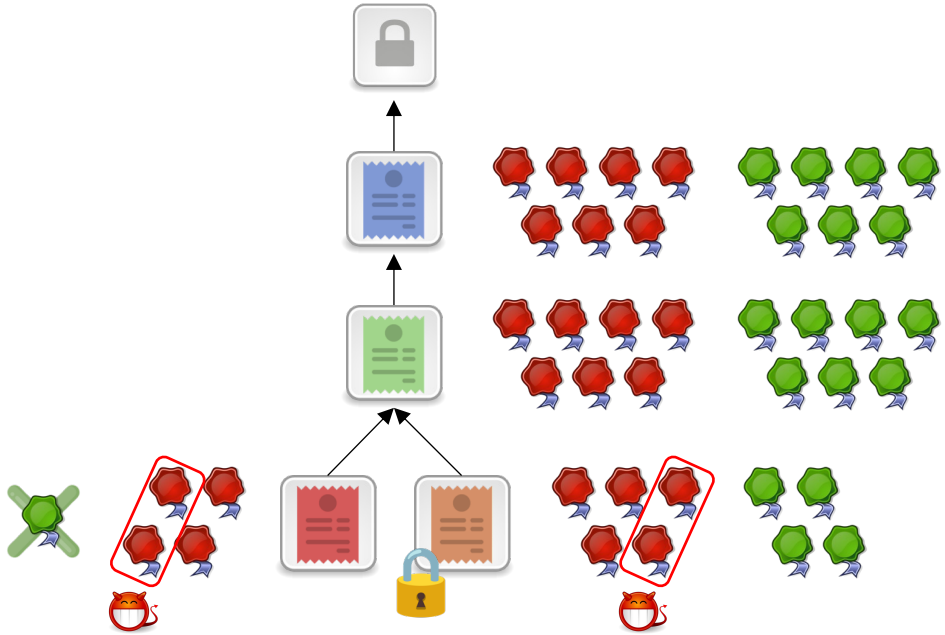

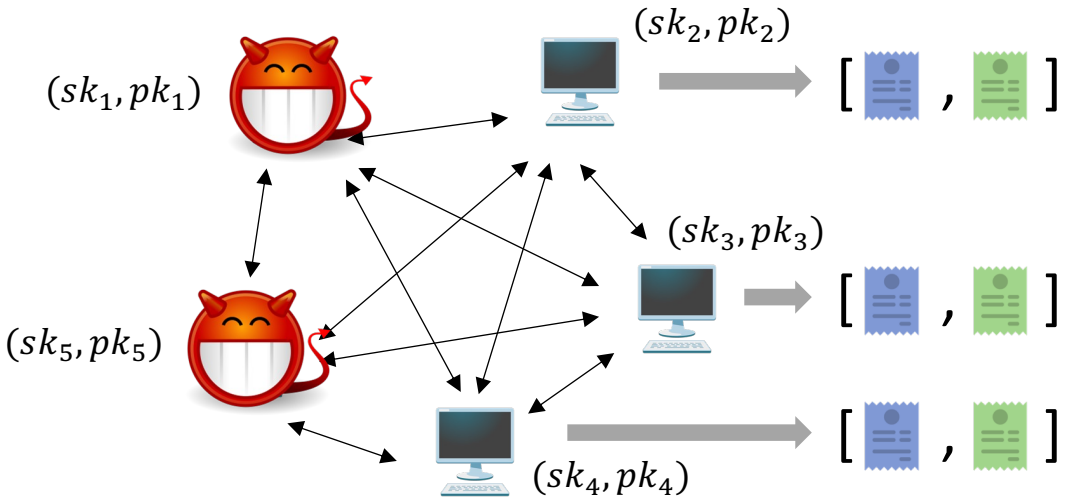

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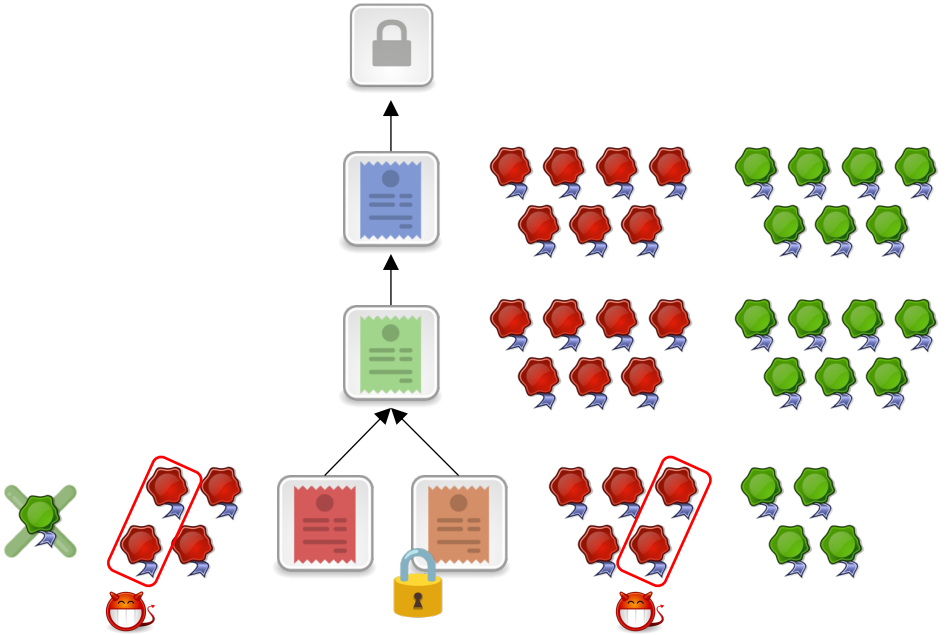

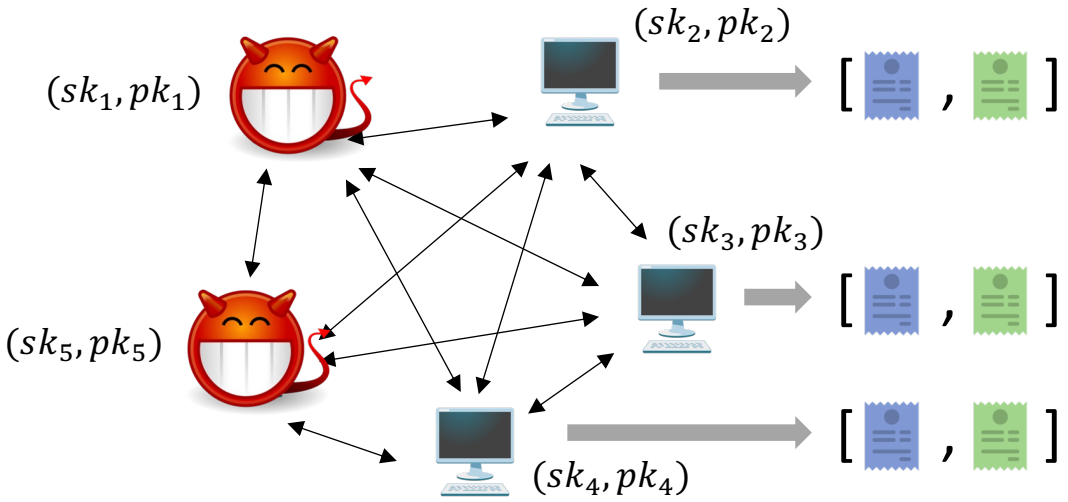

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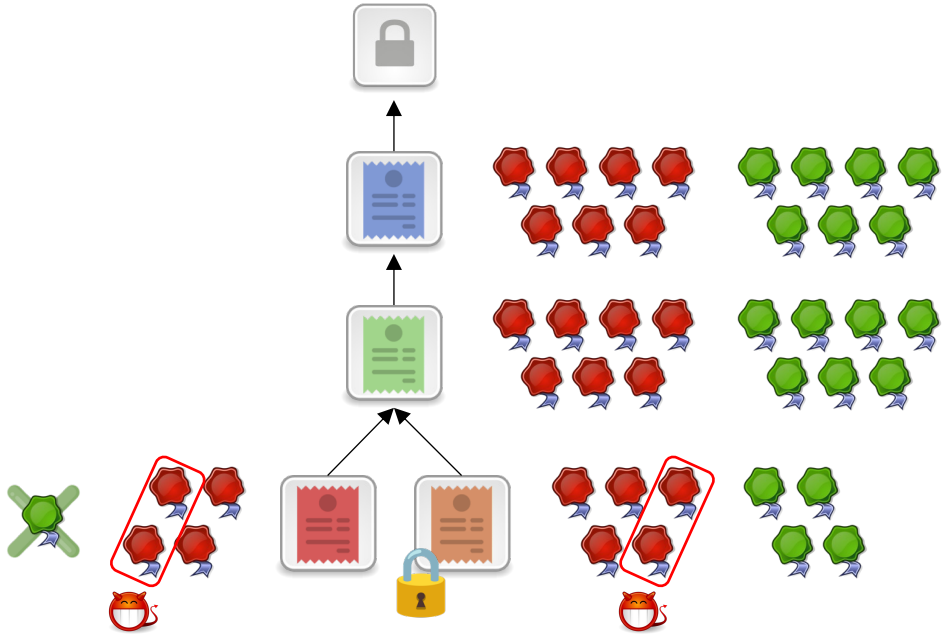

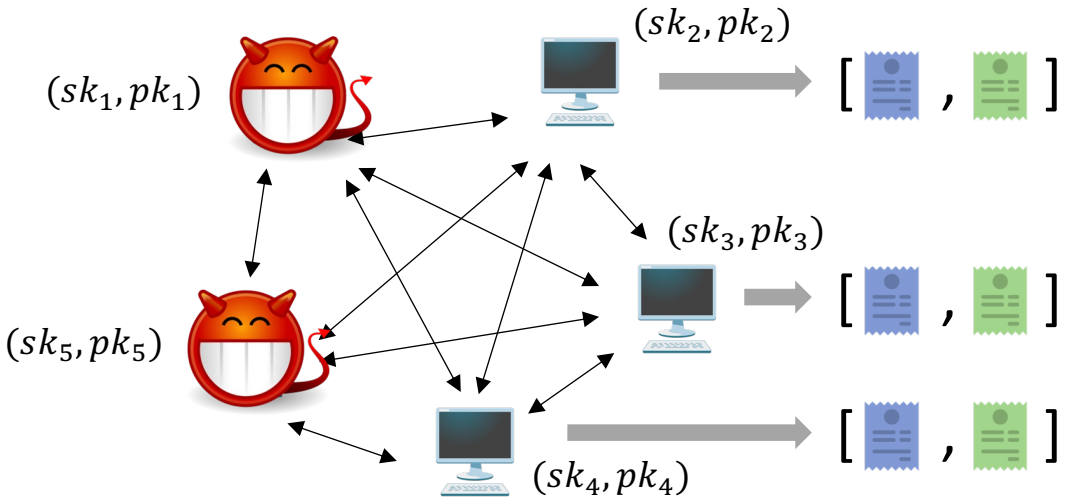

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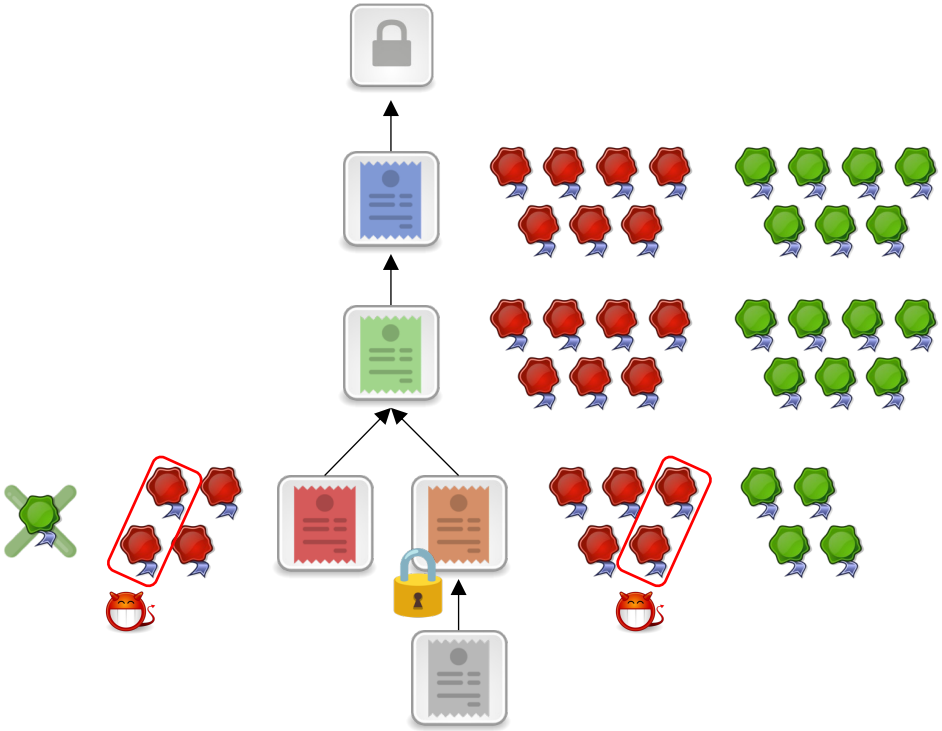

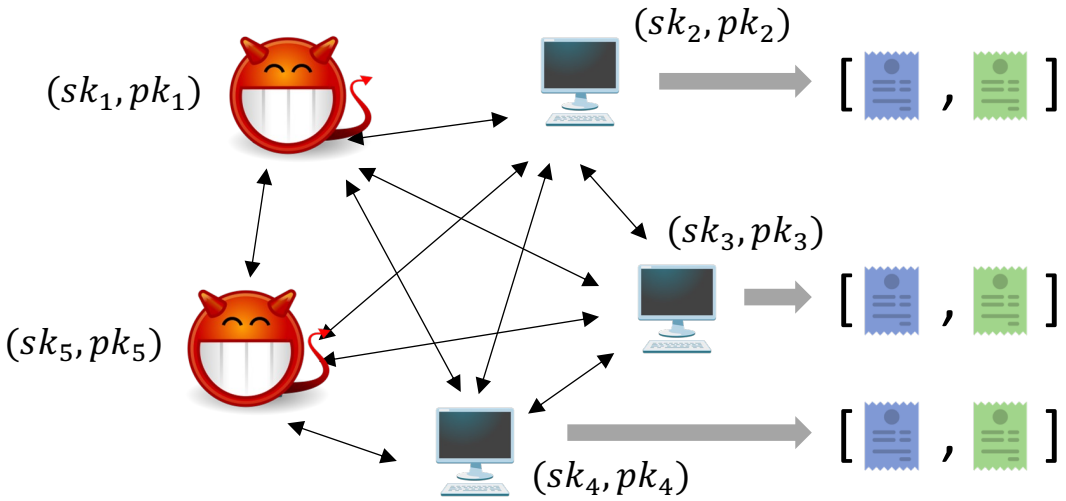

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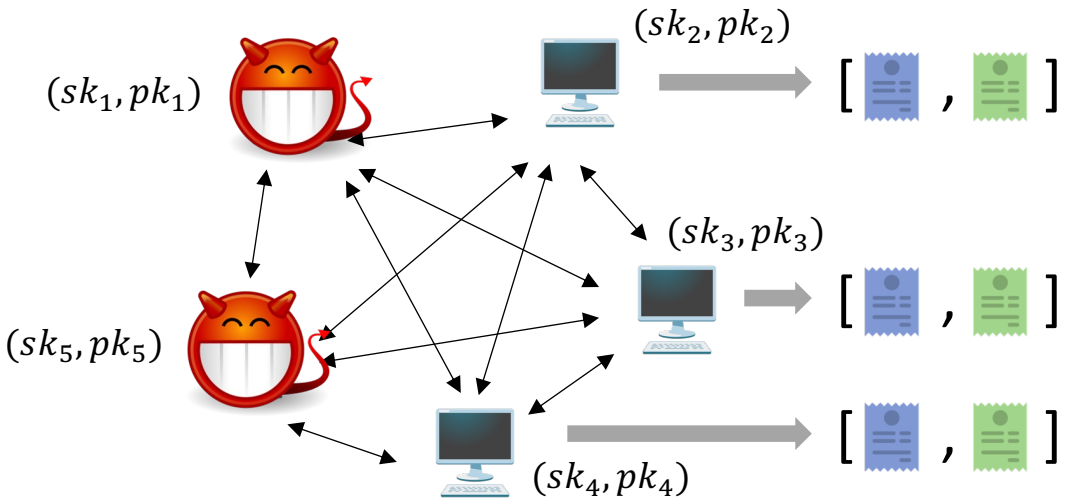

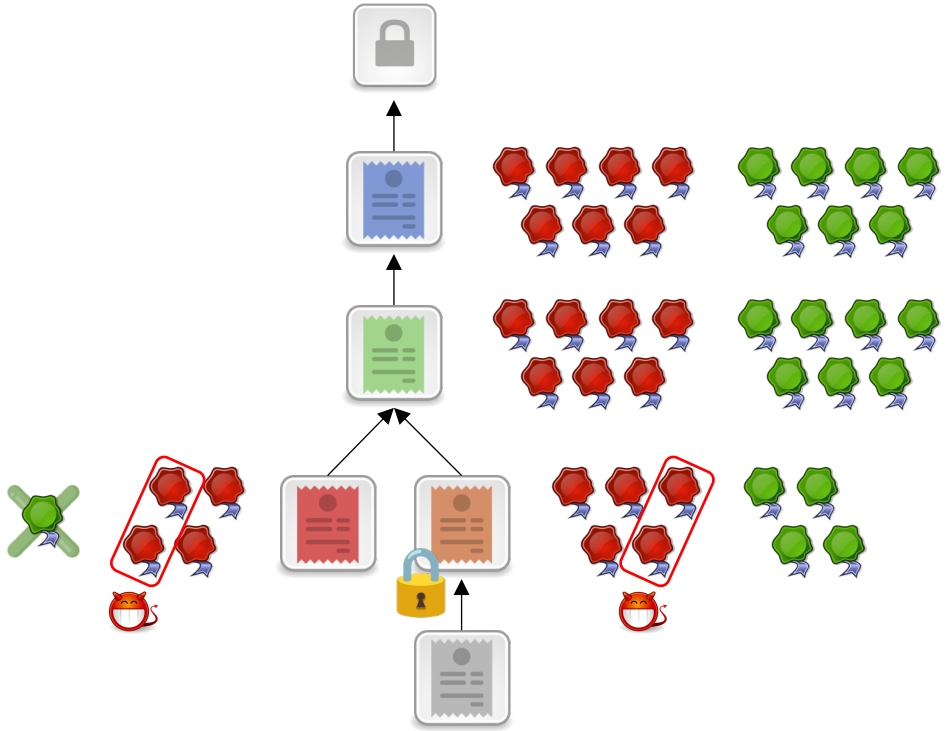

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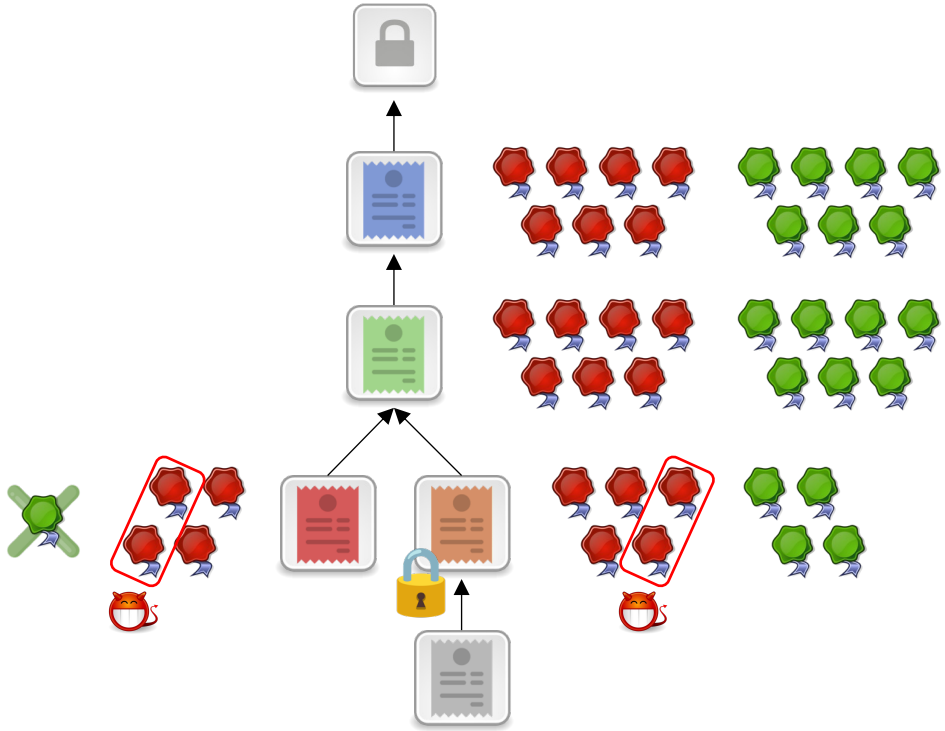

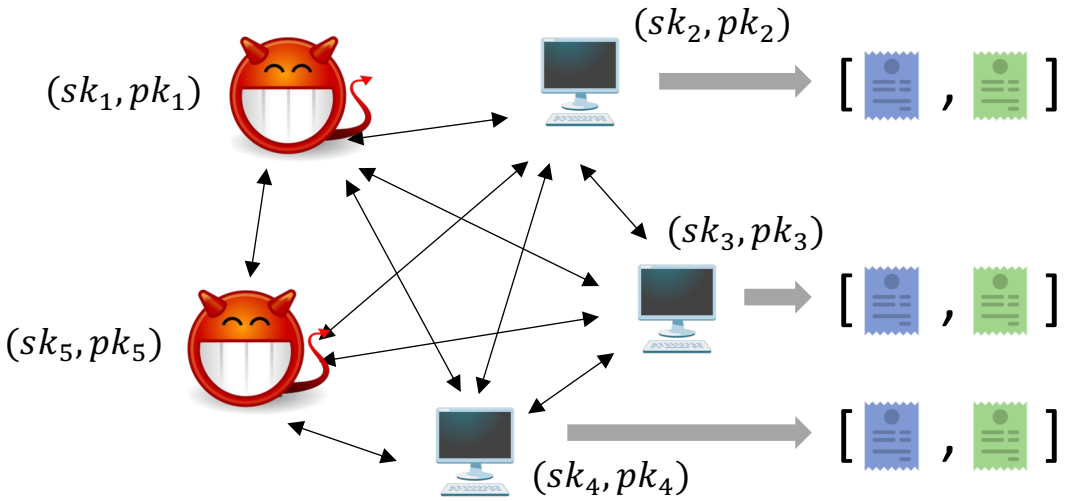

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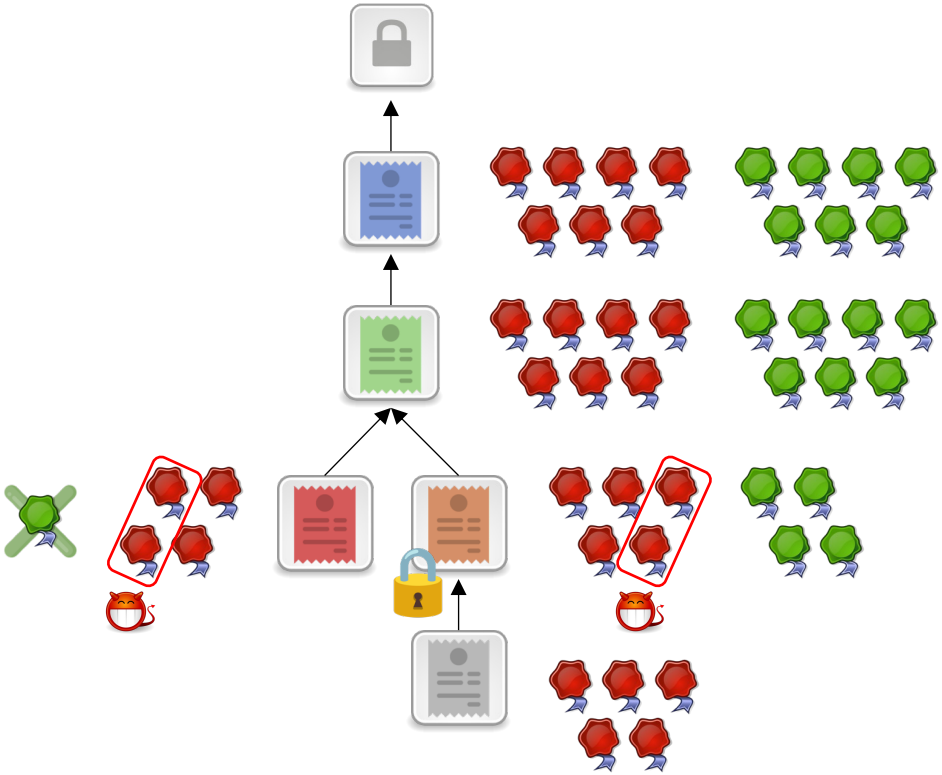

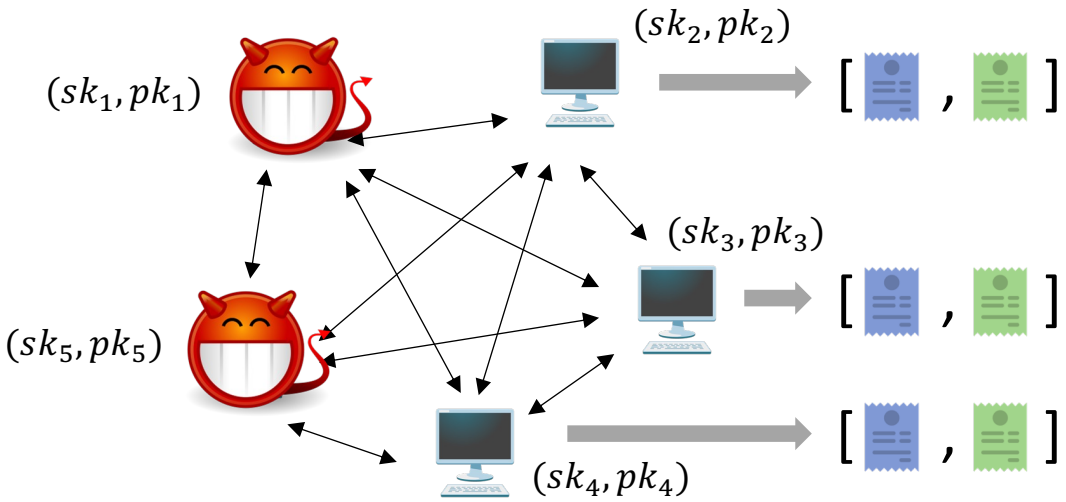

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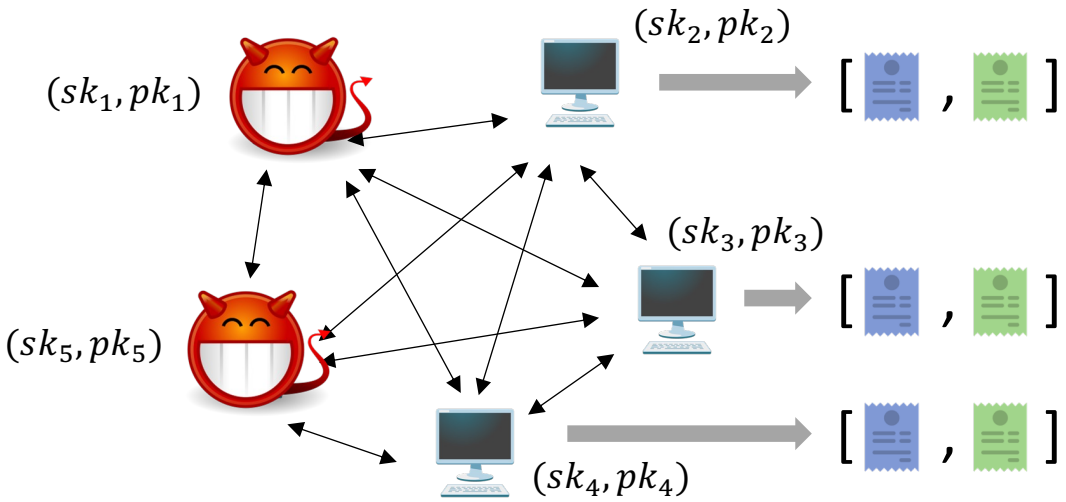

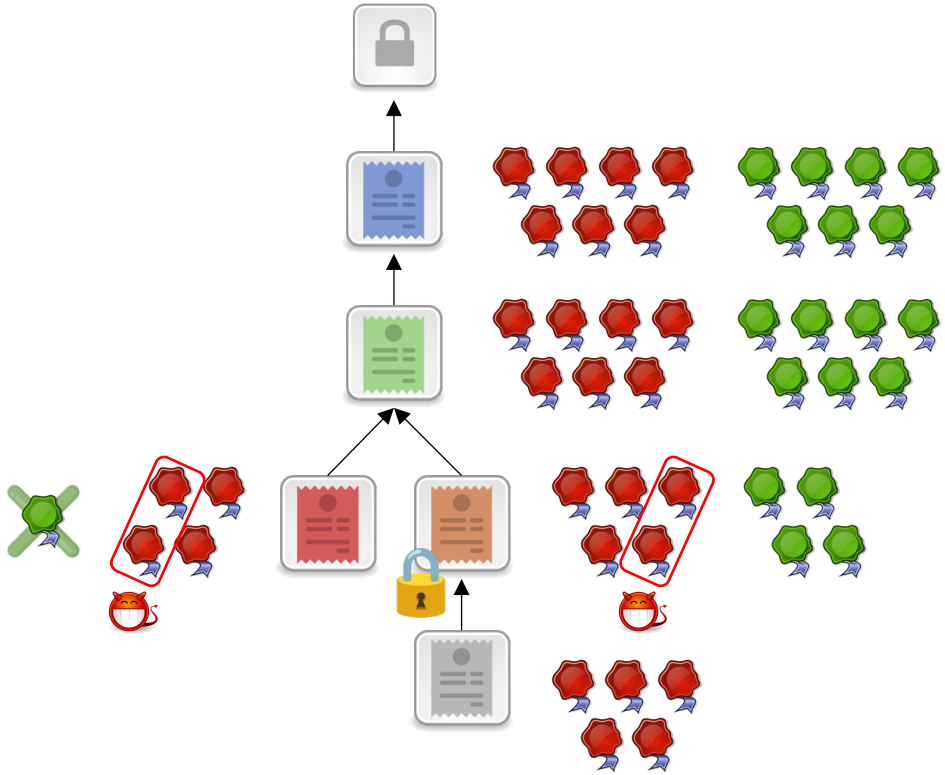

PBFT-Style Consensus

Example: $n = 7, f = 2$ → quorum 5

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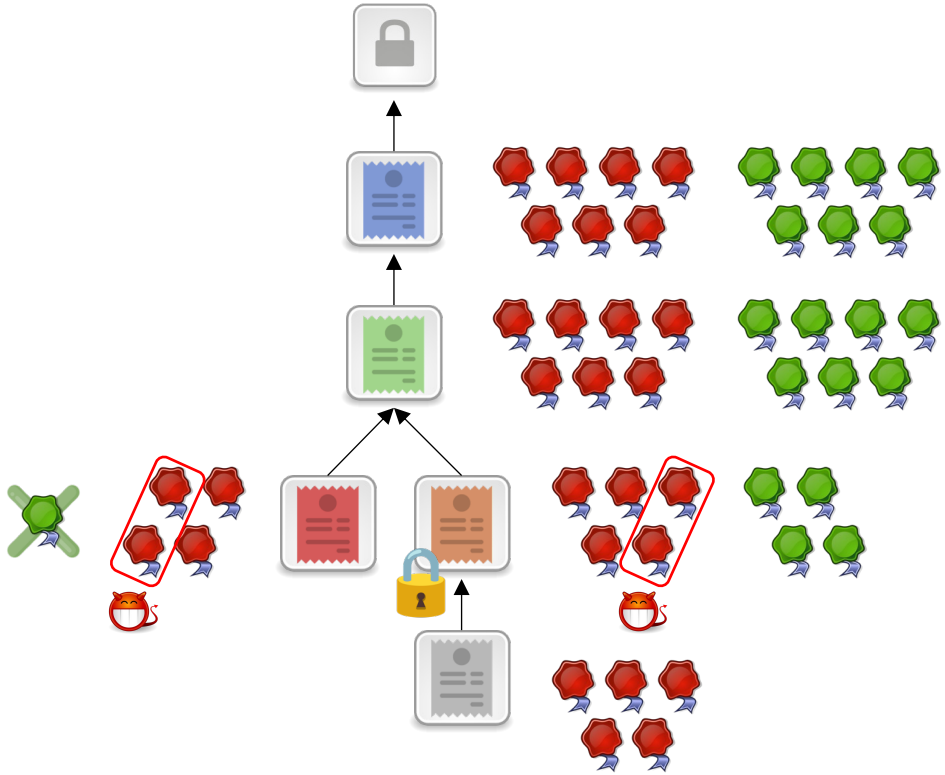

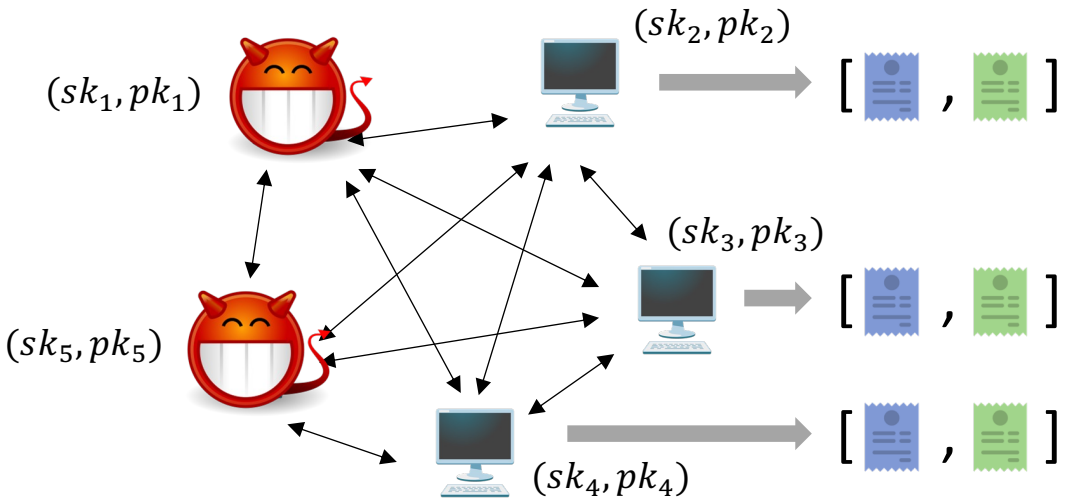

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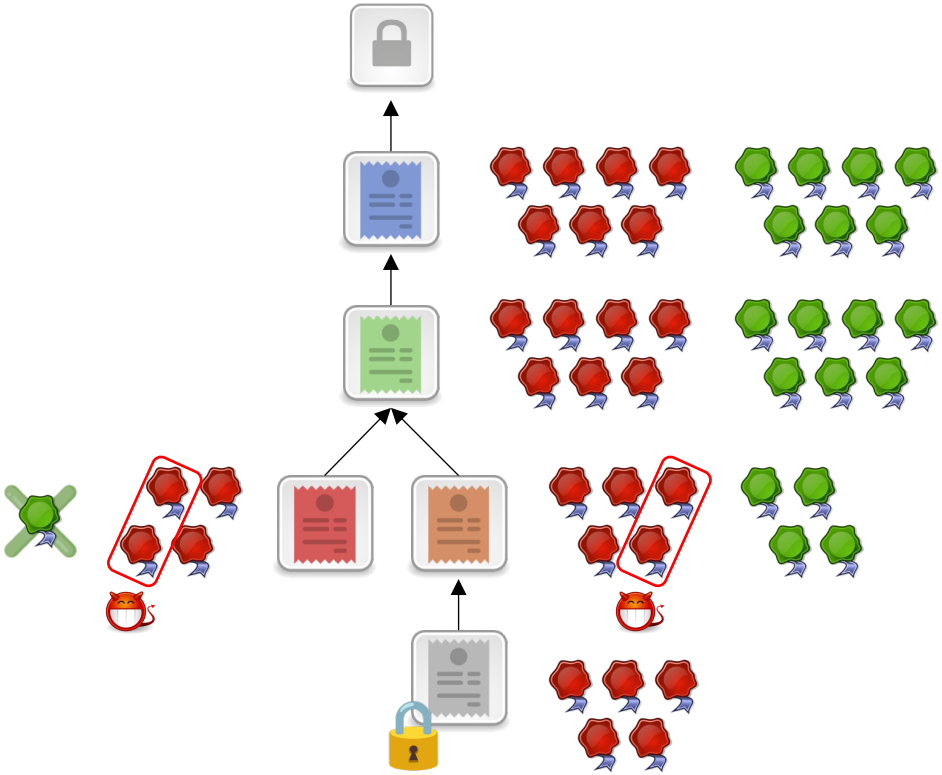

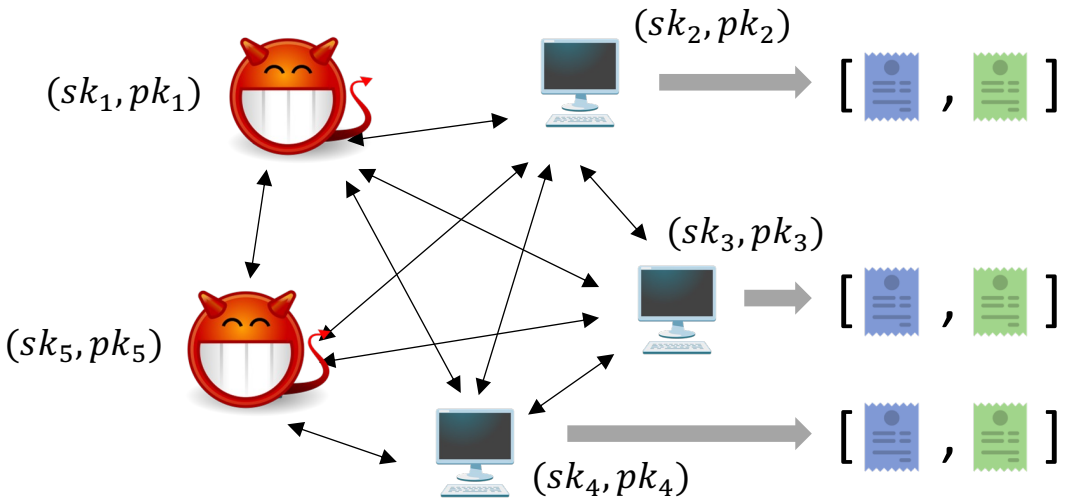

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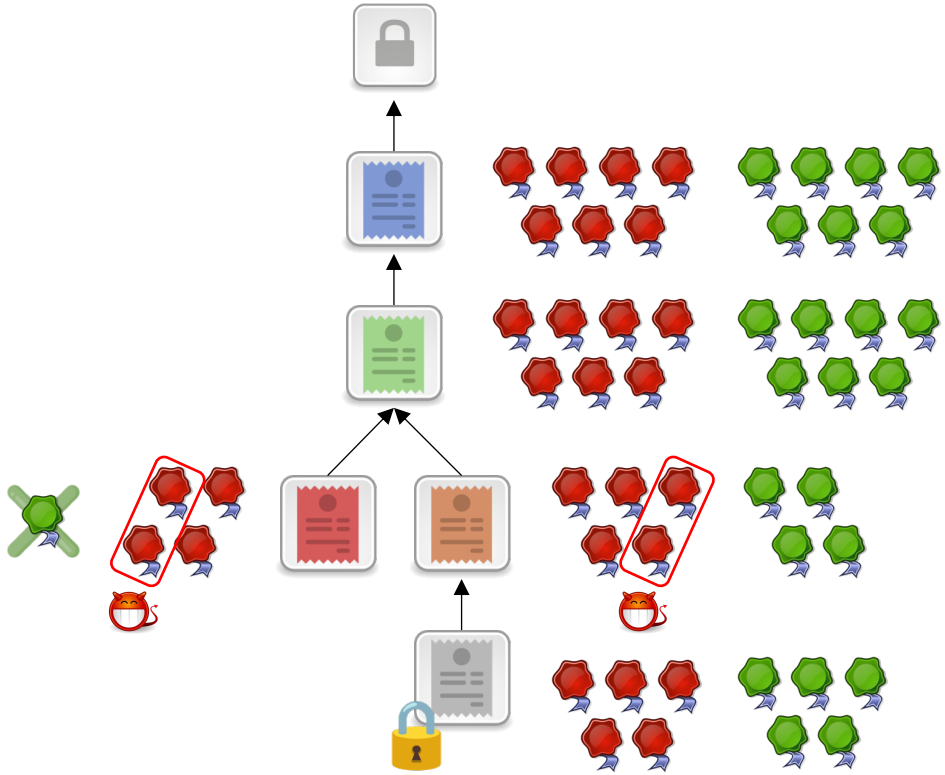

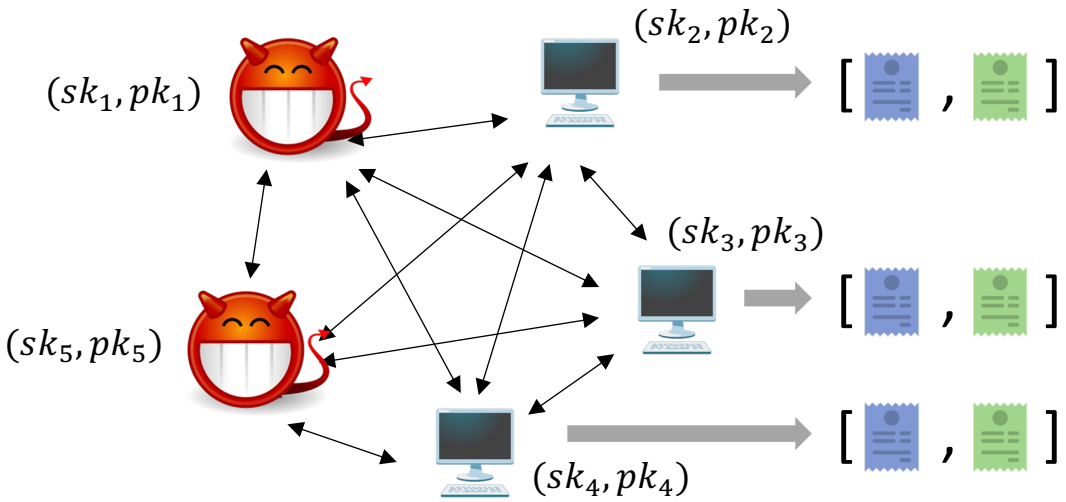

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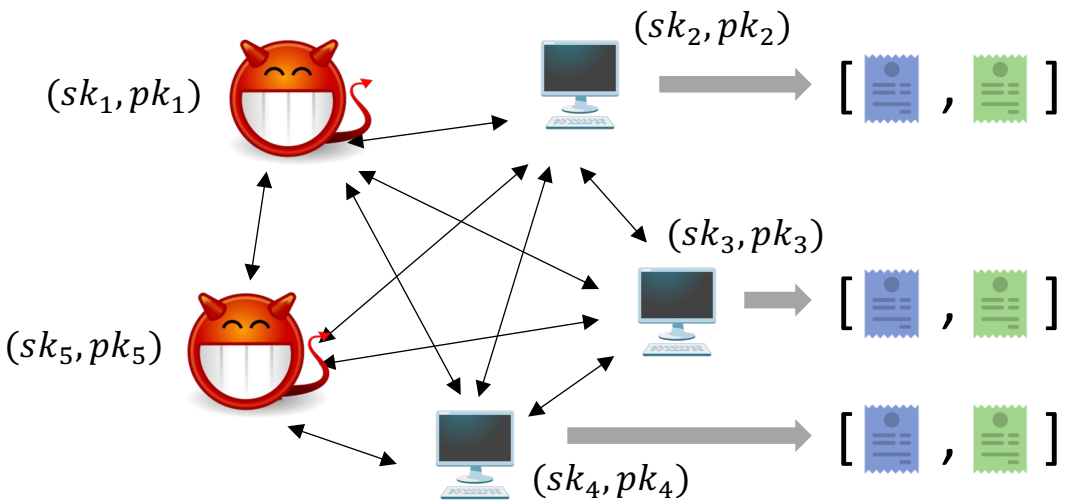

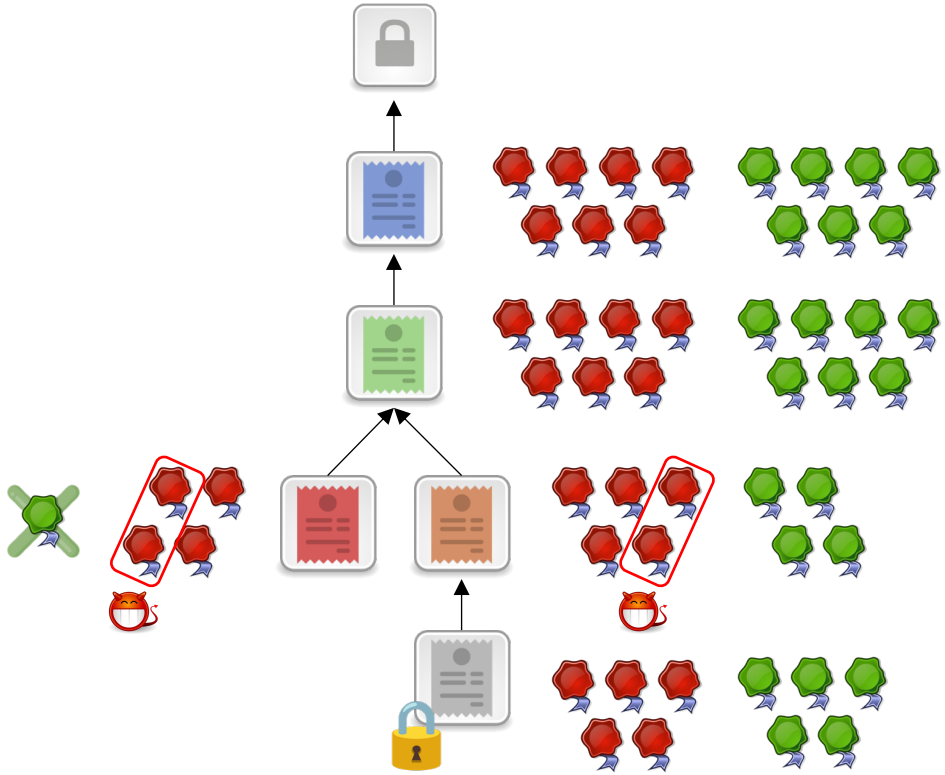

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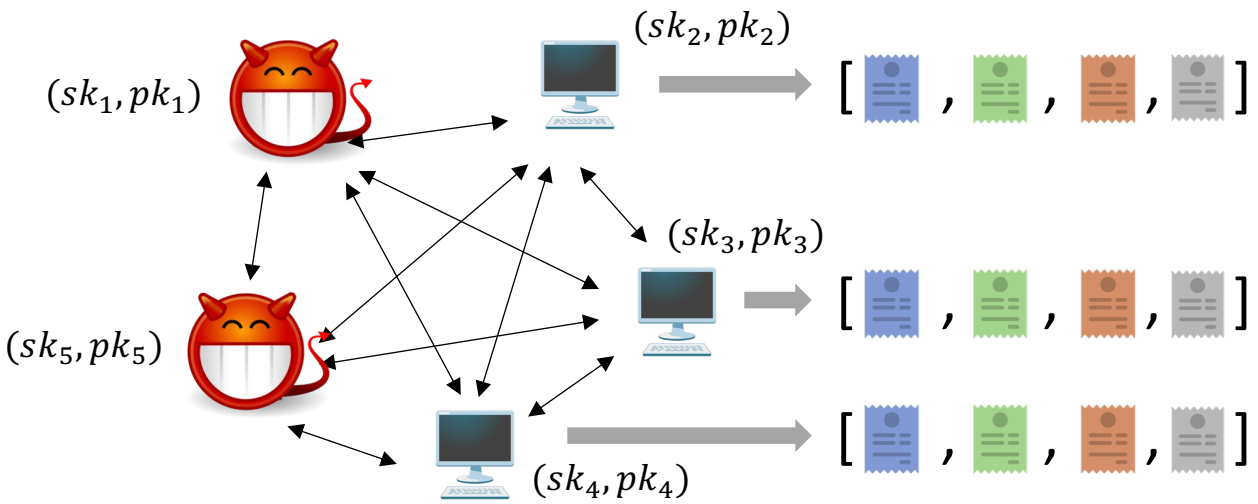

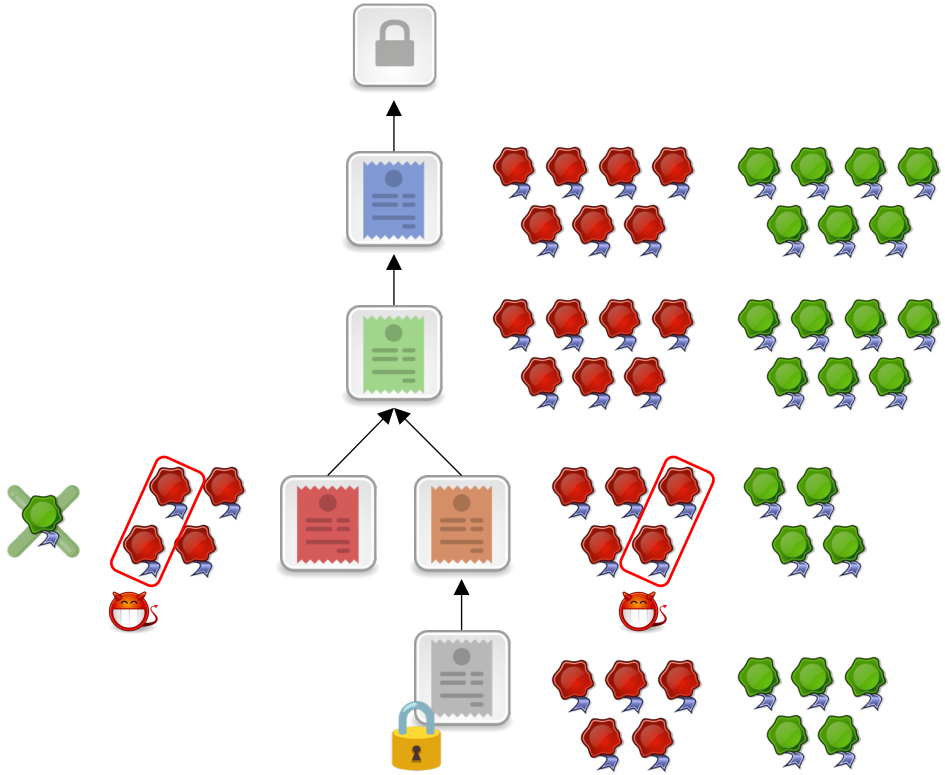

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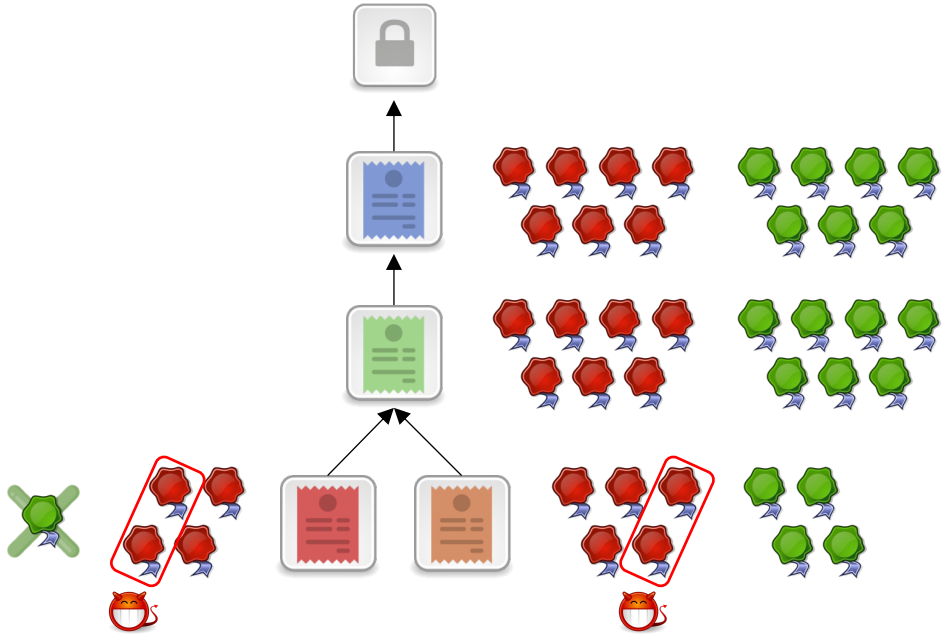

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Safety:

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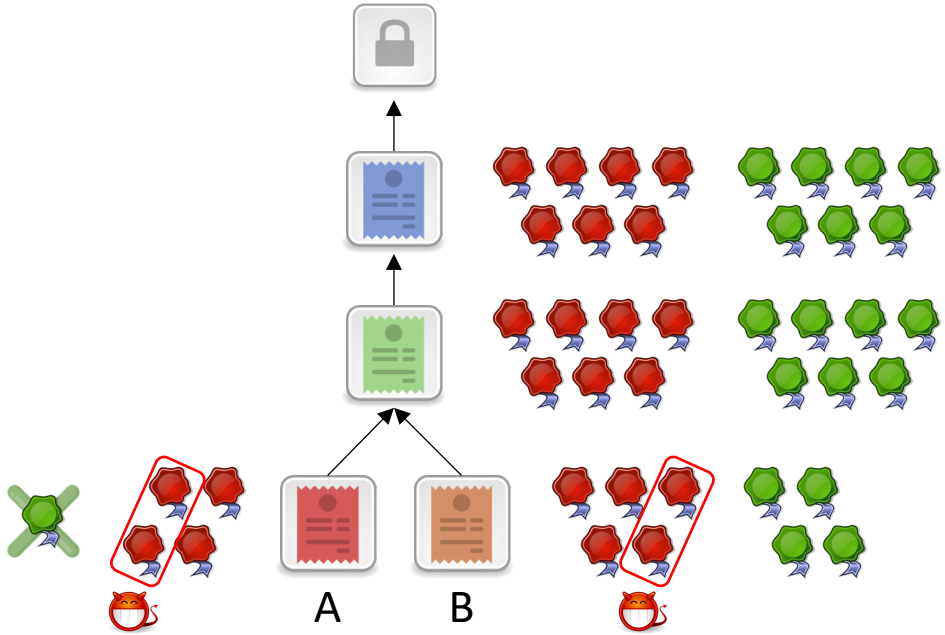

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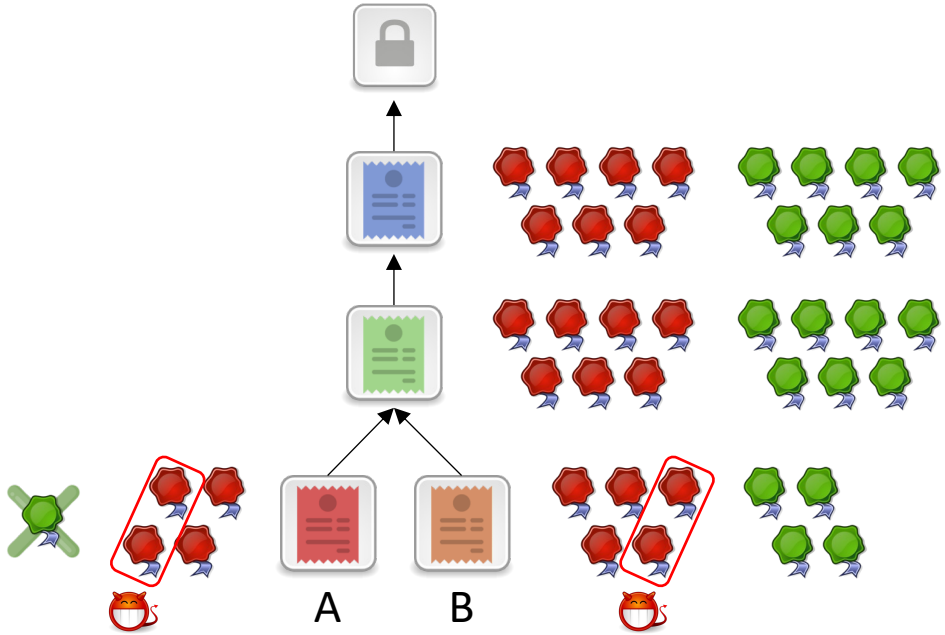

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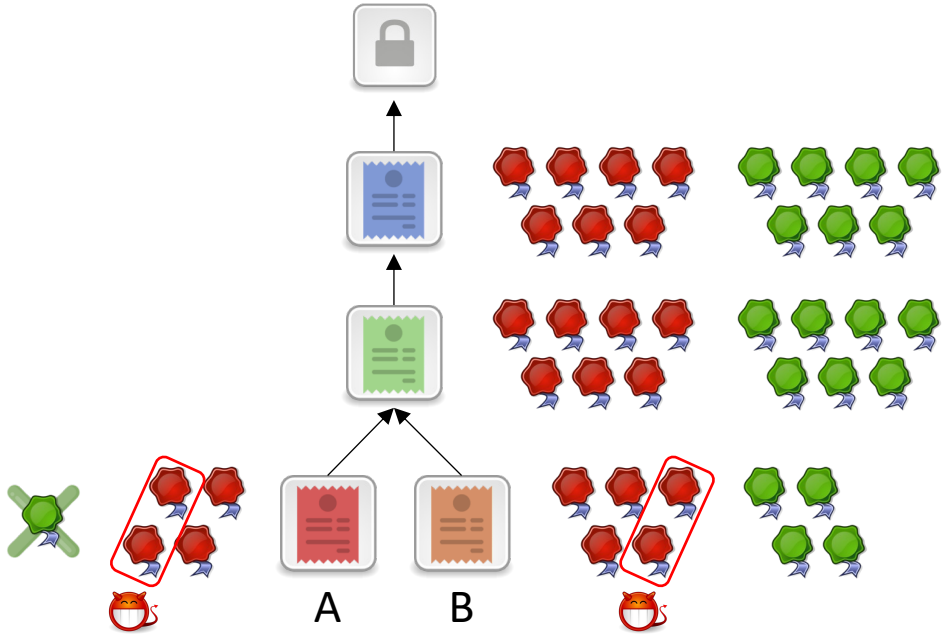

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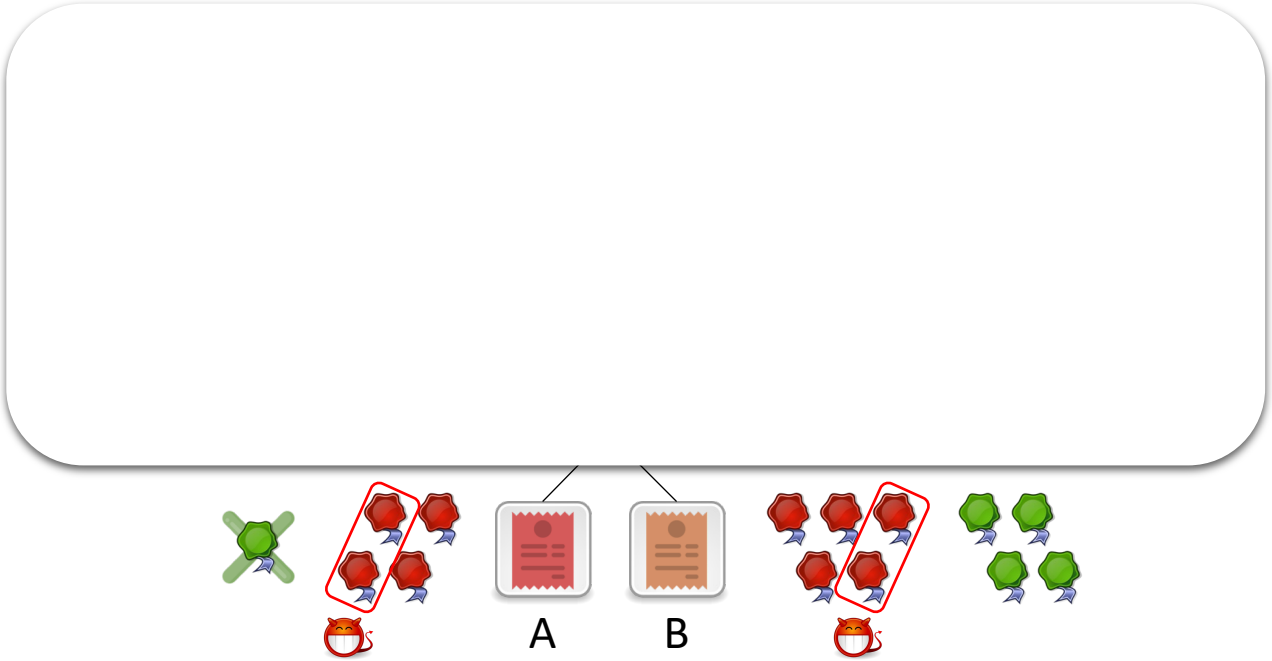

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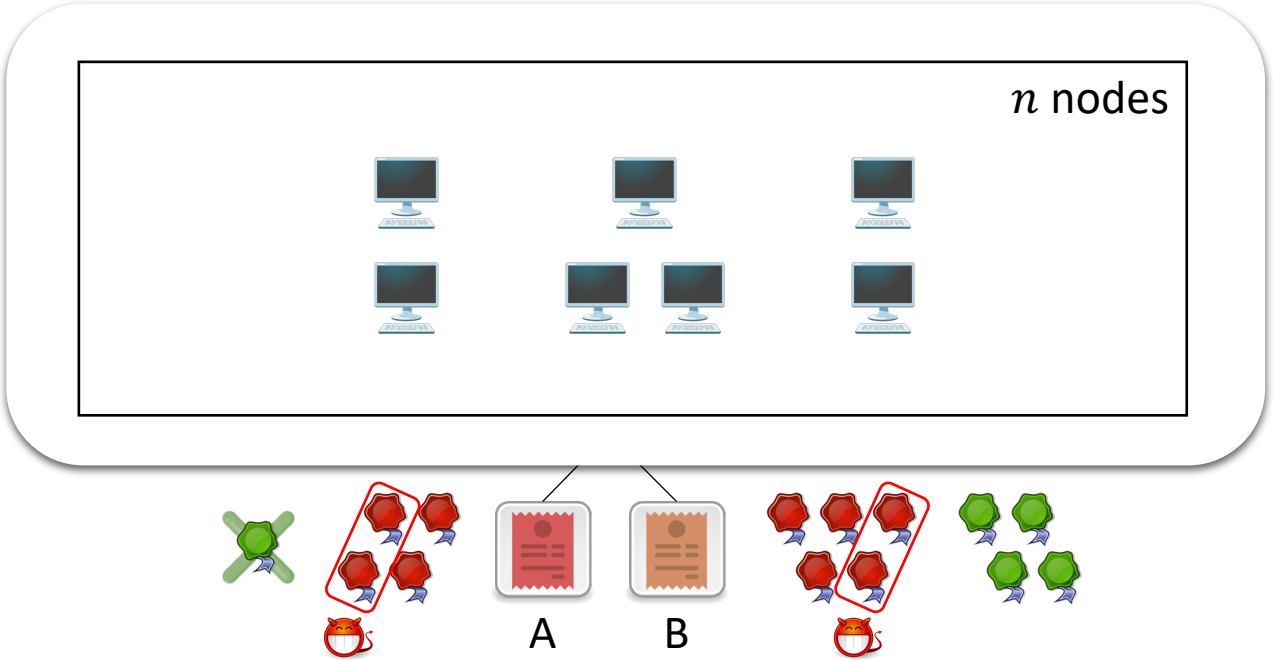

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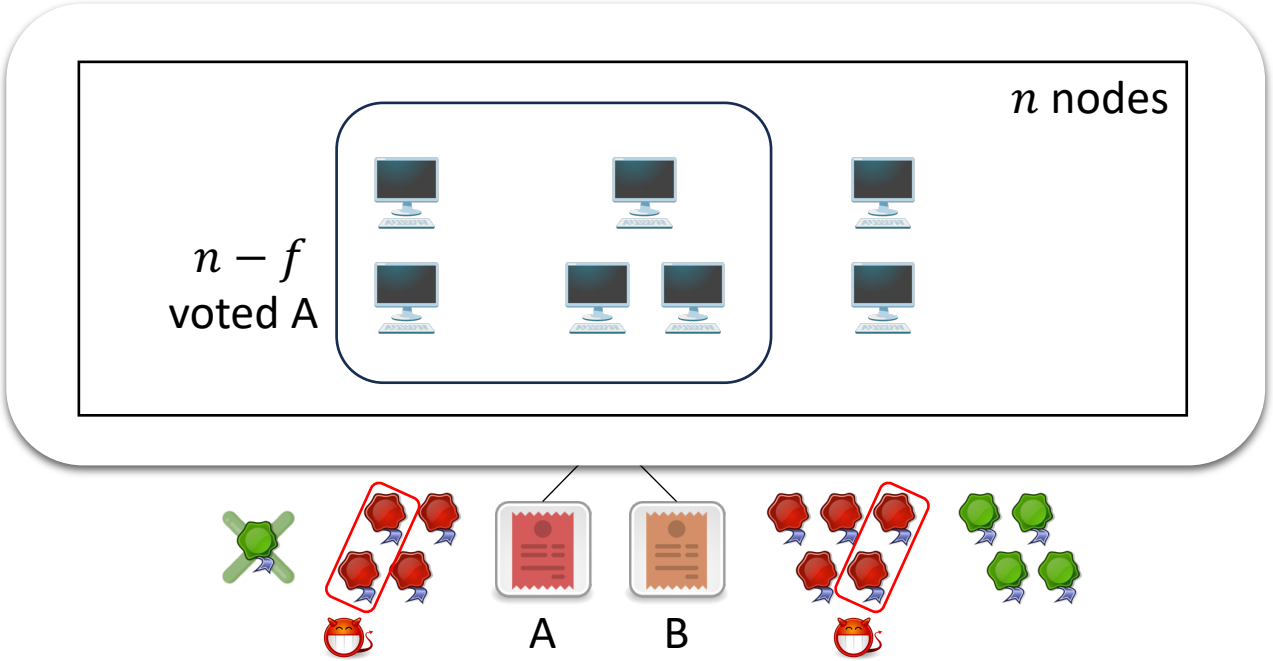

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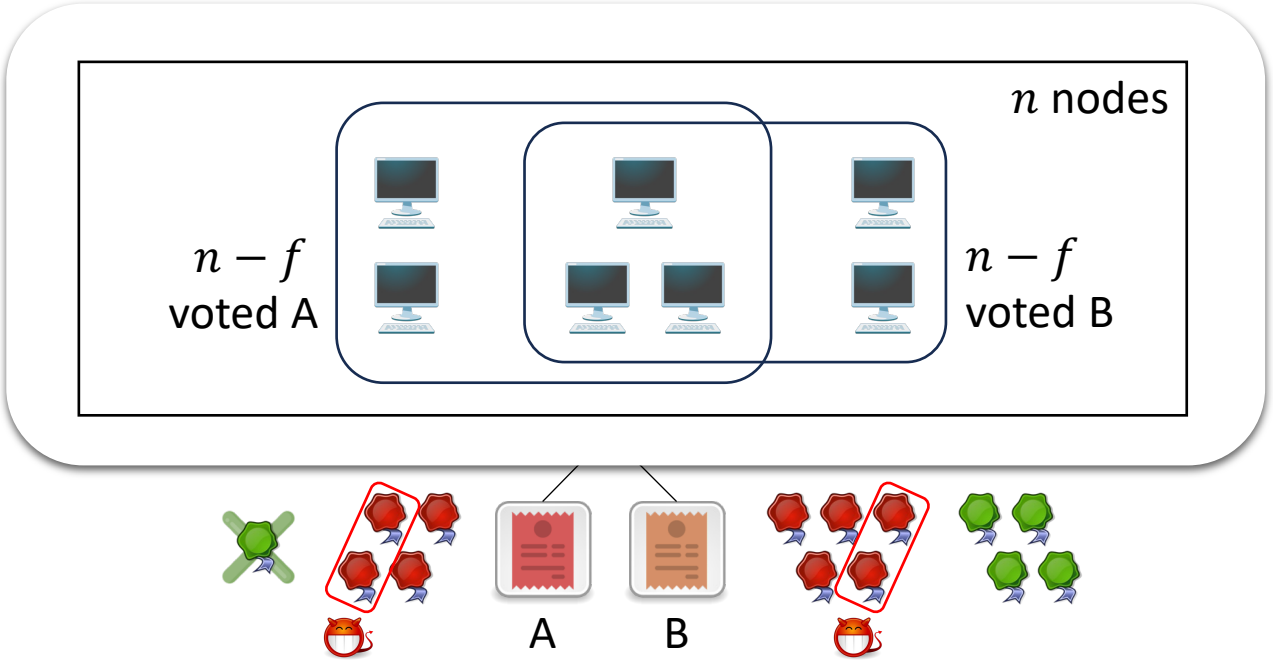

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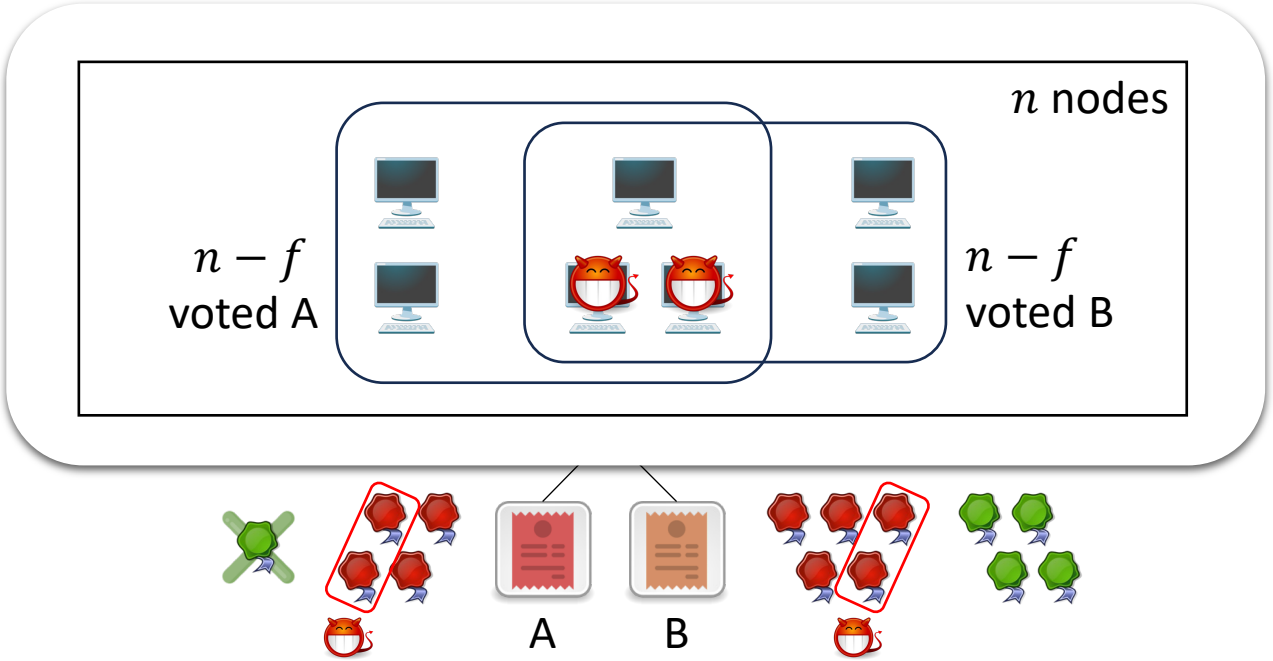
    for first proposal b with $view(Q_{\text{lock}}) \leq view(b.Q)$:
      broadcast $NewVote(b, 1)$
  at time $t = 3\Delta v + 2\Delta$: // all nodes
    for vote-1 quorum Q for proposal b:
      $Q_{\text{lock}} \leftarrow Q$
      broadcast $NewVote(b, 2)$, broadcast Q_{lock}



Liveness:

- Consider v with $3\Delta v \geq GST + \Delta$ and honest leader.
- Proposal b satisfies $view(Q_{\text{lock}}) \leq view(b.Q)$ for all honest nodes. → All honest nodes vote-1 for b.
- All honest nodes see a vote-1 quorum for b.
  → All honest nodes vote-2 for b.
- → Honest proposal b gets confirmed.

Safety:

- Only one vote-1 per honest node. Assume $n > 3f$.
- For contradiction, suppose both A and B confirmed …
- → At least $n - 2f > f$ nodes 1-voted both A and B.
- → An honest node 1-voted both A and B.
- Contradiction! → No conflicting blocks confirmed!

Security

$Q_{\text{lock}} \leftarrow \{\}$
for view $v = 1,2,3, \ldots$:
  at time $t = 3\Delta v + 0\Delta$: // only leader of view v
    $(b, Q) \leftarrow$ block with vote-1 quorum for highest view
    broadcast $NewBlock(v, b, Q, GetPendingTxs())$
  at time $t = 3\Delta v + 1\Delta$: // all nodes
    for first proposal b with $view(Q_{\text{lock}}) \leq view(b.Q)$:
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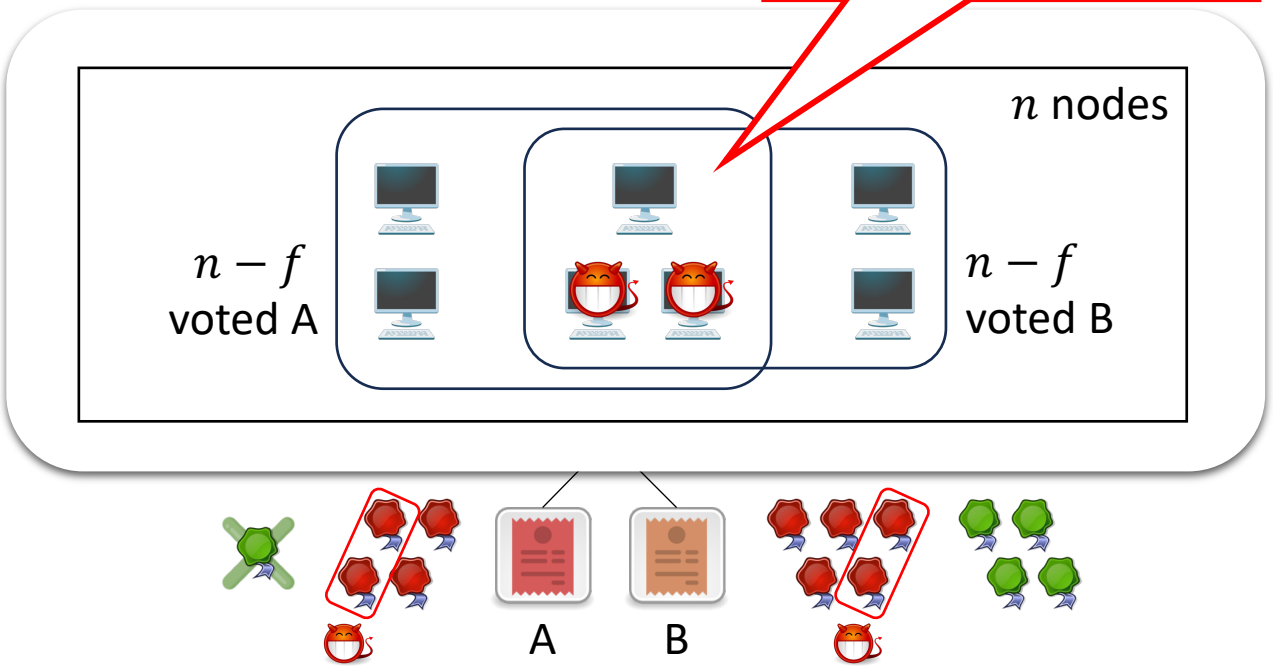
Example: $n = 7, f = 2 \rightarrow$ quorum 5

"Quorum intersection argument"



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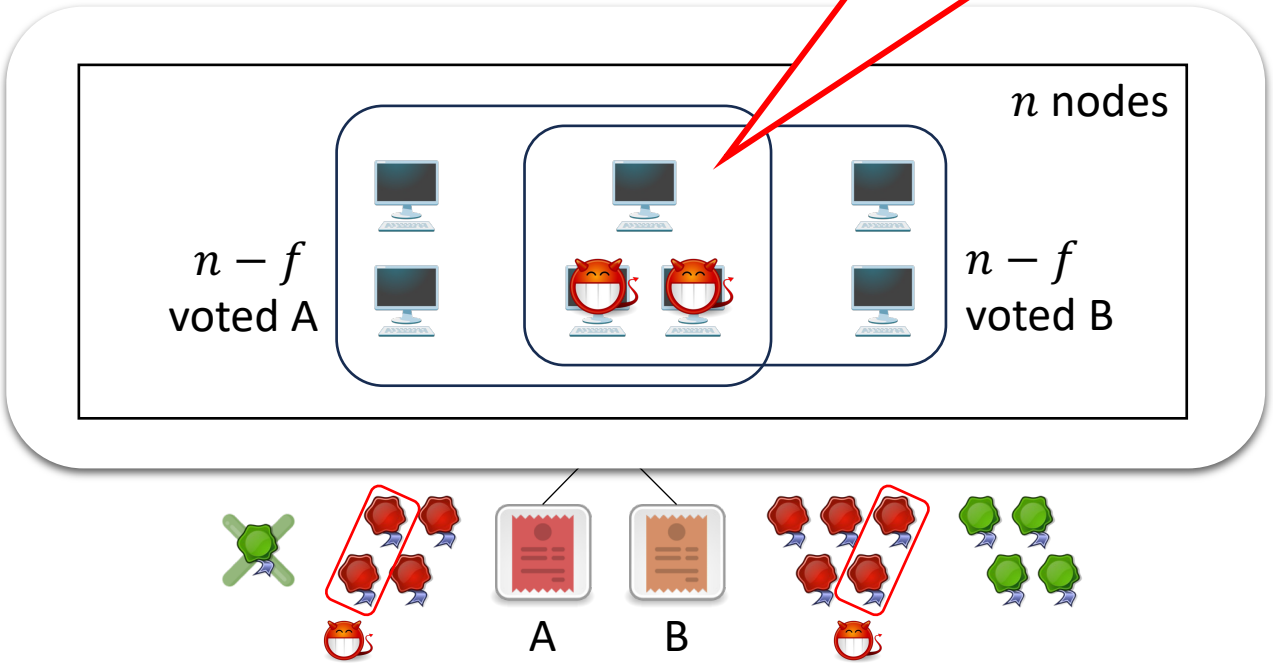

Liveness:

- Consider v with $3\Delta v \geq GST + \Delta$ and honest leader.
- Prop… …ll hone…
- All h… → A…
- → Honest proposal b gets confirmed.

For pedagogy, only considered conflicting blocks from same view. Extension to conflicting blocks from other views requires reasoning with vote-1, vote-2, and lock.

Safety:

- Only one vote-1 per honest node. Assume $n > 3f$.
- For contradiction, suppose both A and B confirmed …
- → At least $n - 2f > f$ nodes 1-voted both A and B.
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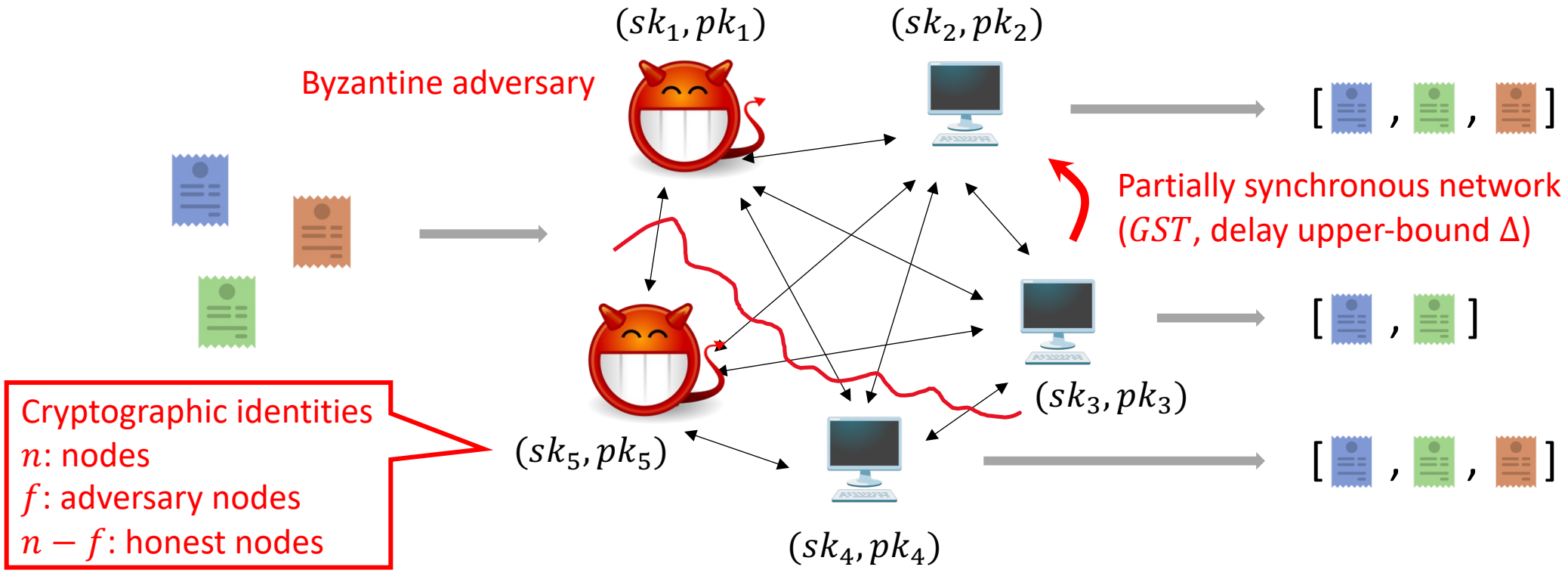
SMR Example 2: Permissioned PBFT-Style Consensus



Theorem

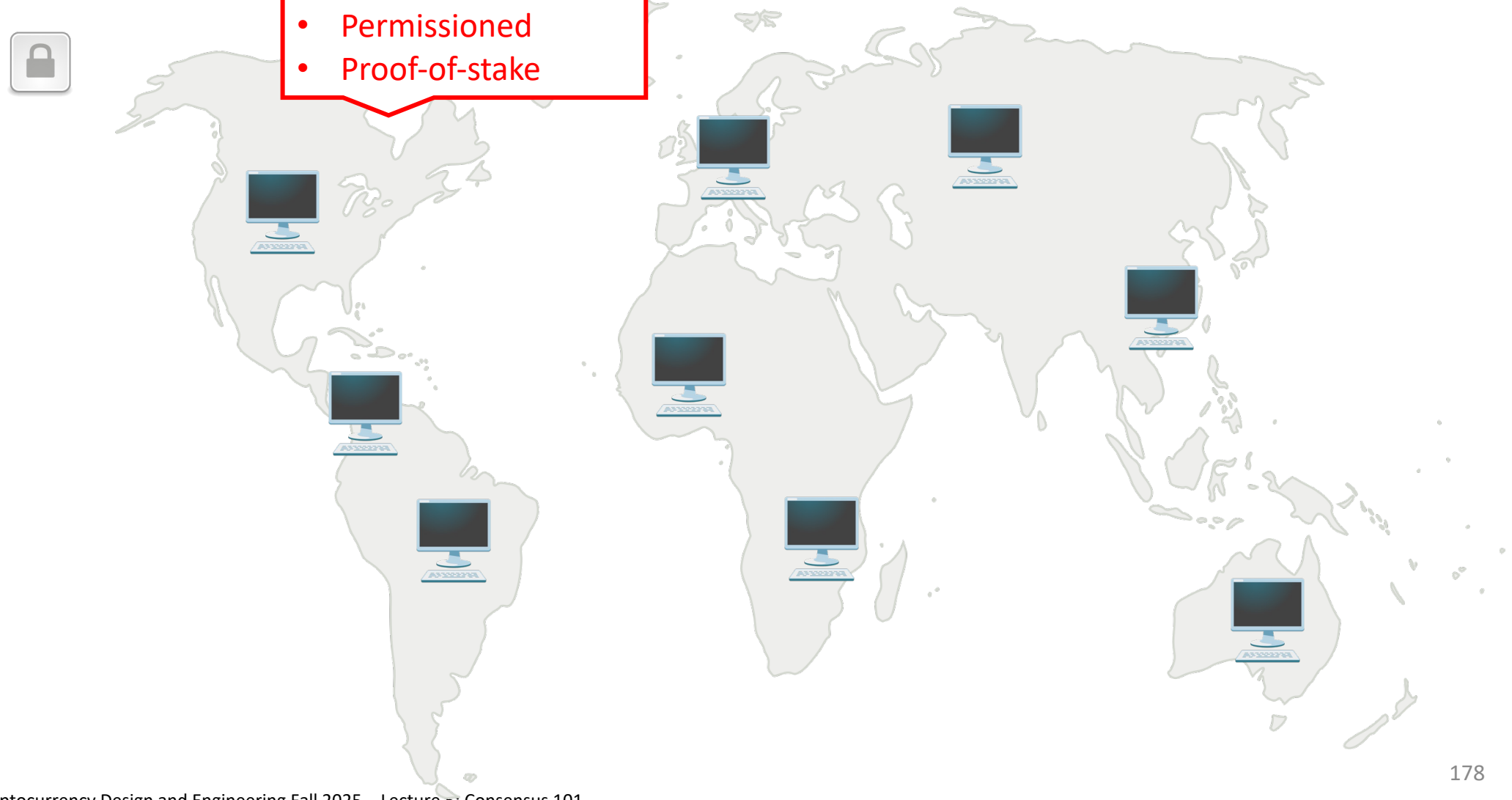
PBFT-style consensus is safe and live iff $f < n/3$, under partial synchrony.

SMR Example 3: Flexible Consensus

Combination of **Example 1: Nakamoto consensus** and **Example 2: PBFT-style consensus**

Nakamoto Consensus: Dynamically Available

- Proof-of-work
- Permissioned
- Proof-of-stake



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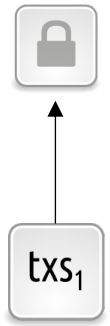

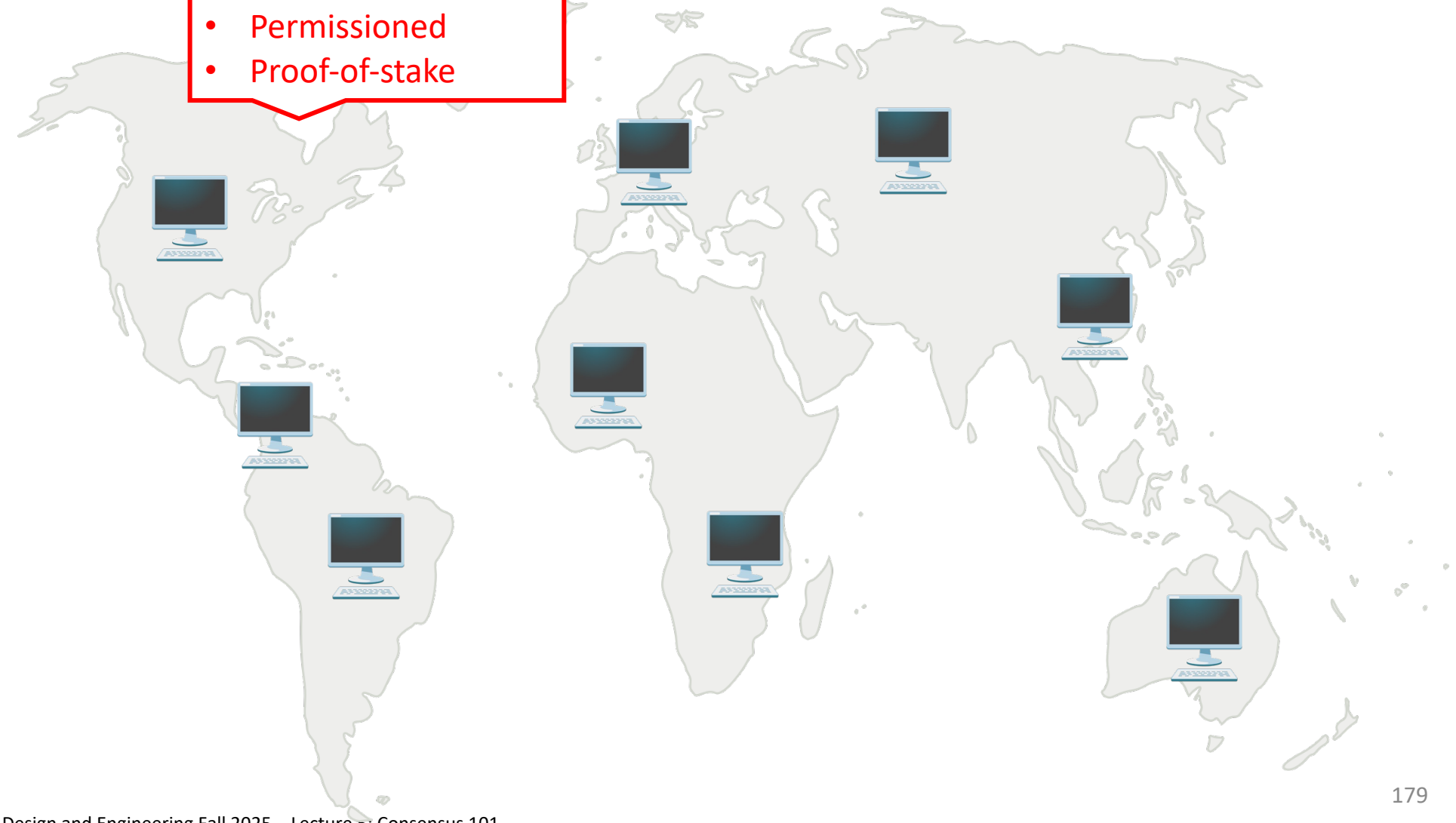

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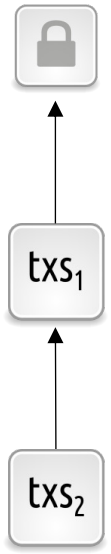

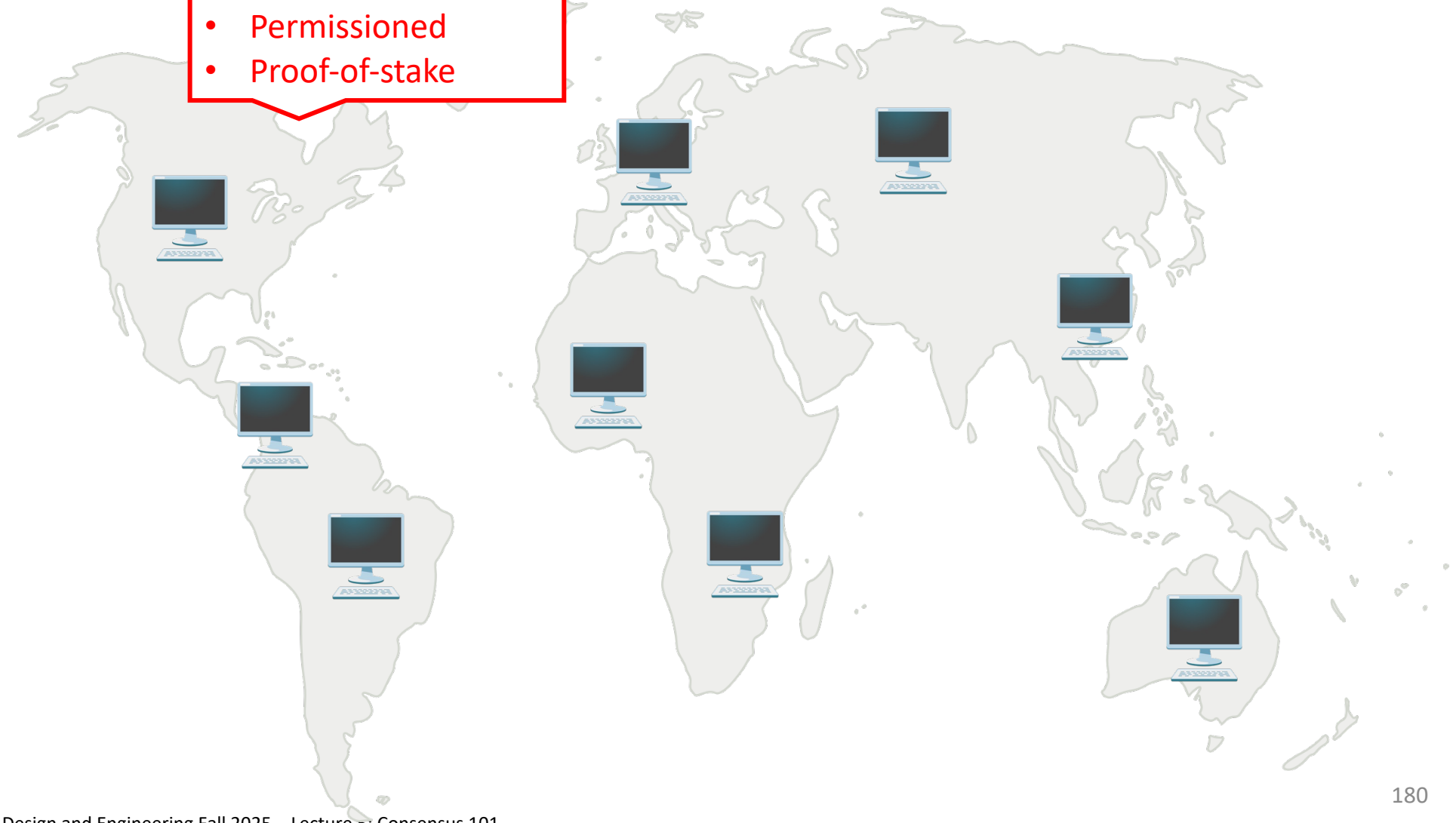

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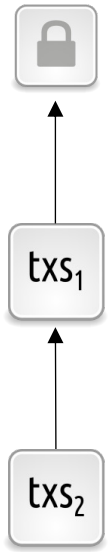

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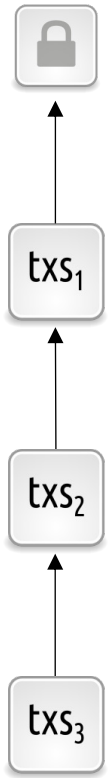

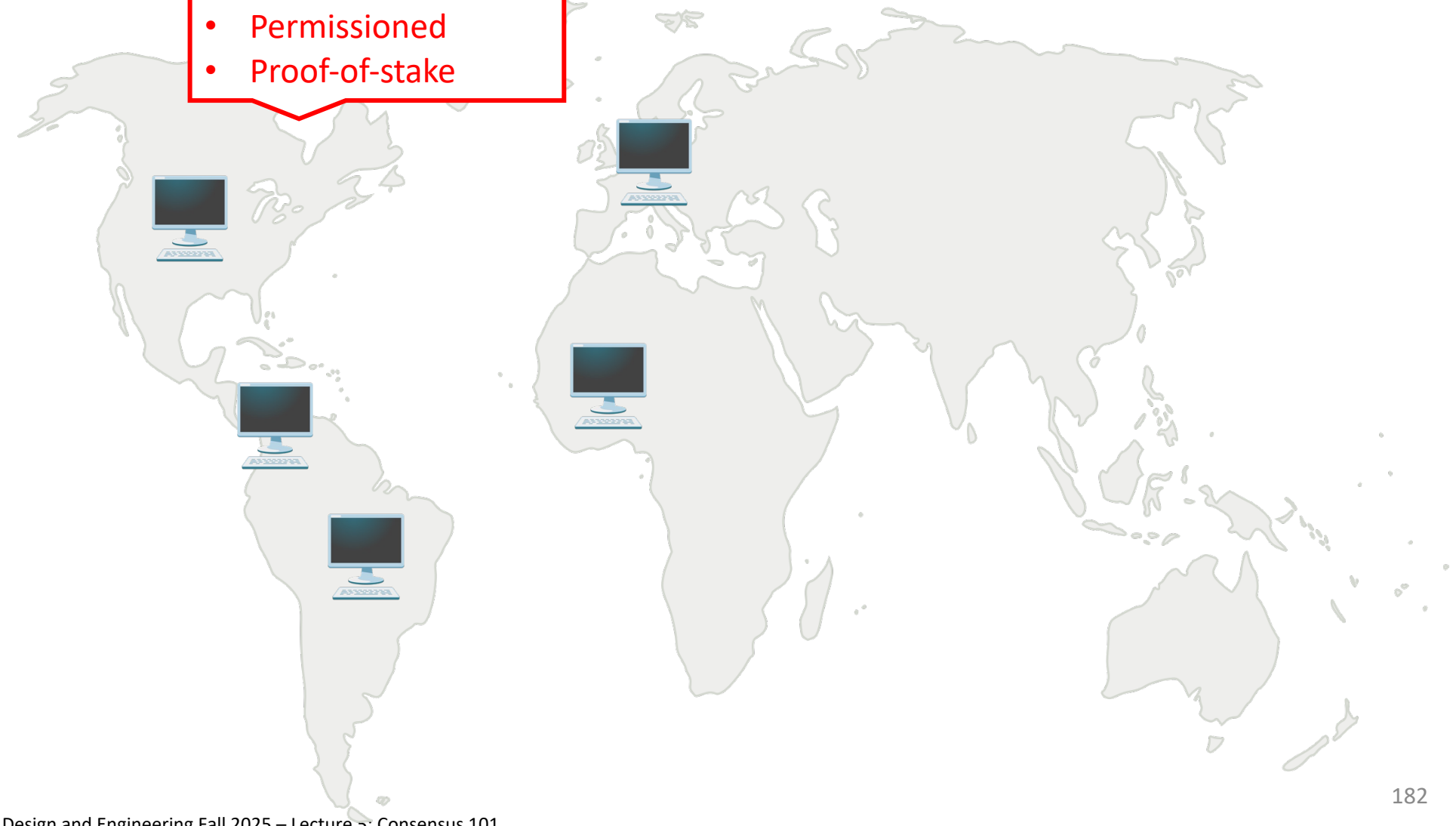

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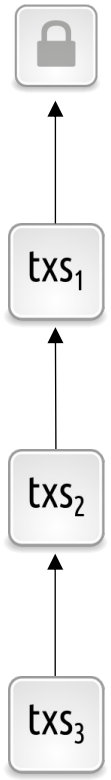

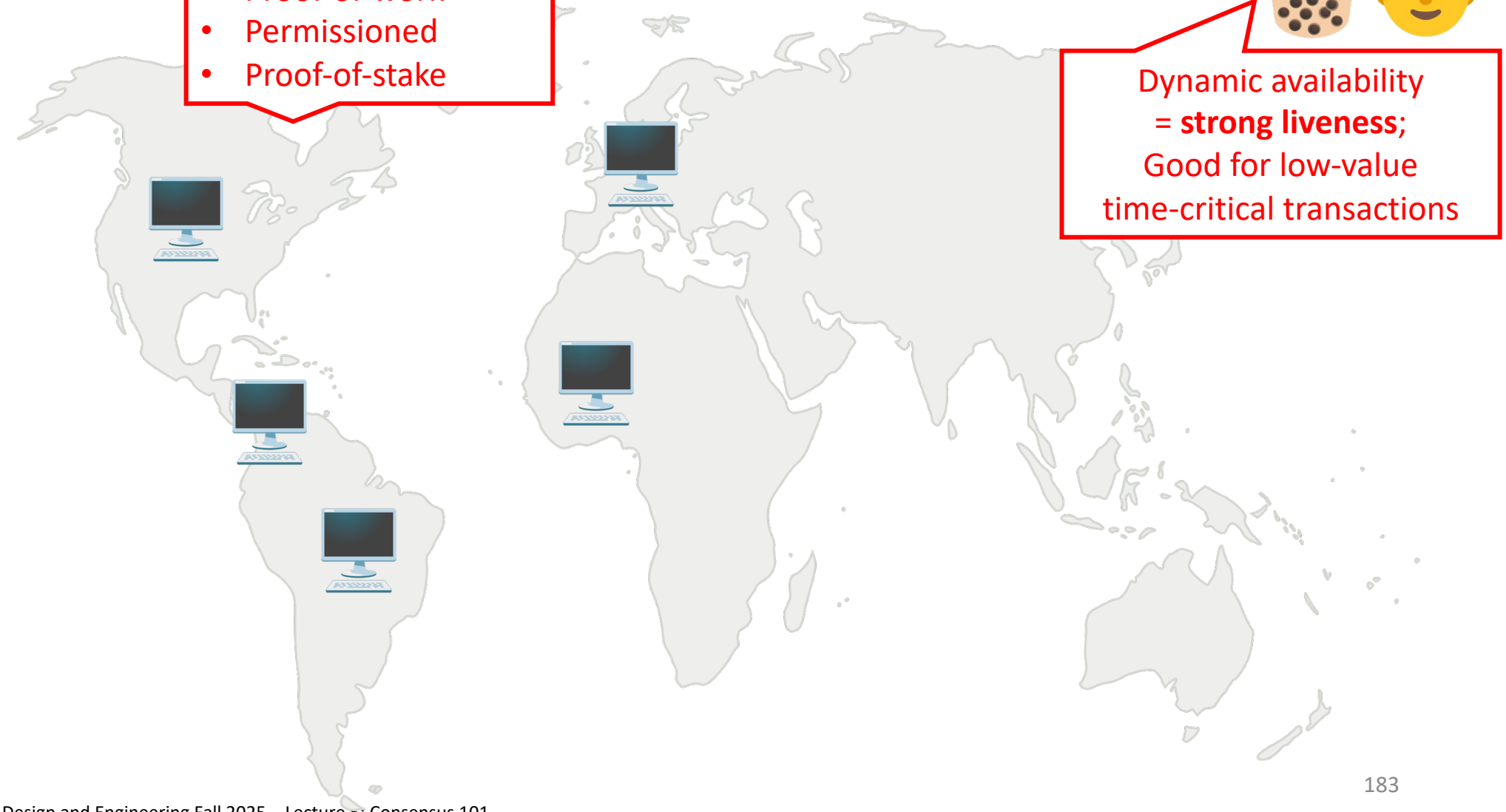

Dynamic availability
= **strong liveness**;
Good for low-value
time-critical transactions

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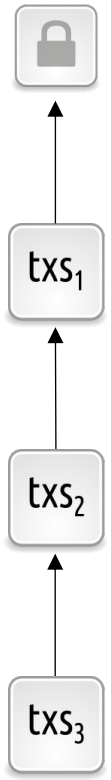

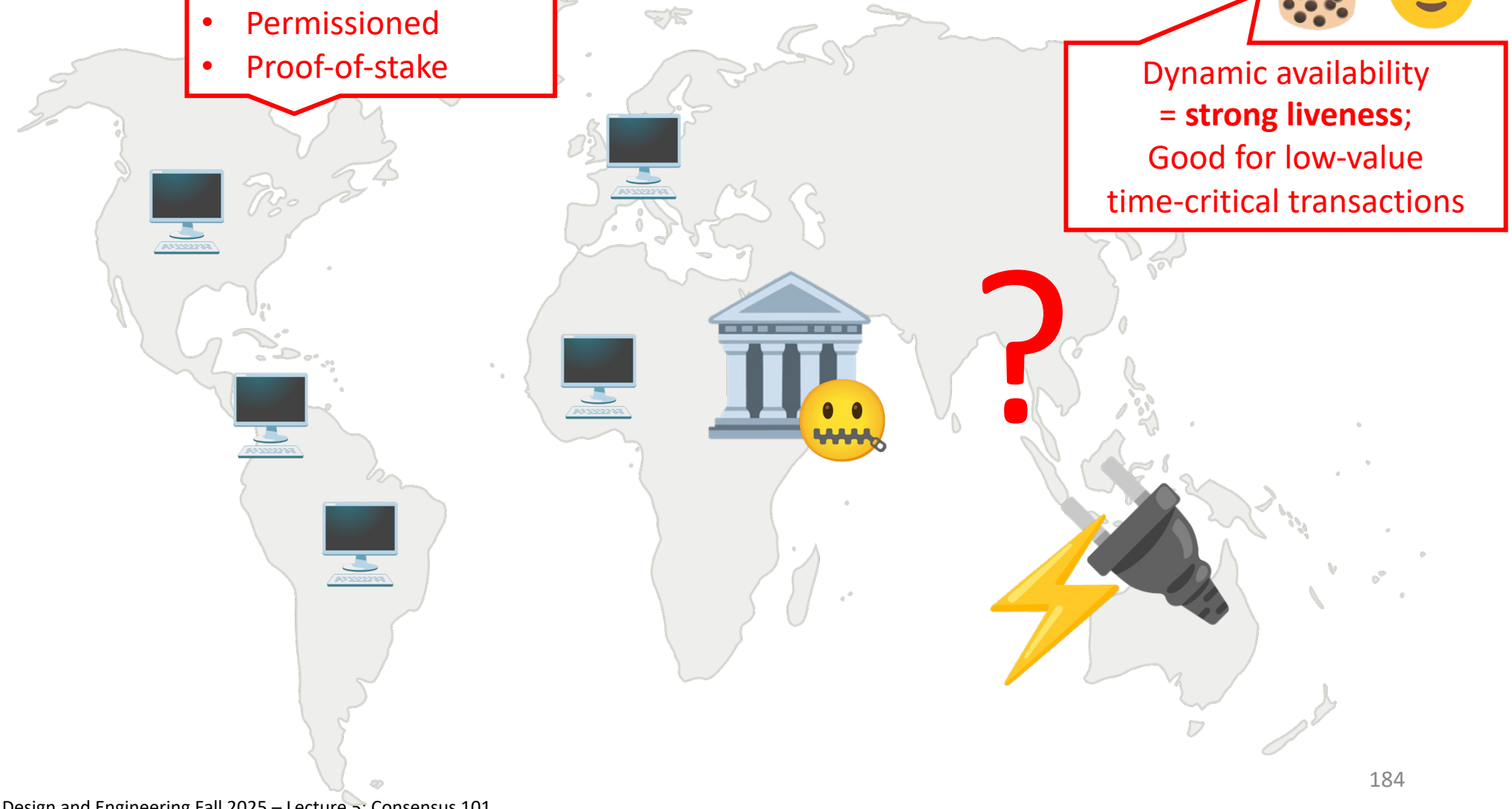

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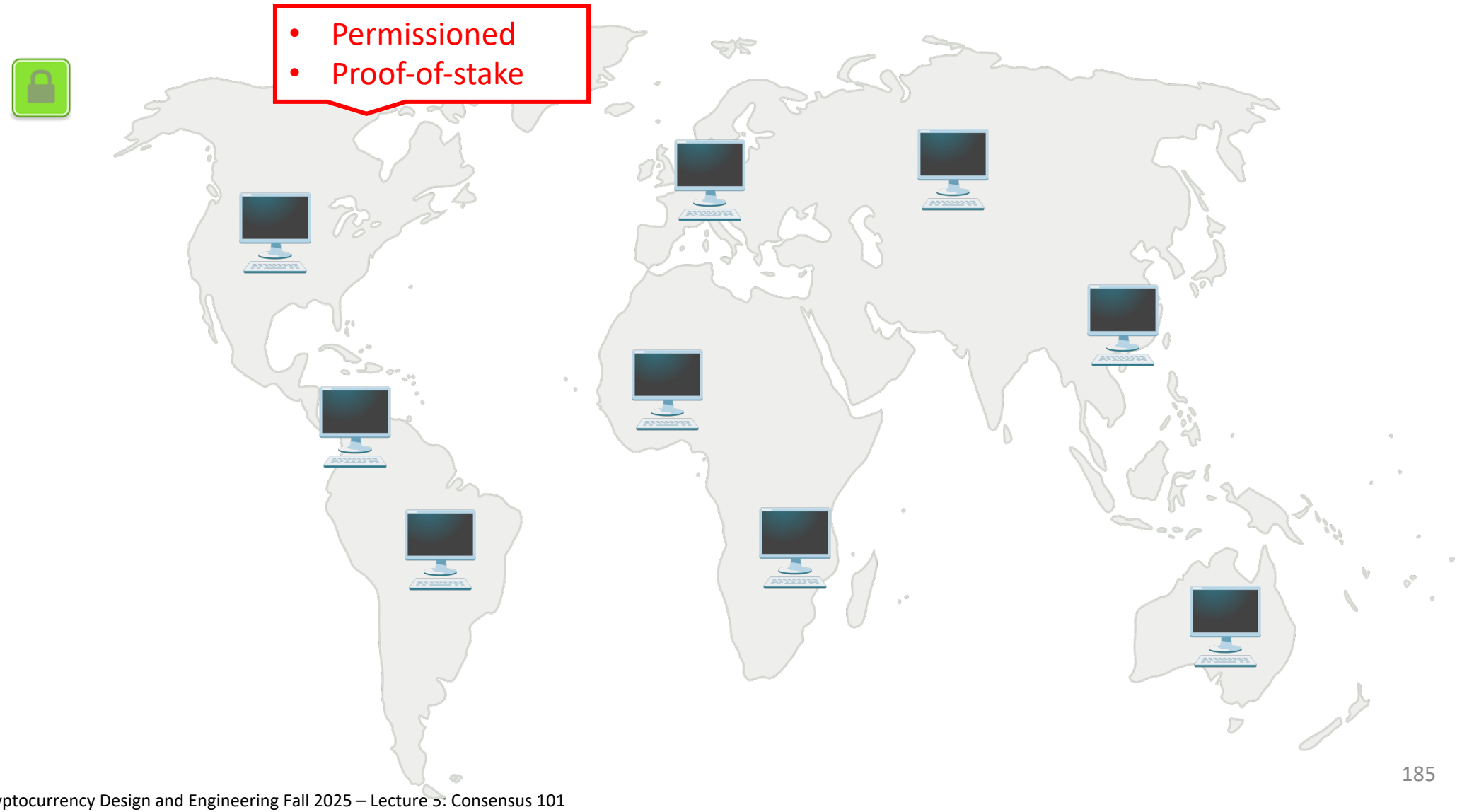
PBFT-Style Consensus: Accountably Safe



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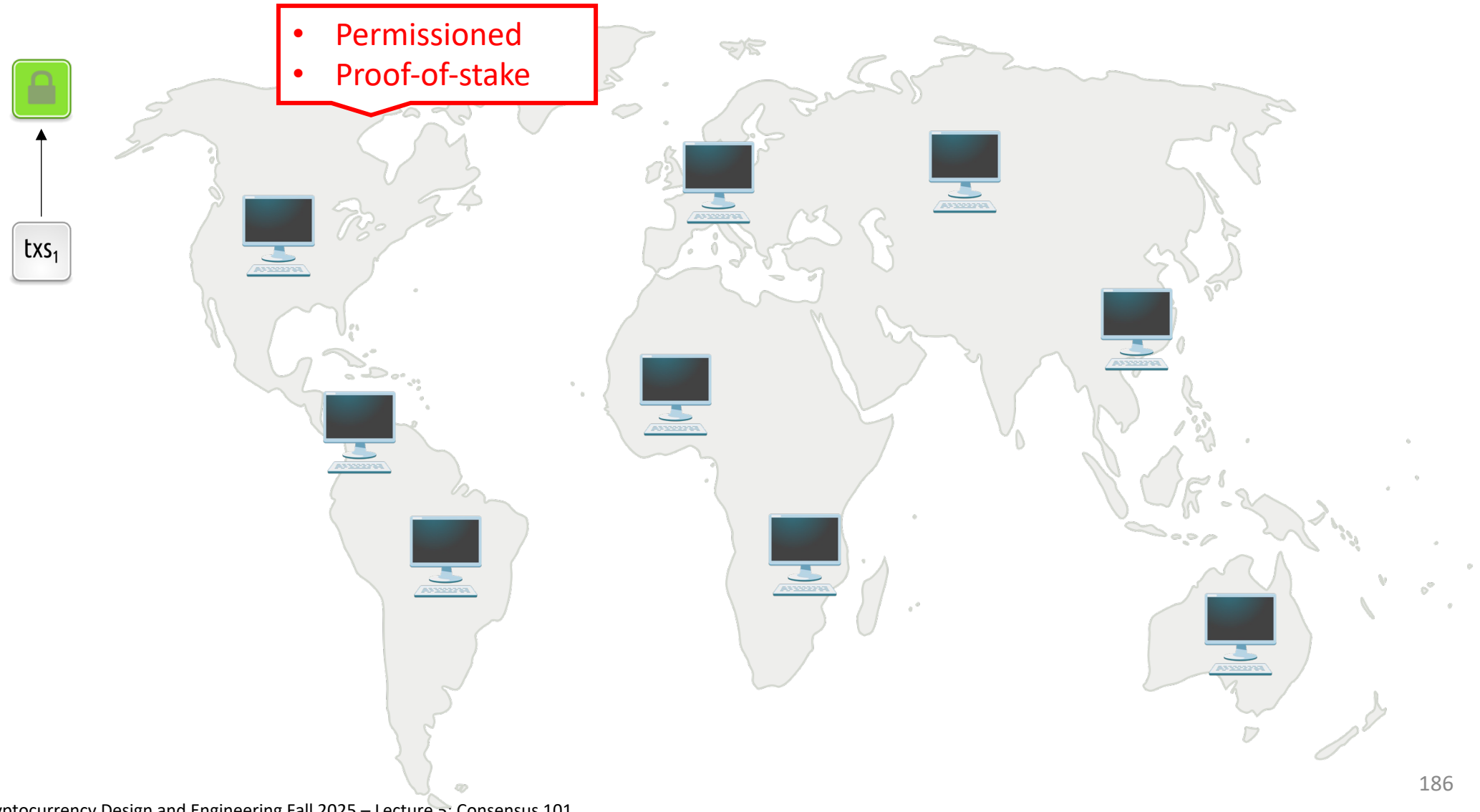

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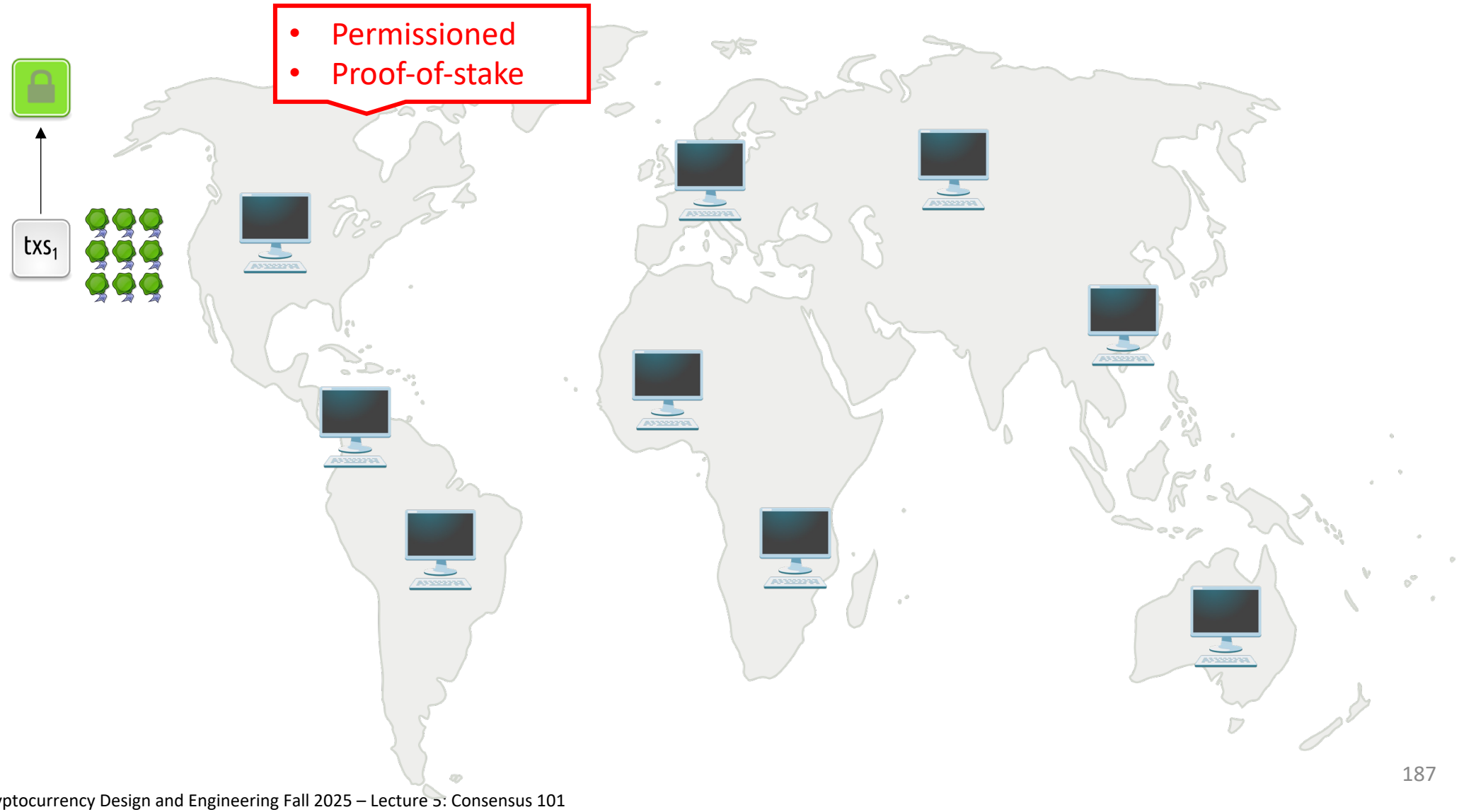

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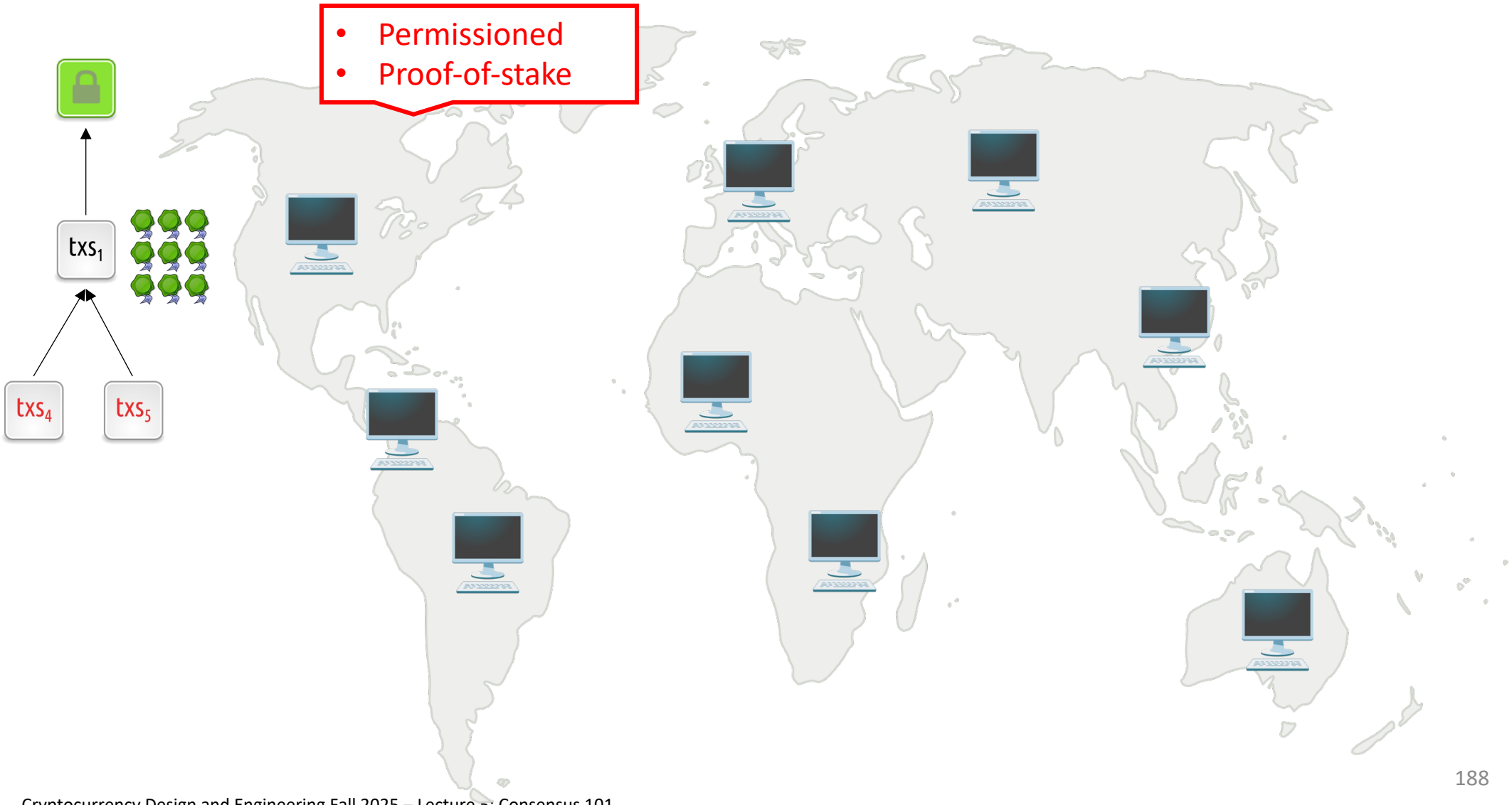

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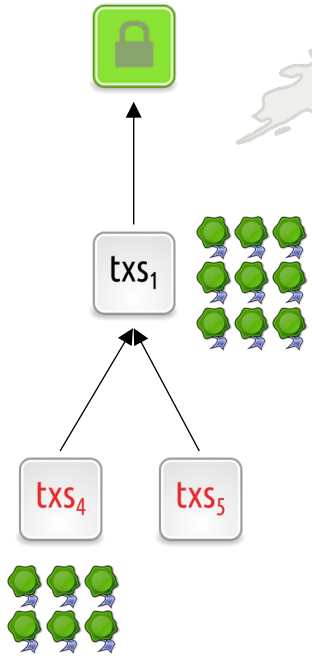

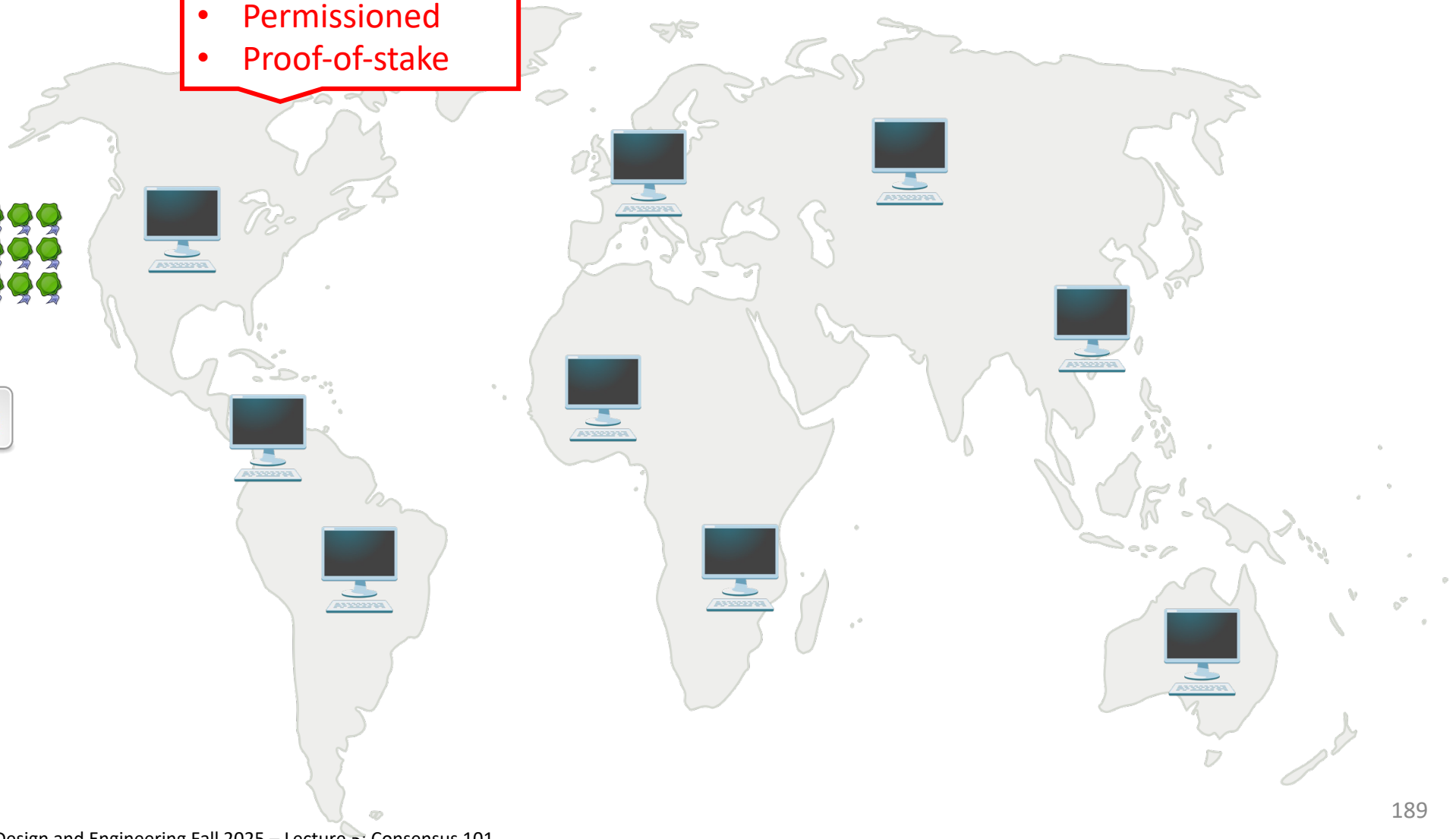

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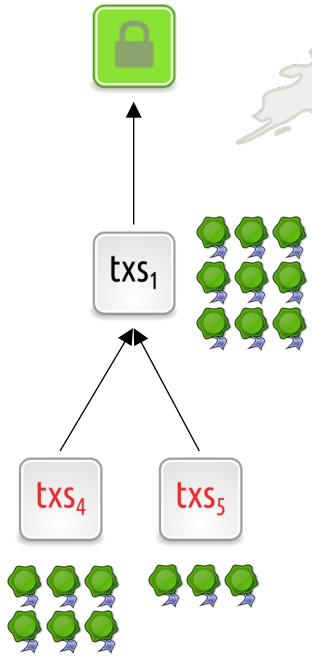

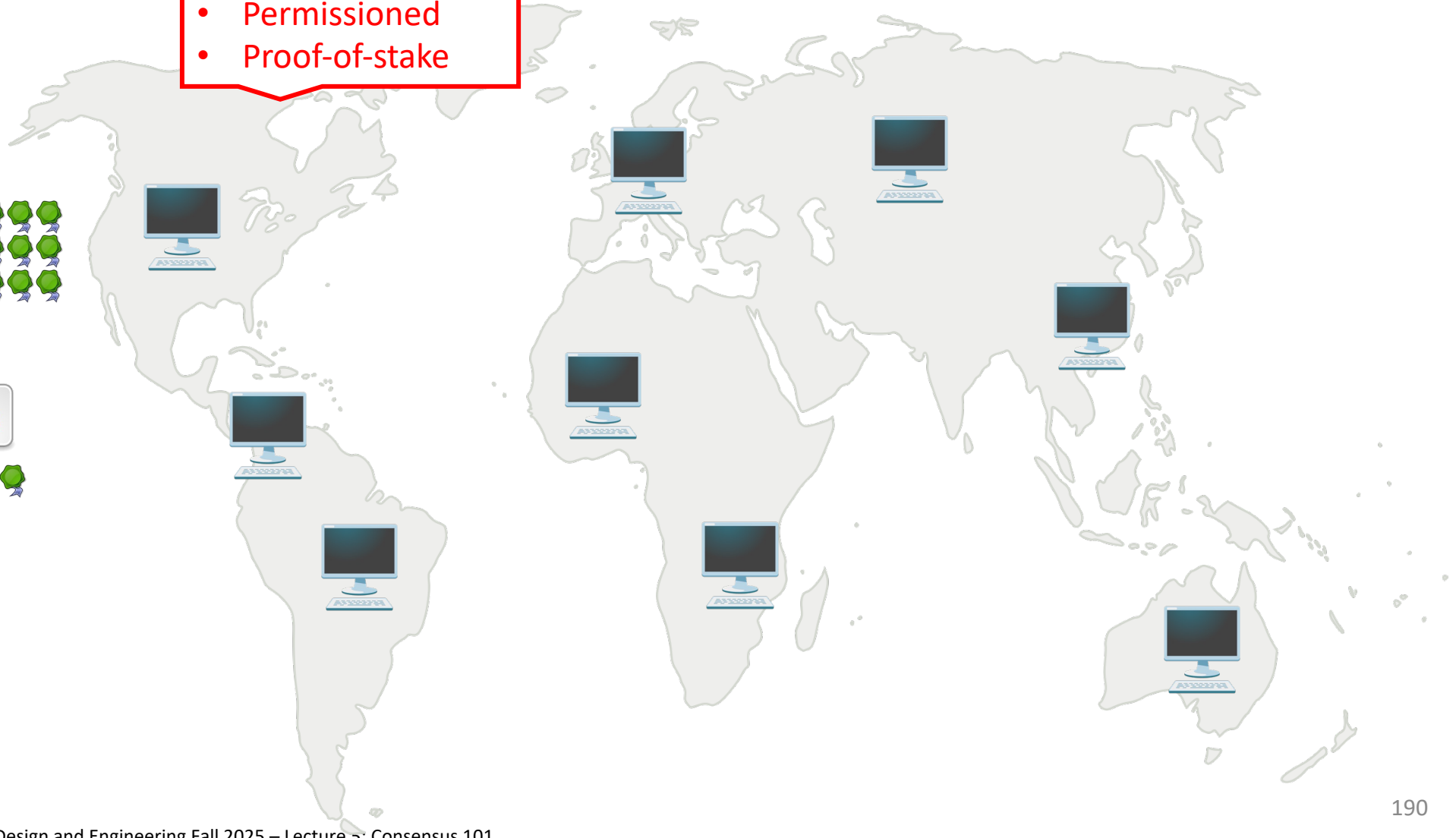

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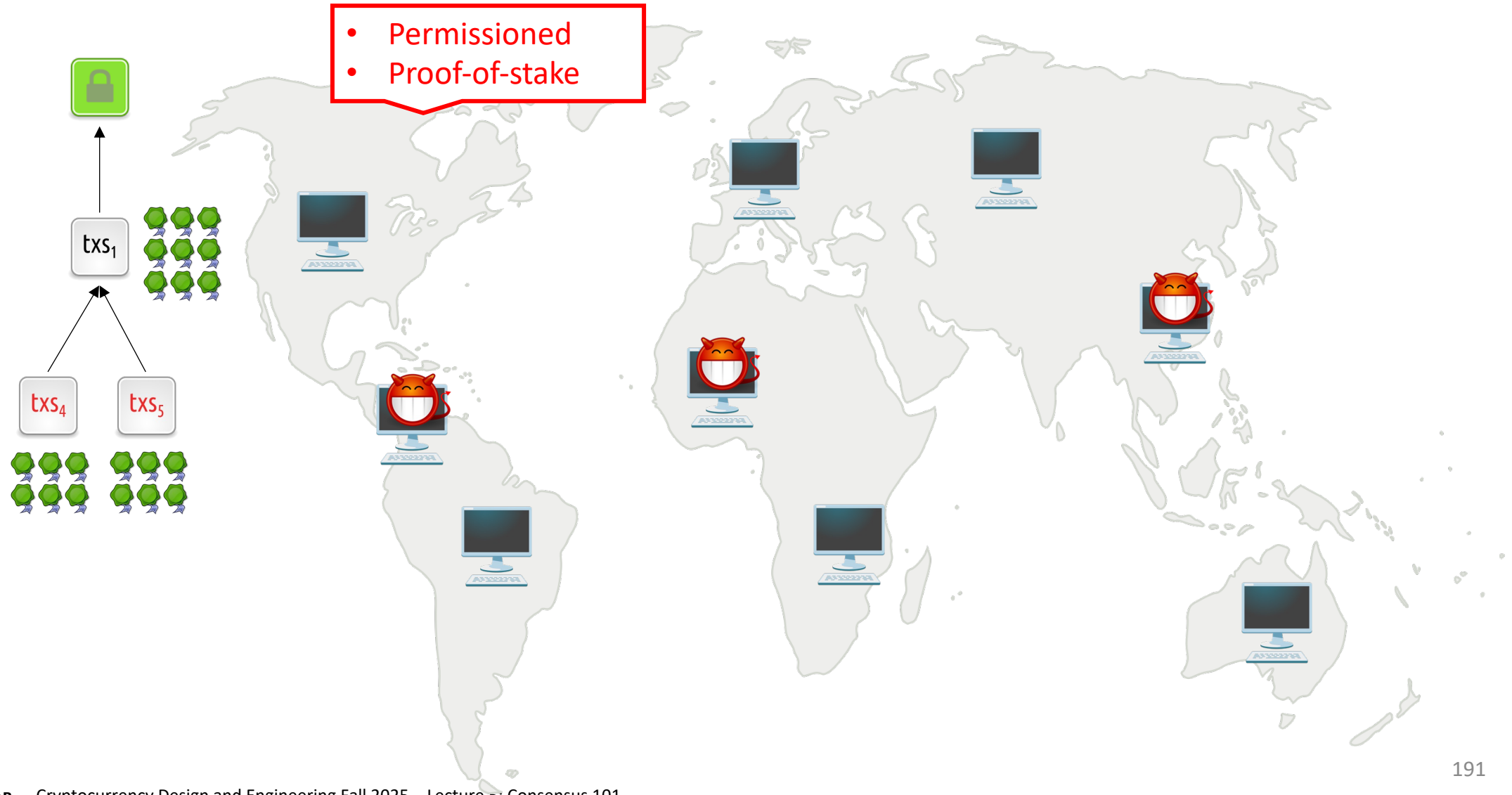

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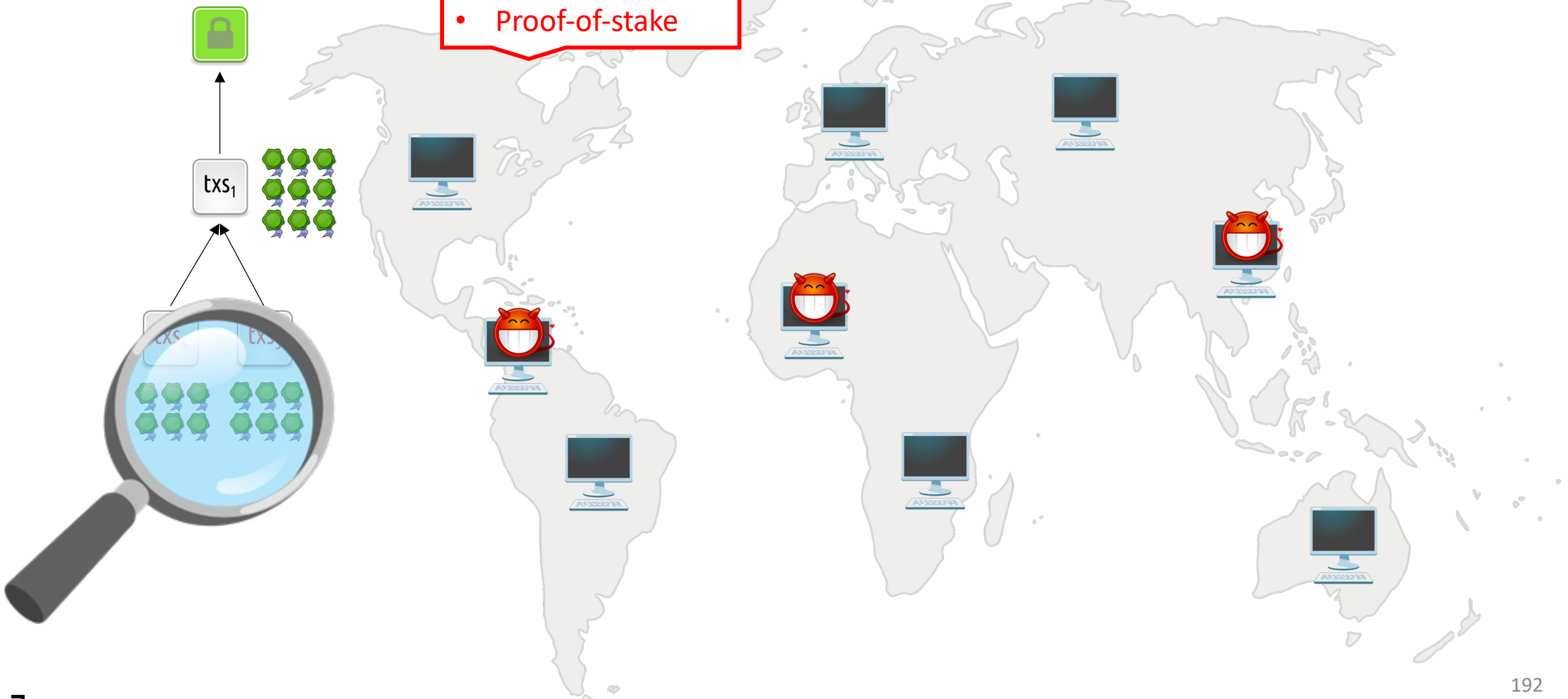

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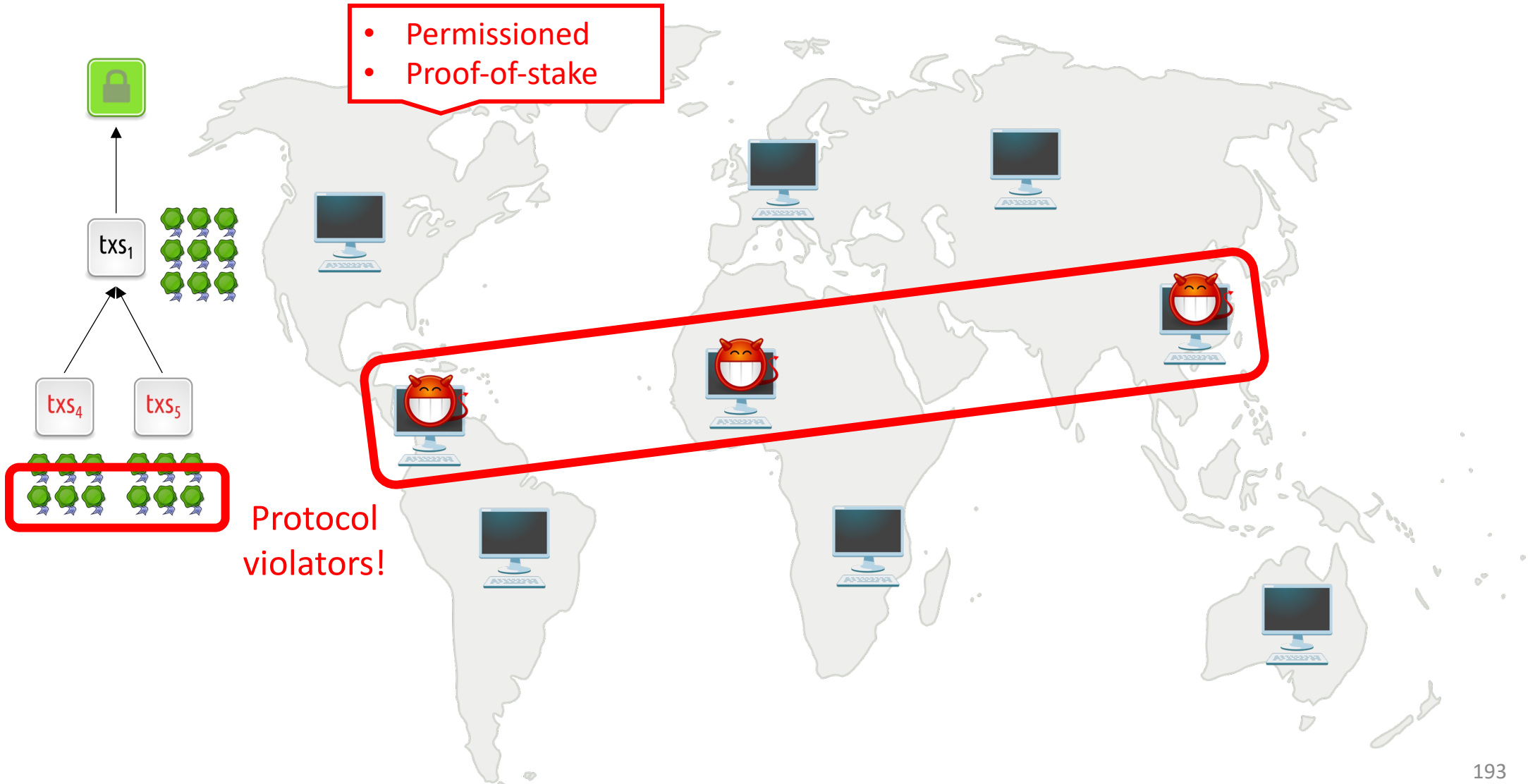

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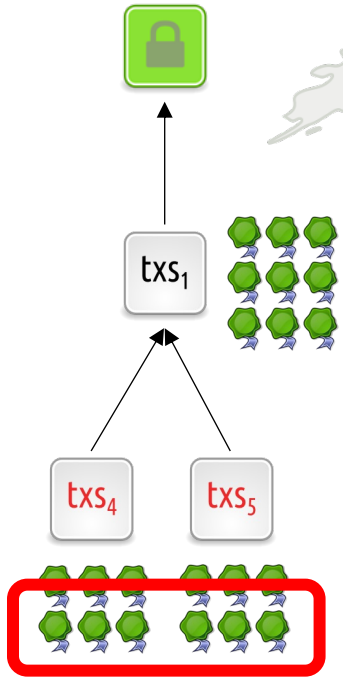

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Protocol violators!

Accountable safety
= **strong safety**;
Good for high-value
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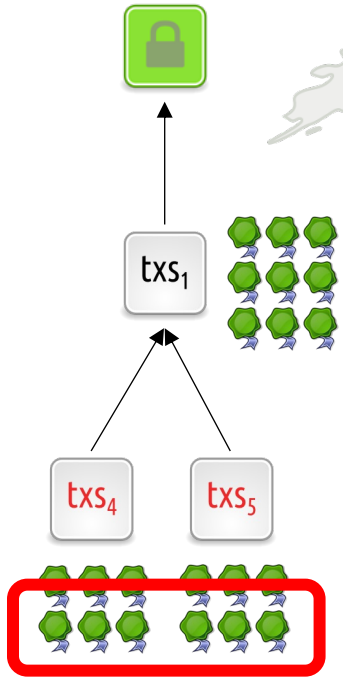

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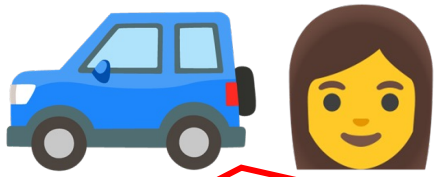

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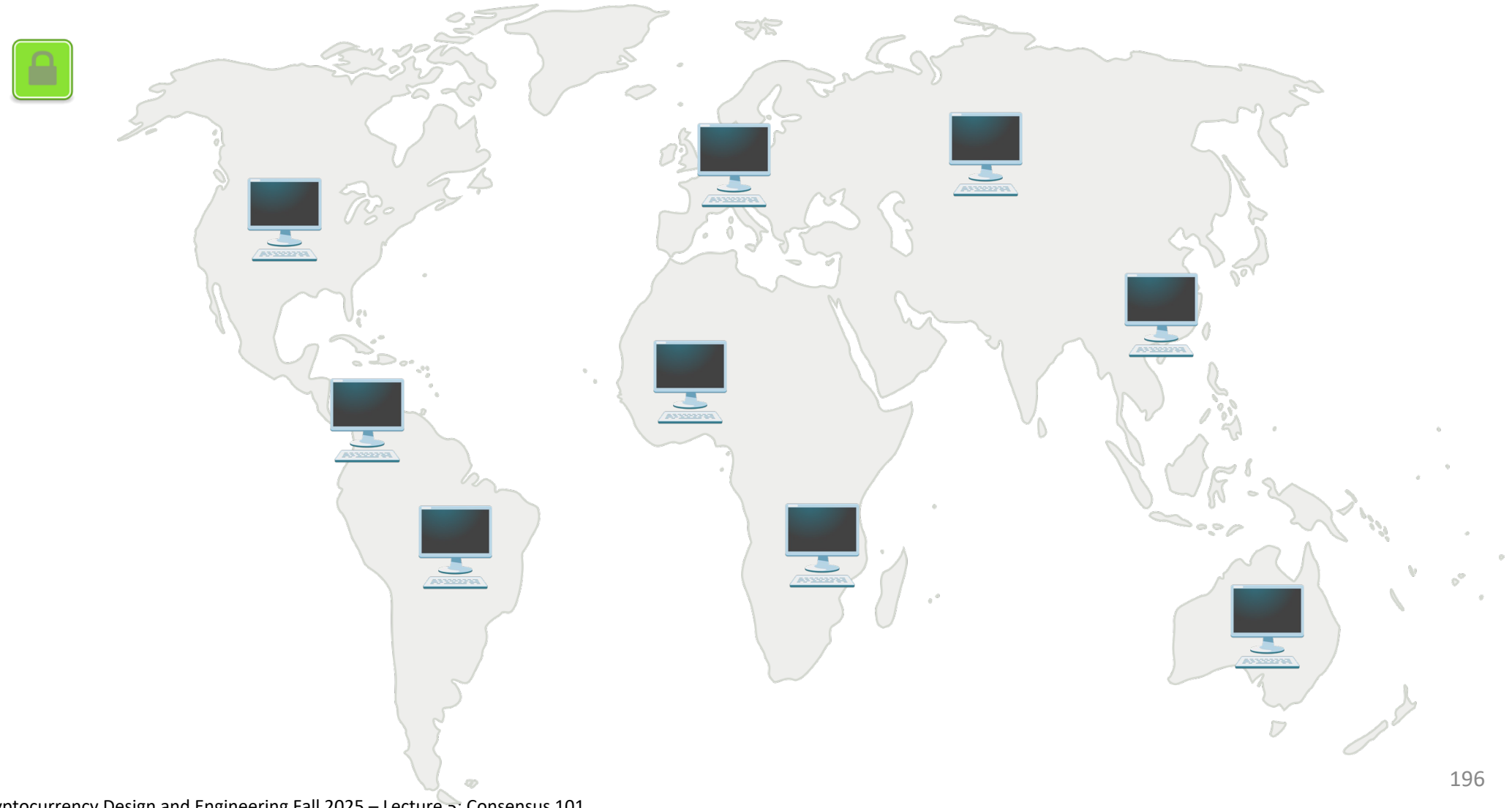

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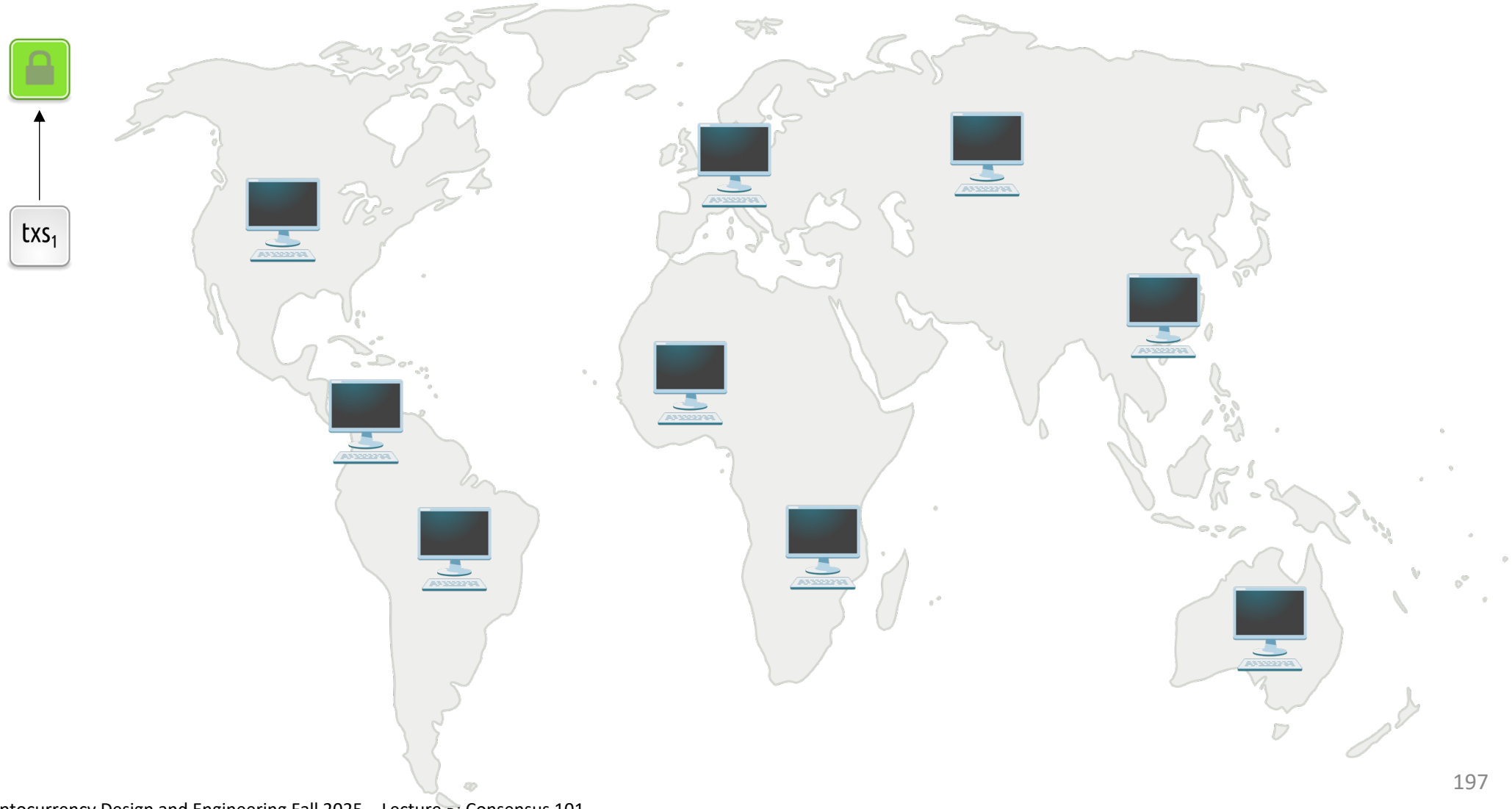

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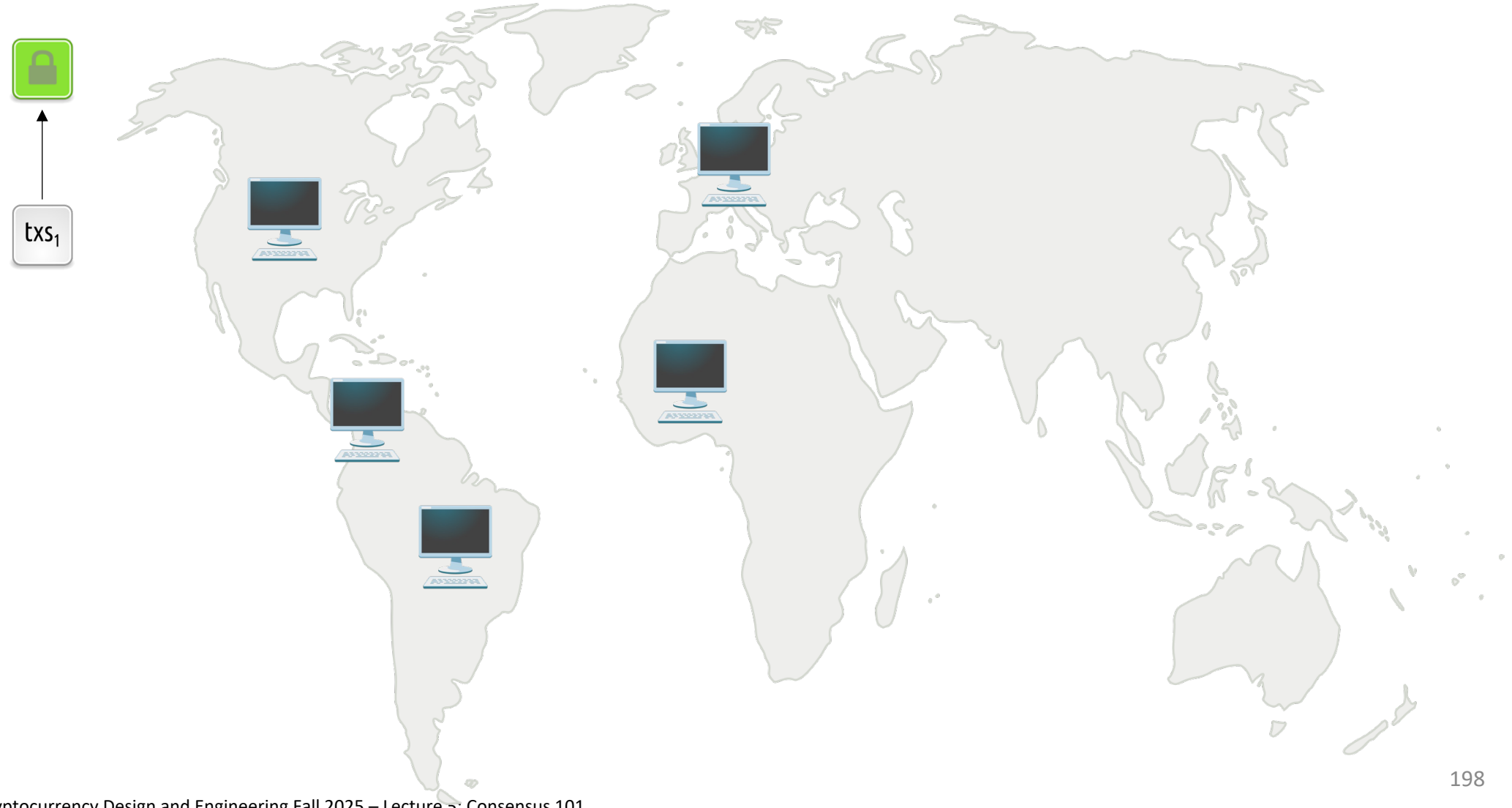

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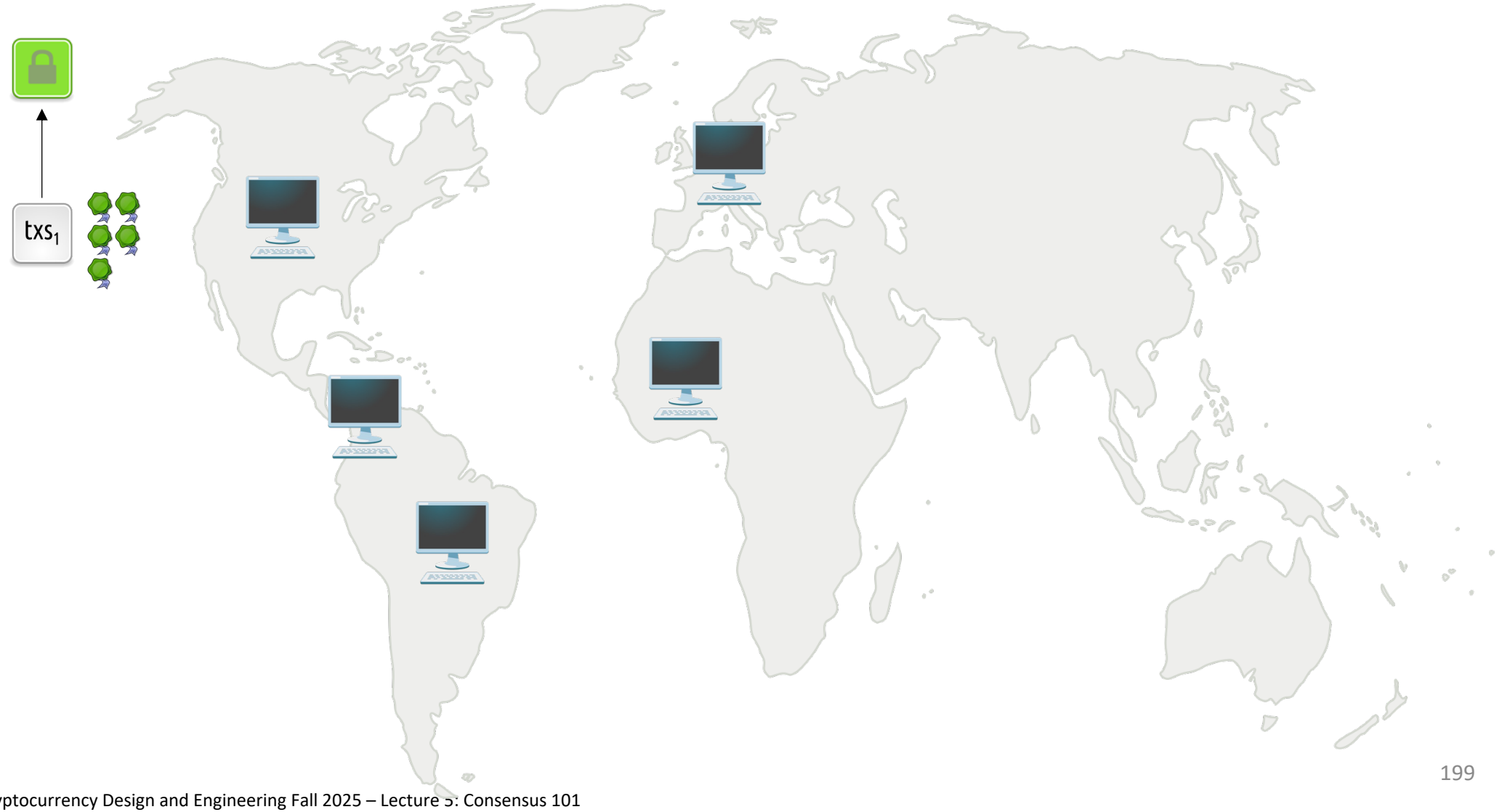

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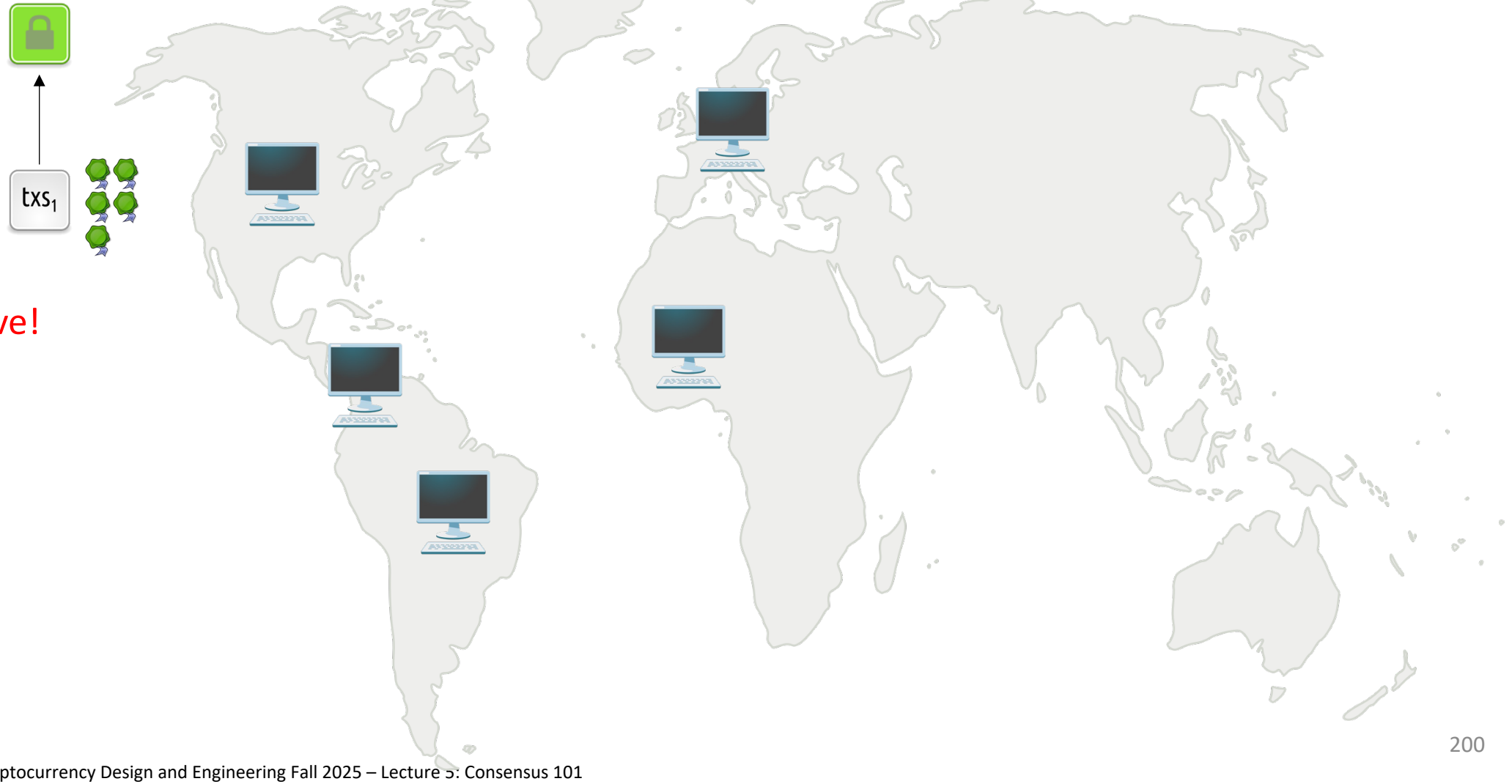

Not live!

Gilbert, Lynch 2002; Lewis-Pye, Roughgarden 2020; Neu et al. 2024

Nakamoto Consensus: Not Accountably Safe

Gilbert, Lynch 2002; Lewis-Pye, Roughgarden 2020; Neu et al. 2024

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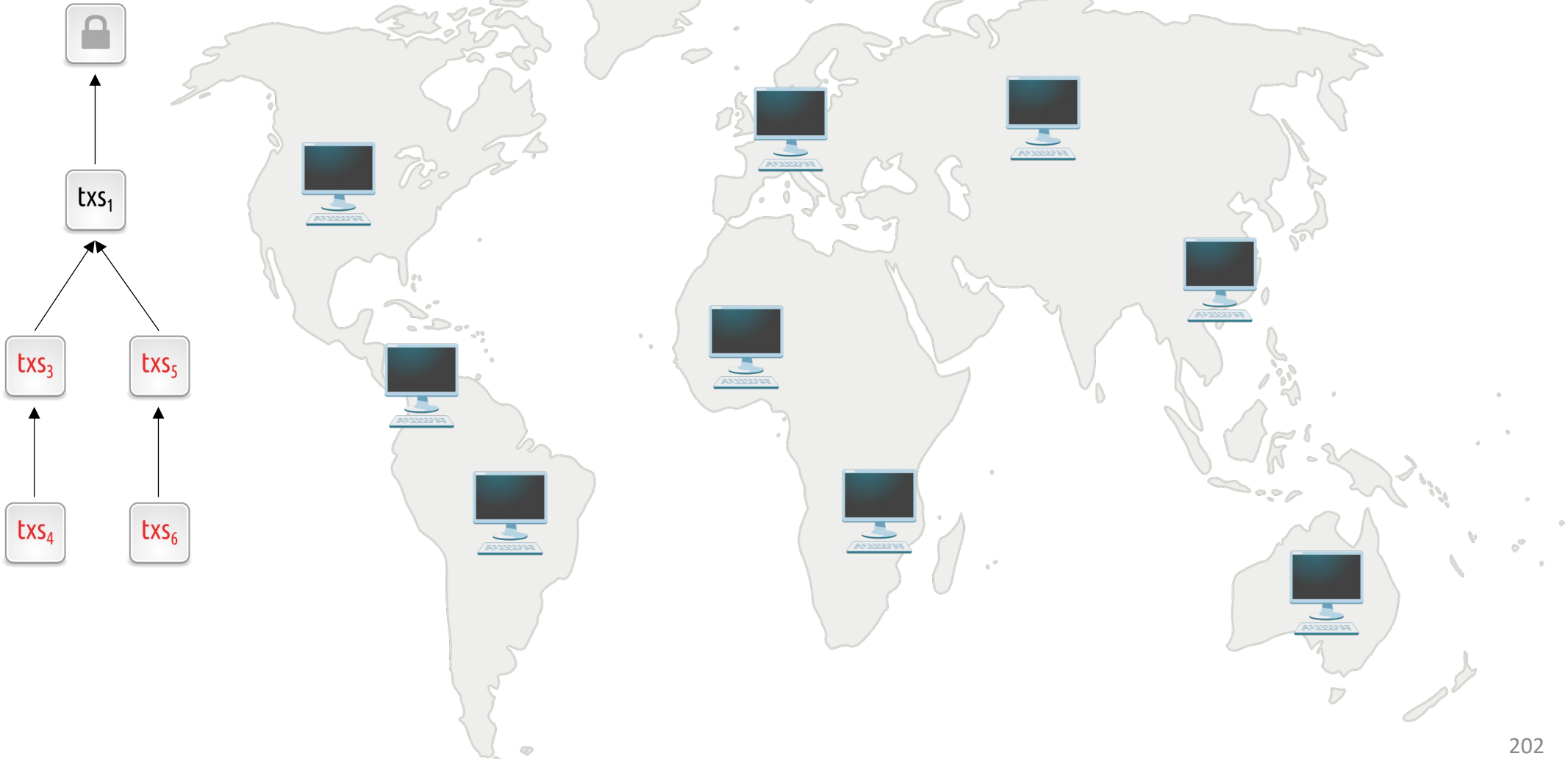

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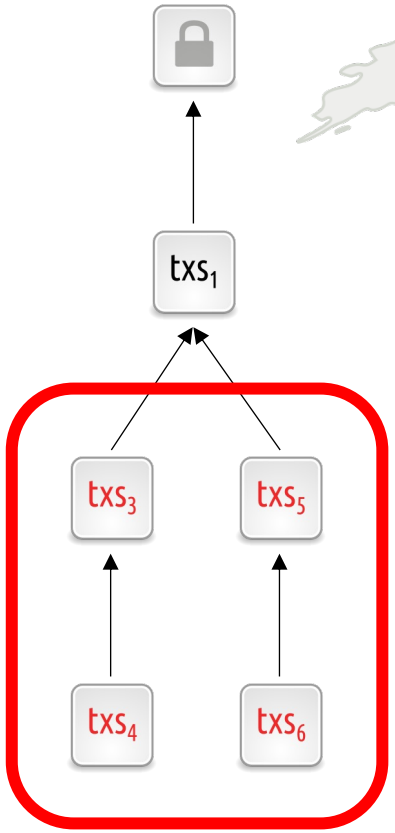
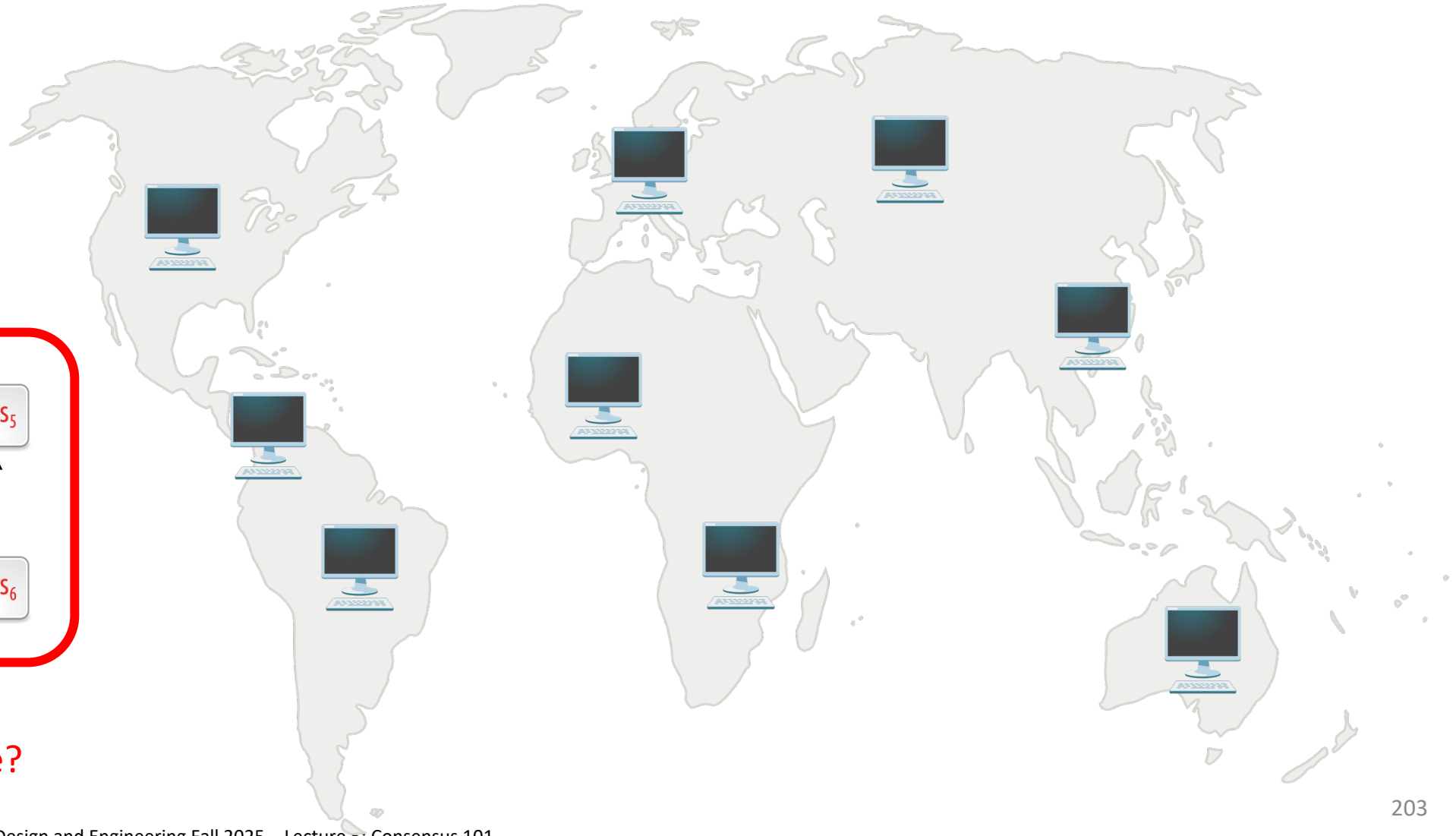
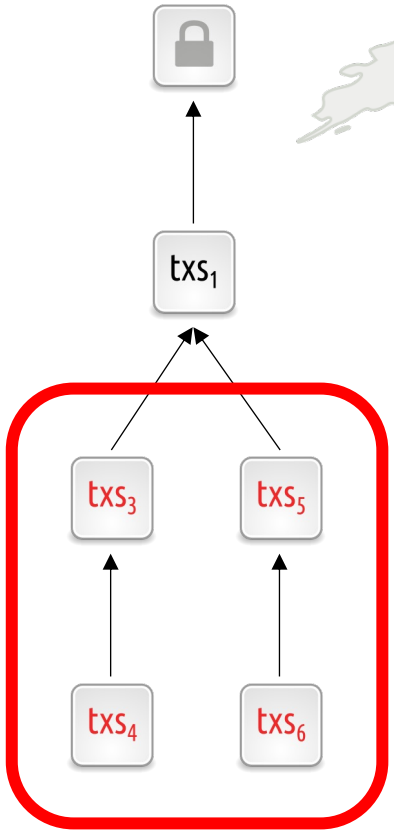




Safety violation.
Who is to blame?

Gilbert, Lynch 2002; Lewis-Pye, Roughgarden 2020; Neu et al. 2024

Nakamoto Consensus: Not Accountably Safe



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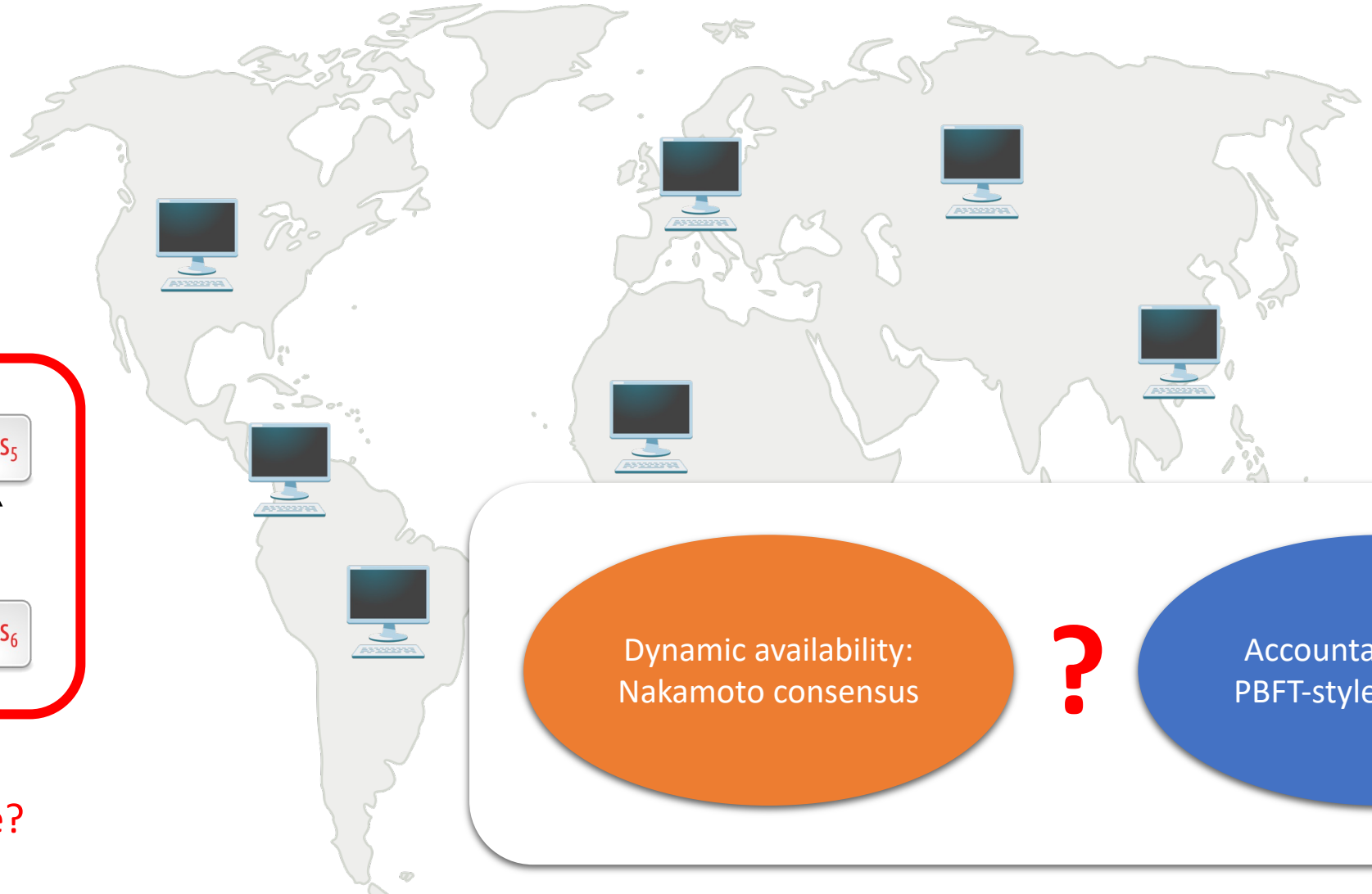


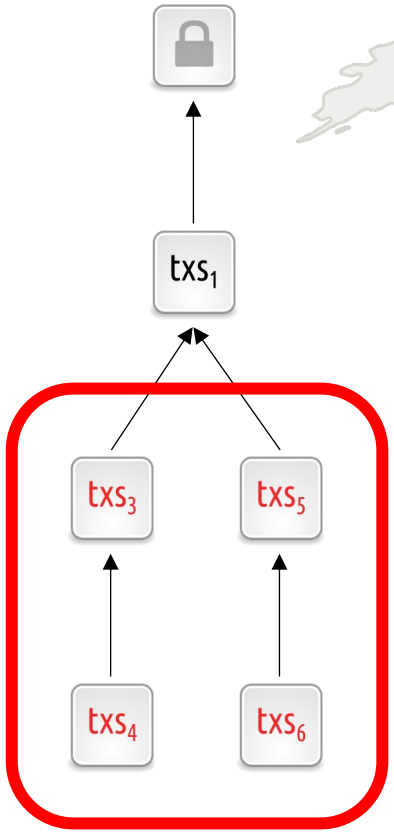
Dynamic availability:
Nakamoto consensus

?

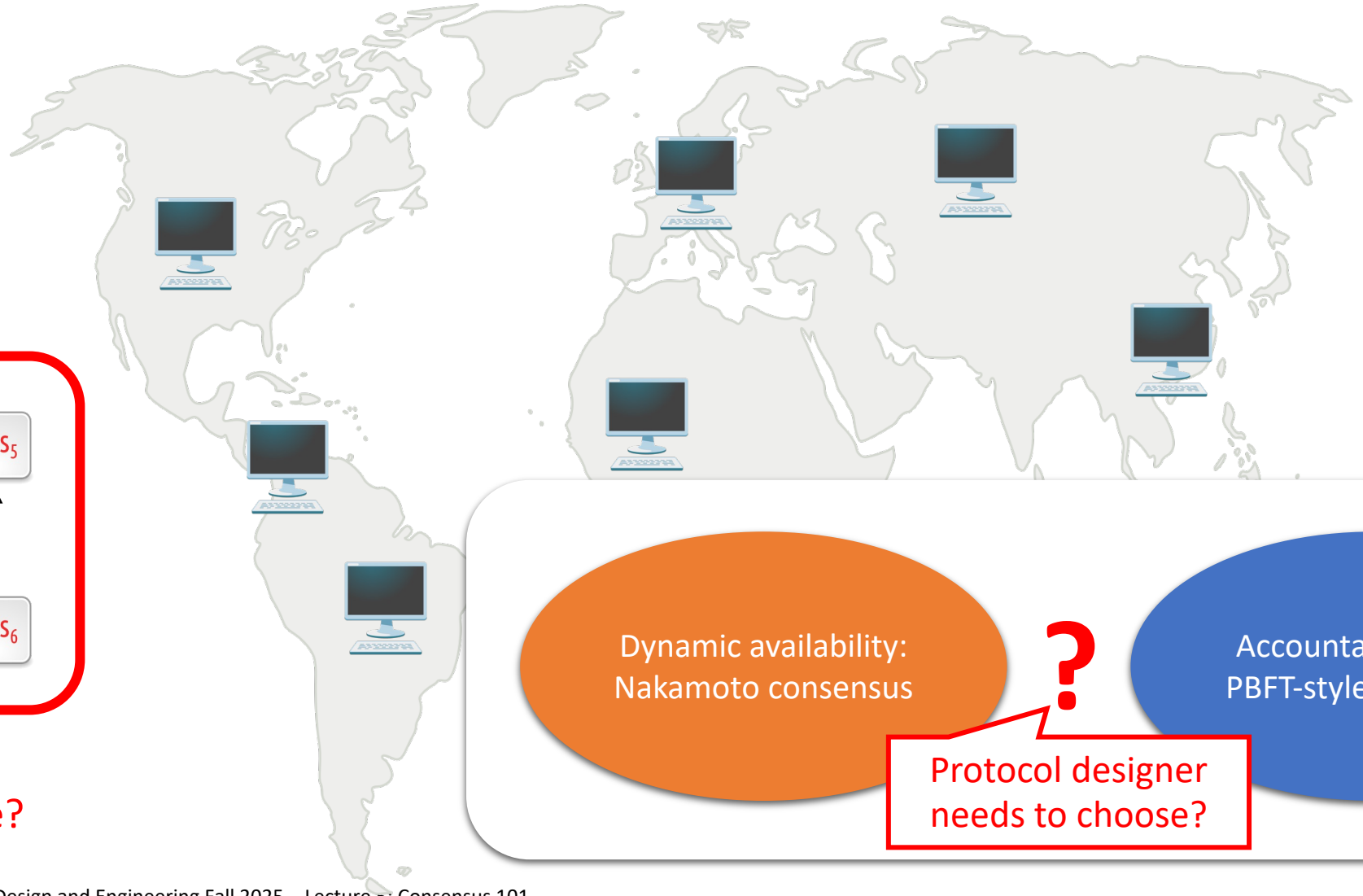
Accountable safety:
PBFT-style consensus

Gilbert, Lynch 2002; Lewis-Pye, Roughgarden 2020; Neu et al. 2024

Nakamoto Consensus: Not Accountably Safe



Safety violation.
Who is to blame?



Dynamic availability:
Nakamoto consensus

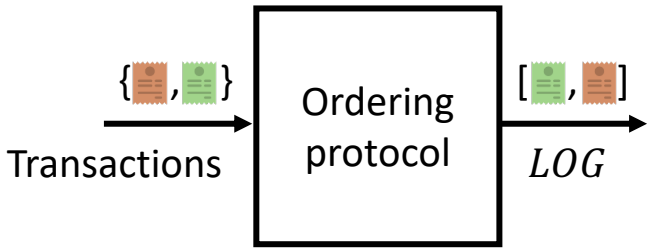
?

Accountable safety:
PBFT-style consensus

Protocol designer
needs to choose?

"Ebb-and-Flow Protocols: A Resolution of the Availability-Finality Dilemma", Neu et al. 2021

Dynamic Availability + Accountable Safety



Single log: $tx_1, tx_2, tx_3, \ldots$

Protocol designer needs to choose?

Impossible!

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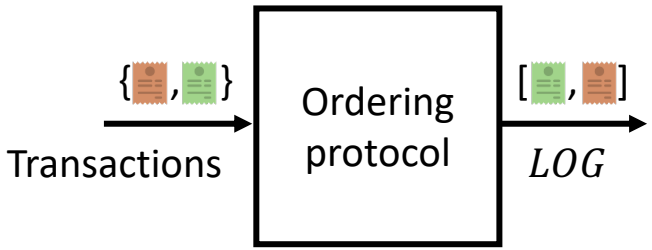
Dynamic Availability + Accountable Safety



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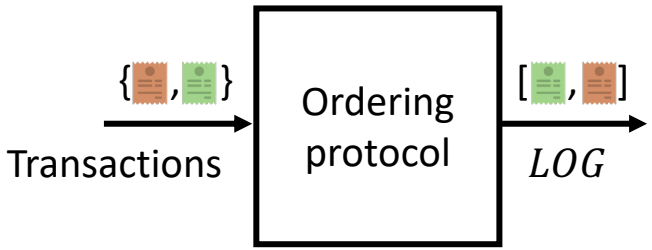

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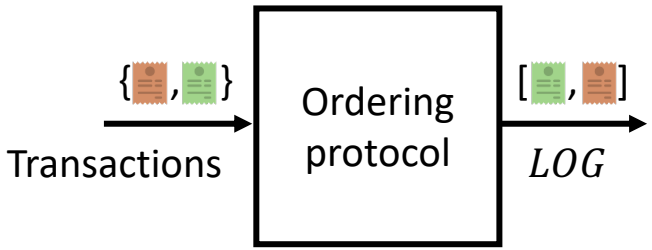

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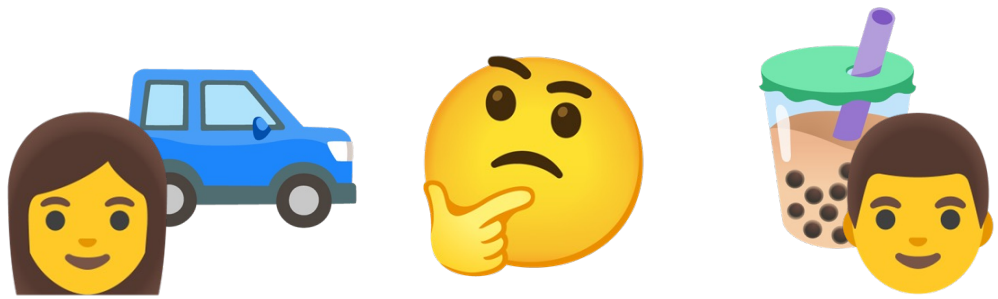

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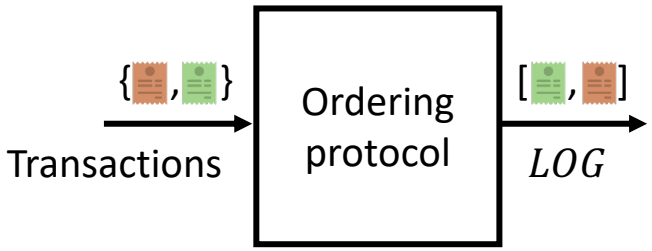
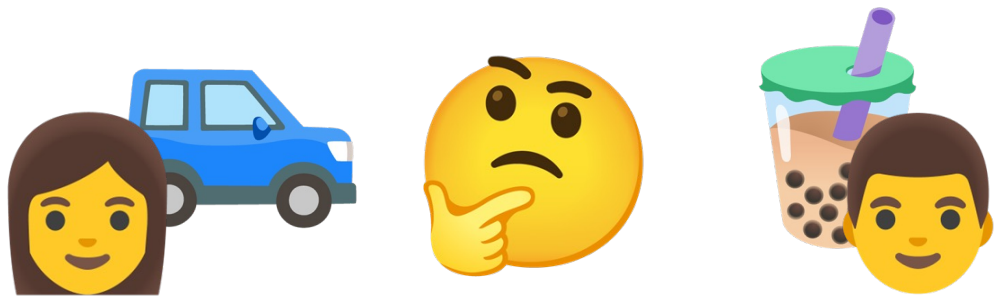


Single log: $tx_1, tx_2, tx_3, \ldots$

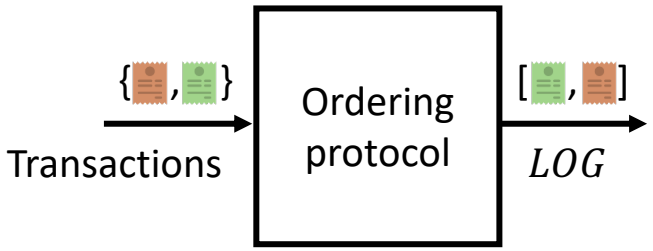
Protocol designer needs to choose?

Impossible!

Available *full* log



Dynamic Availability + Accountable Safety



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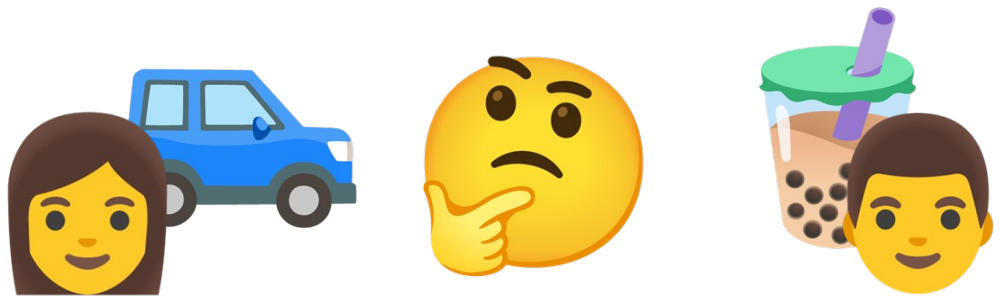
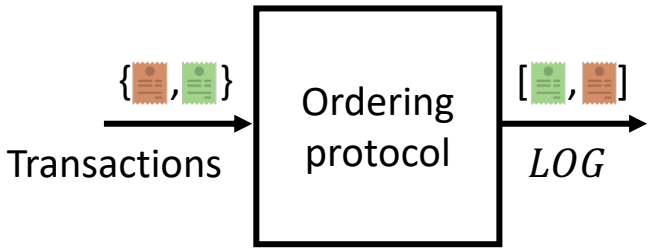
Protocol designer needs to choose?

Impossible!

Accountable *prefix* log | Available *full* log



Dynamic Availability + Accountable Safety



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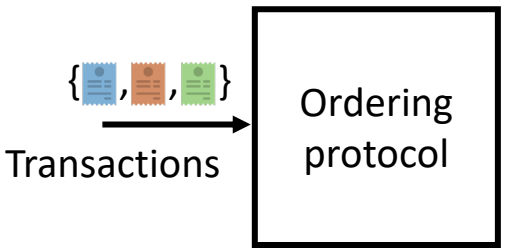

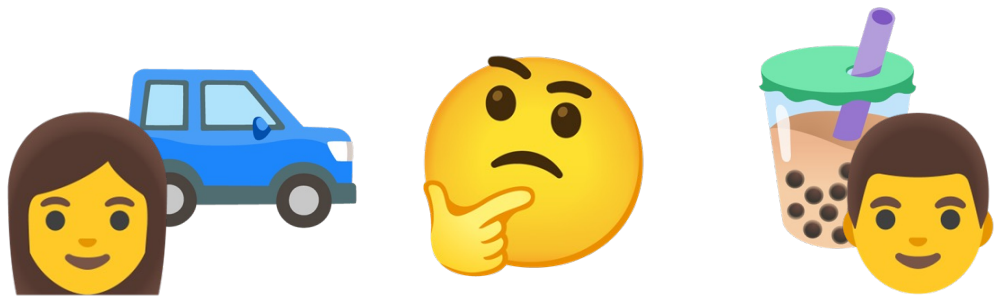

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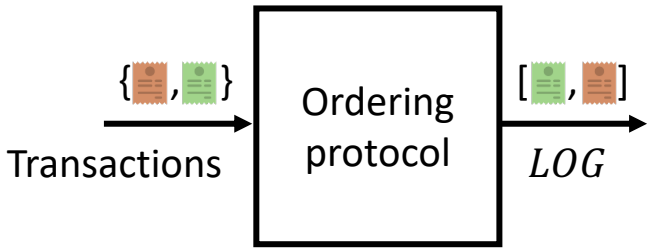

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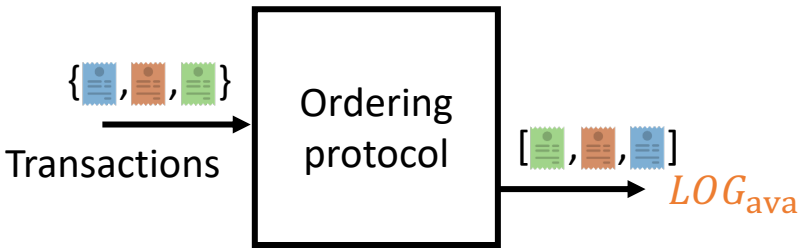

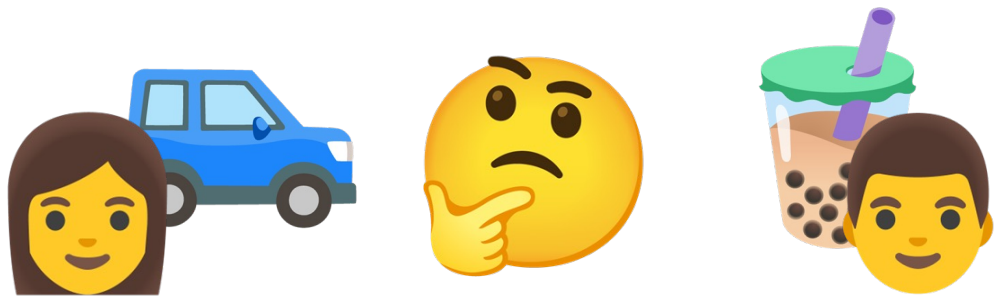

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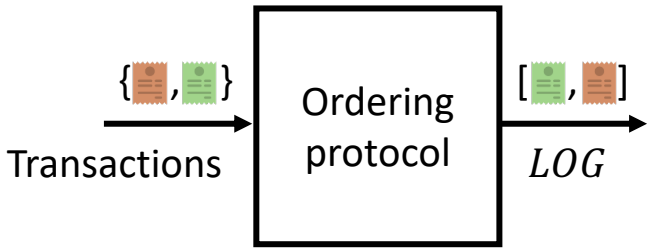

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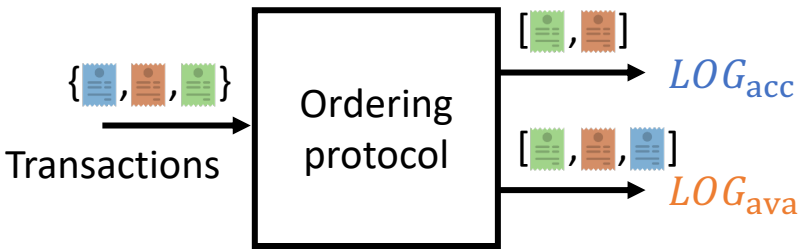

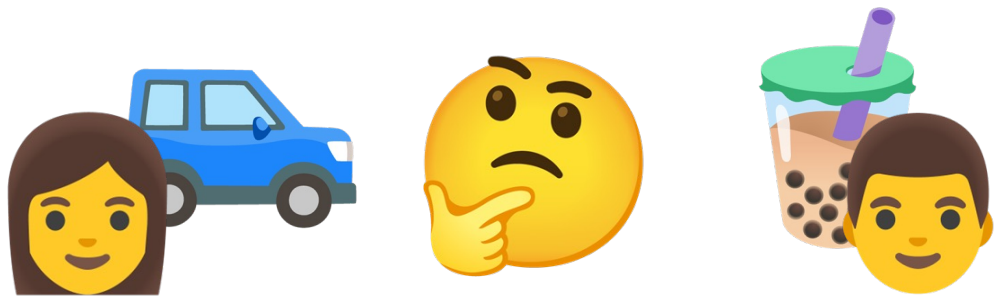

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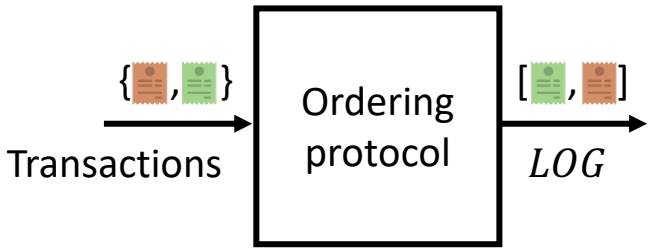

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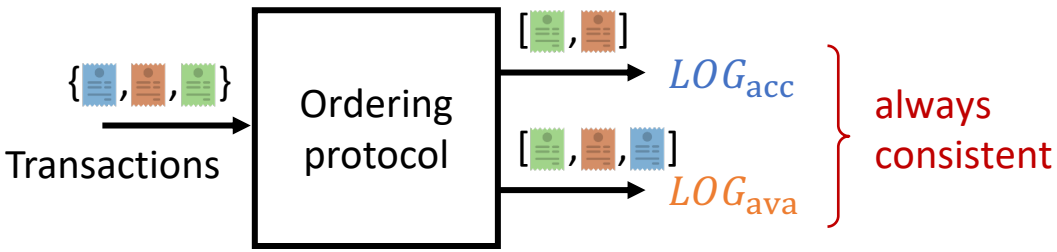
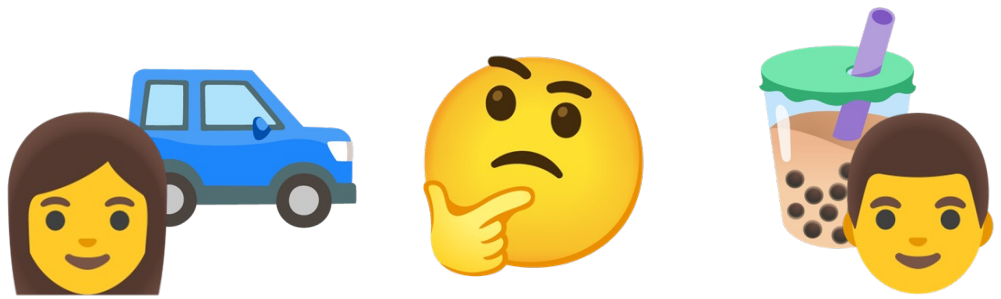
Accountable *prefix* log | Available *full* log





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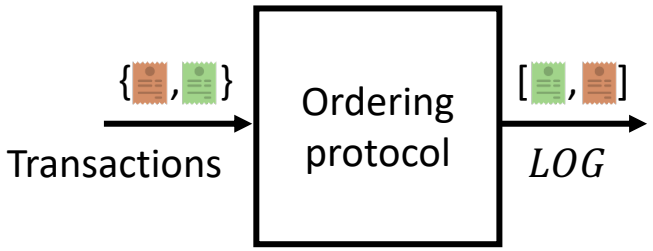

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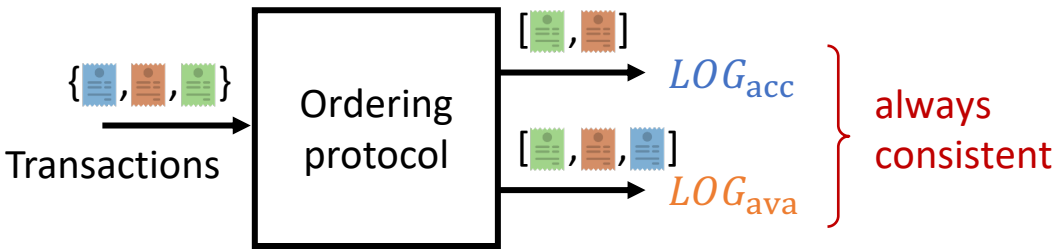
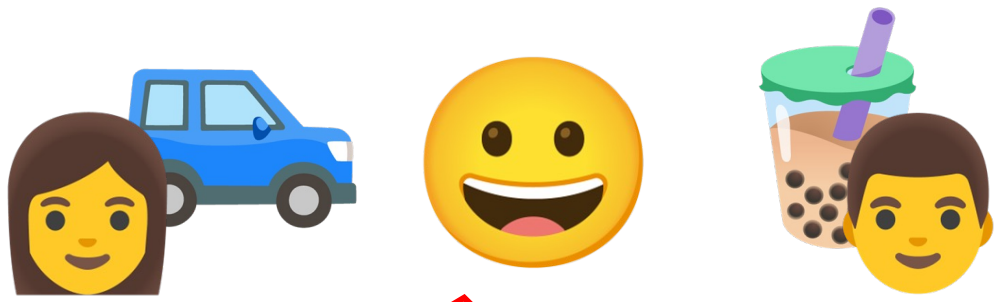
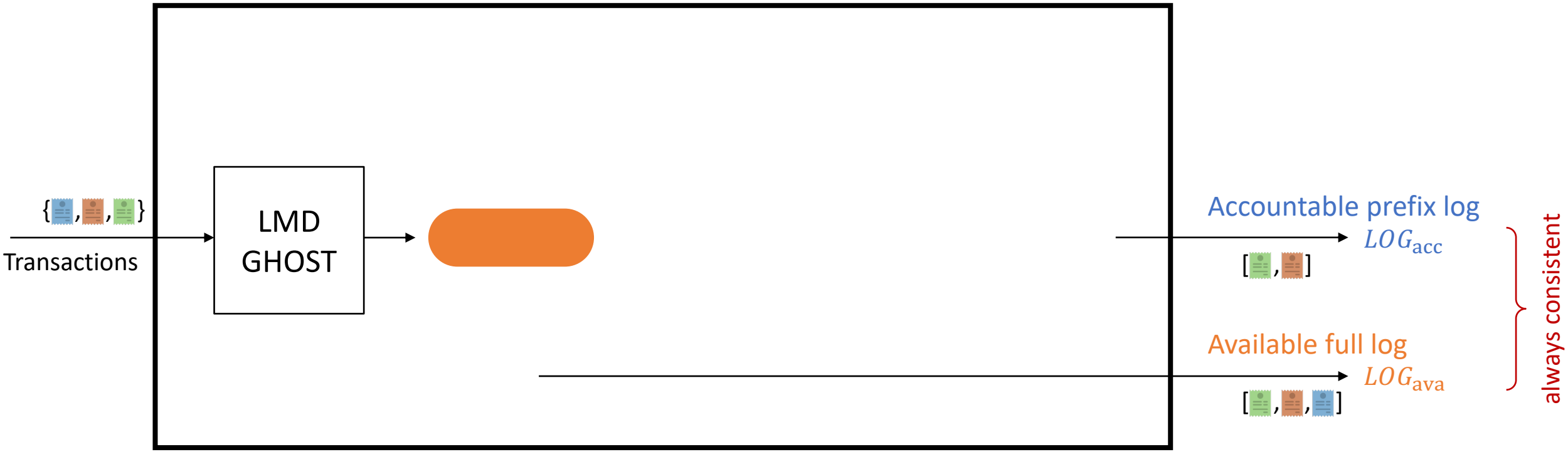




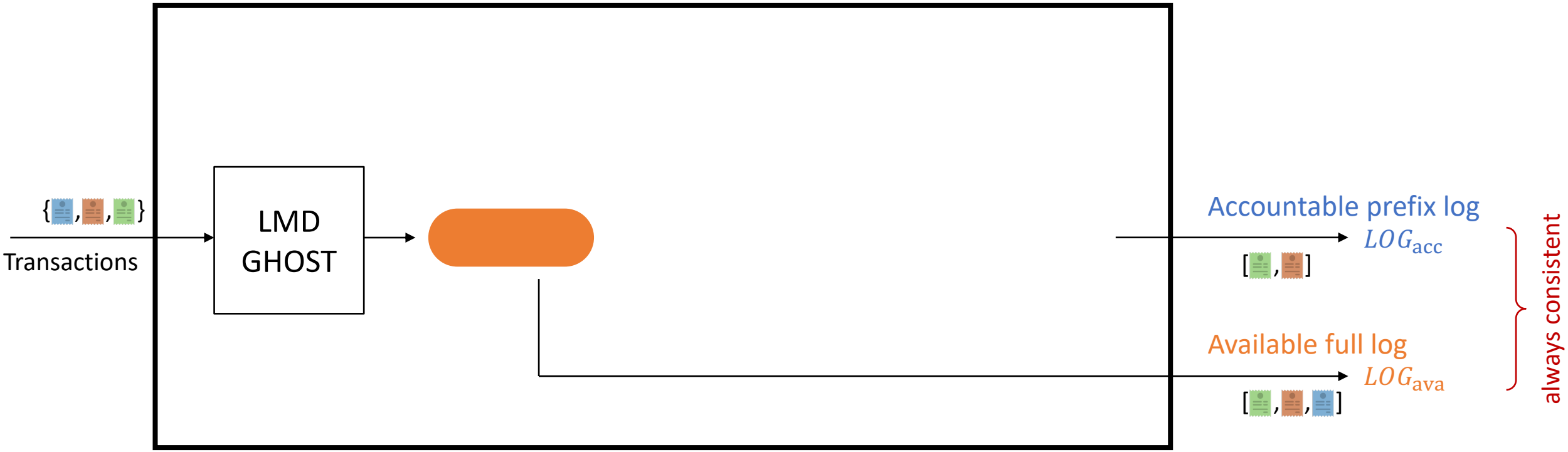
Each user can choose!

Ethereum Consensus

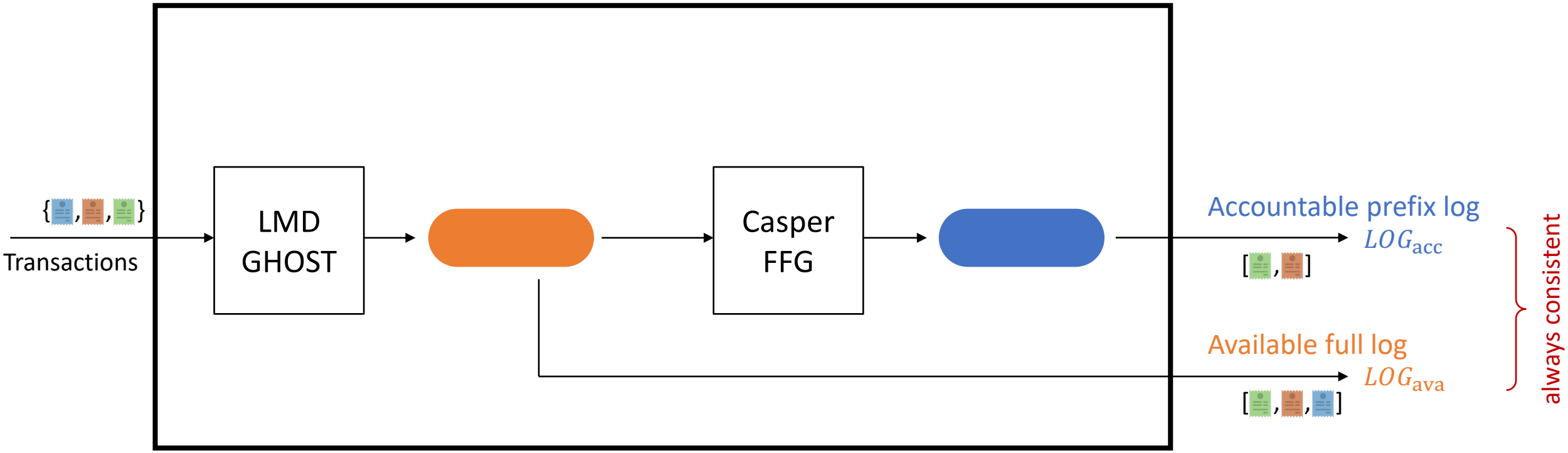
Ethereum Consensus



Ethereum Consensus



Ethereum Consensus



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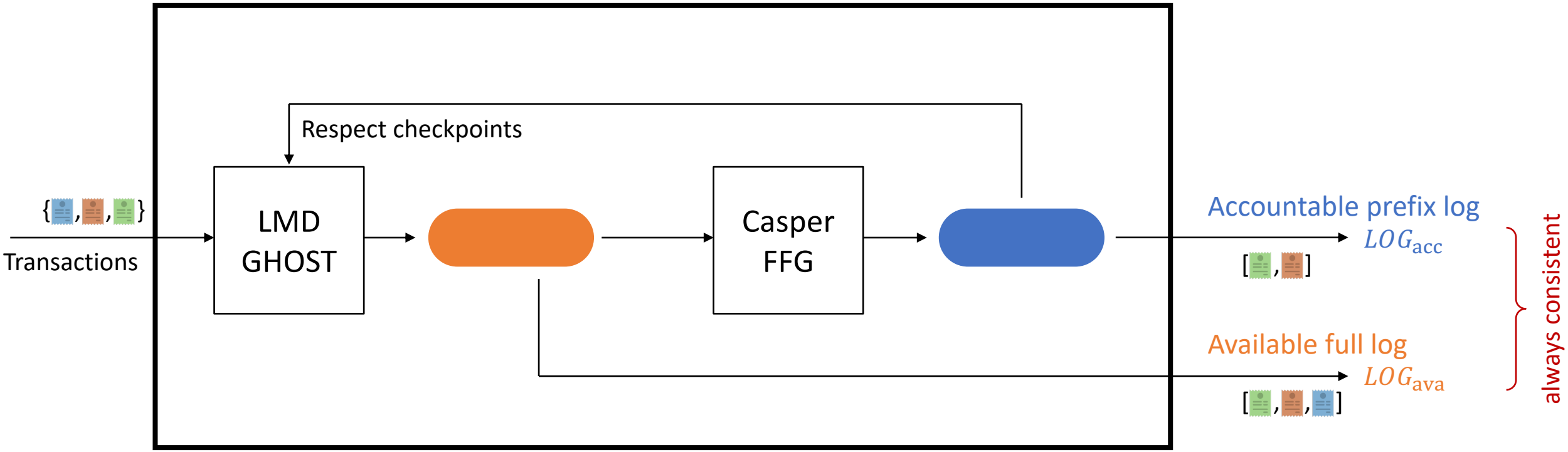

Ethereum Consensus

"Combining GHOST and Casper", Buterin et al. 2020
Construction: Neu et al. 2021, Sankagiri et al. 2021, Neu et al. 2022, Neu et al. 2024
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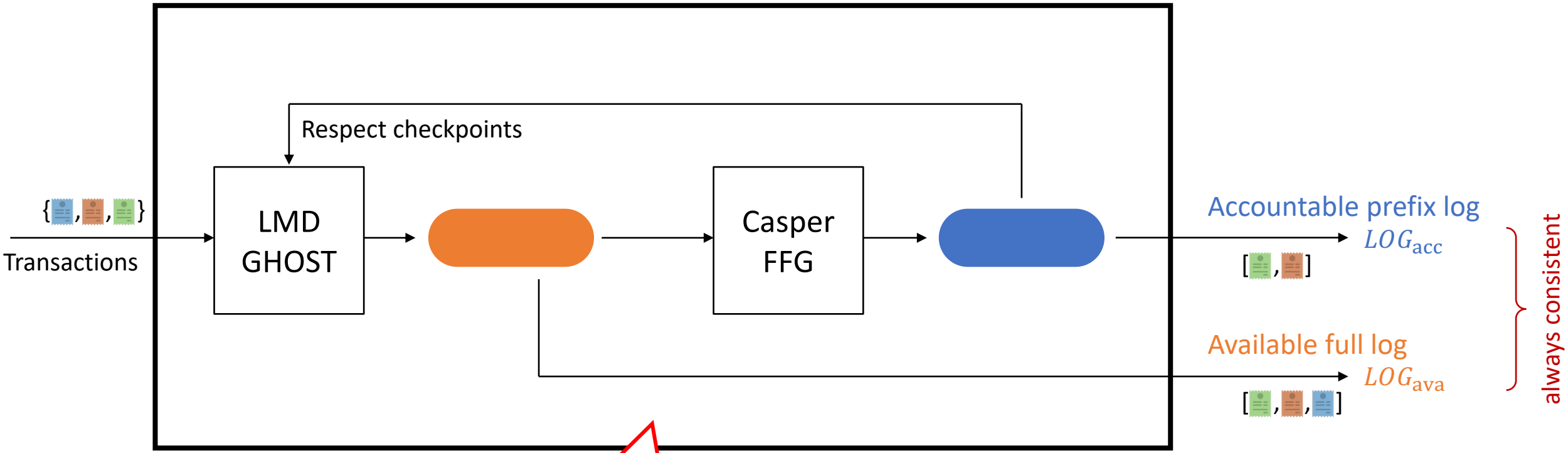

May look innocuous, but took a series of papers to get right!

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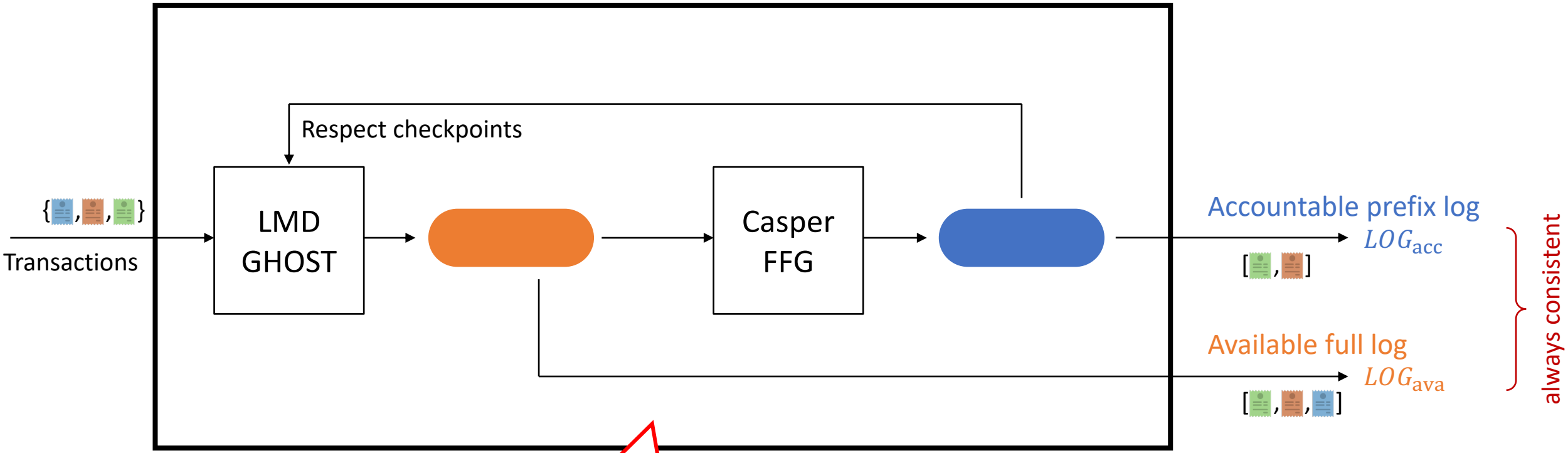

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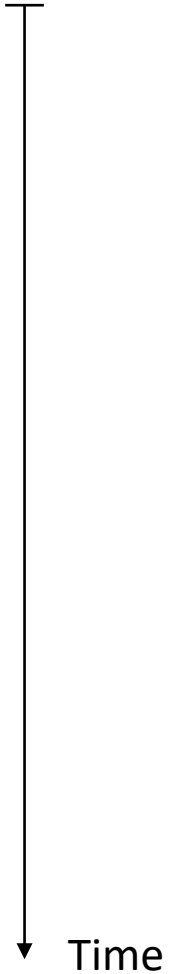
"Don't roll your own crypto(graphy)"
→ "don't roll your own consensus"

Proof-of-Stake

How to construct Π_{PoS} from $\Pi_{\mathrm{permissioned}}$

Proof-of-Stake

How to construct Π_{PoS} from $\Pi_{\mathrm{permissioned}}$



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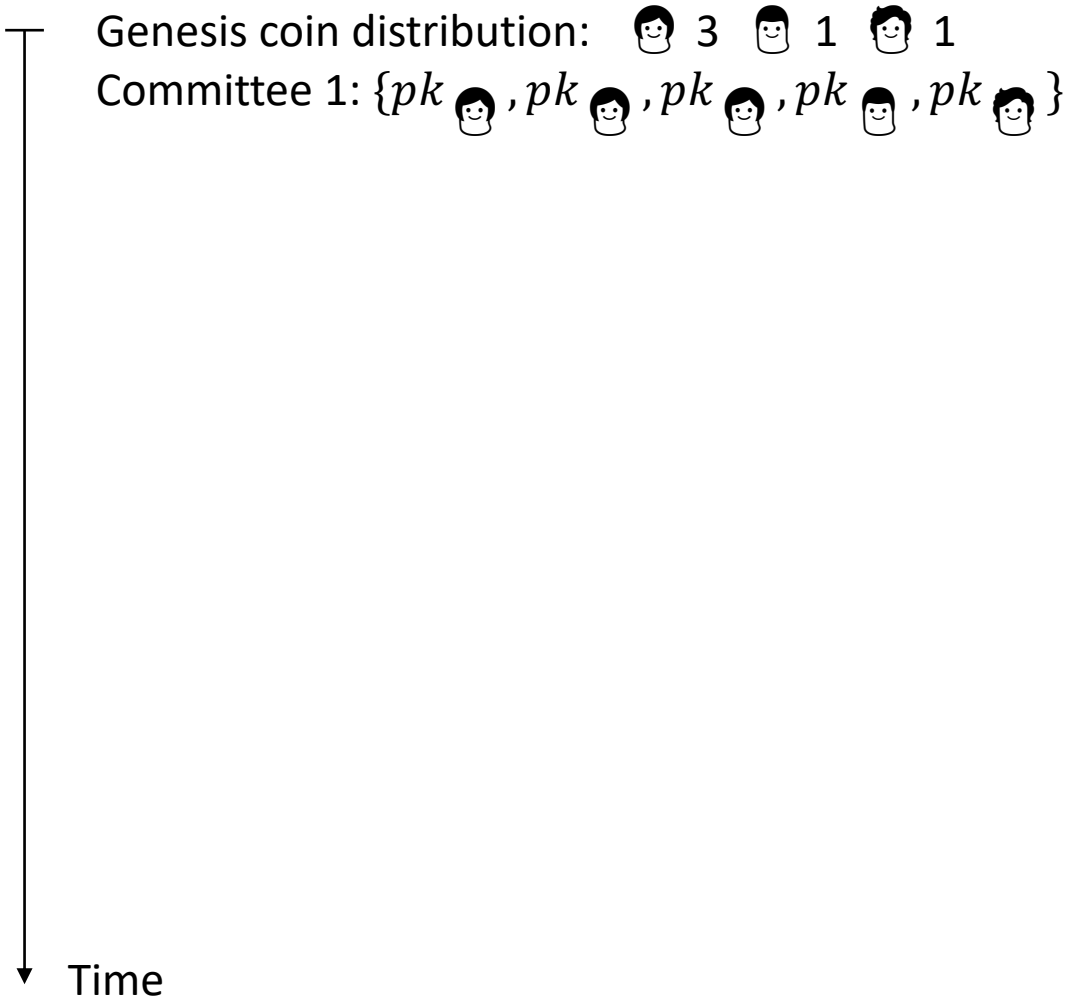

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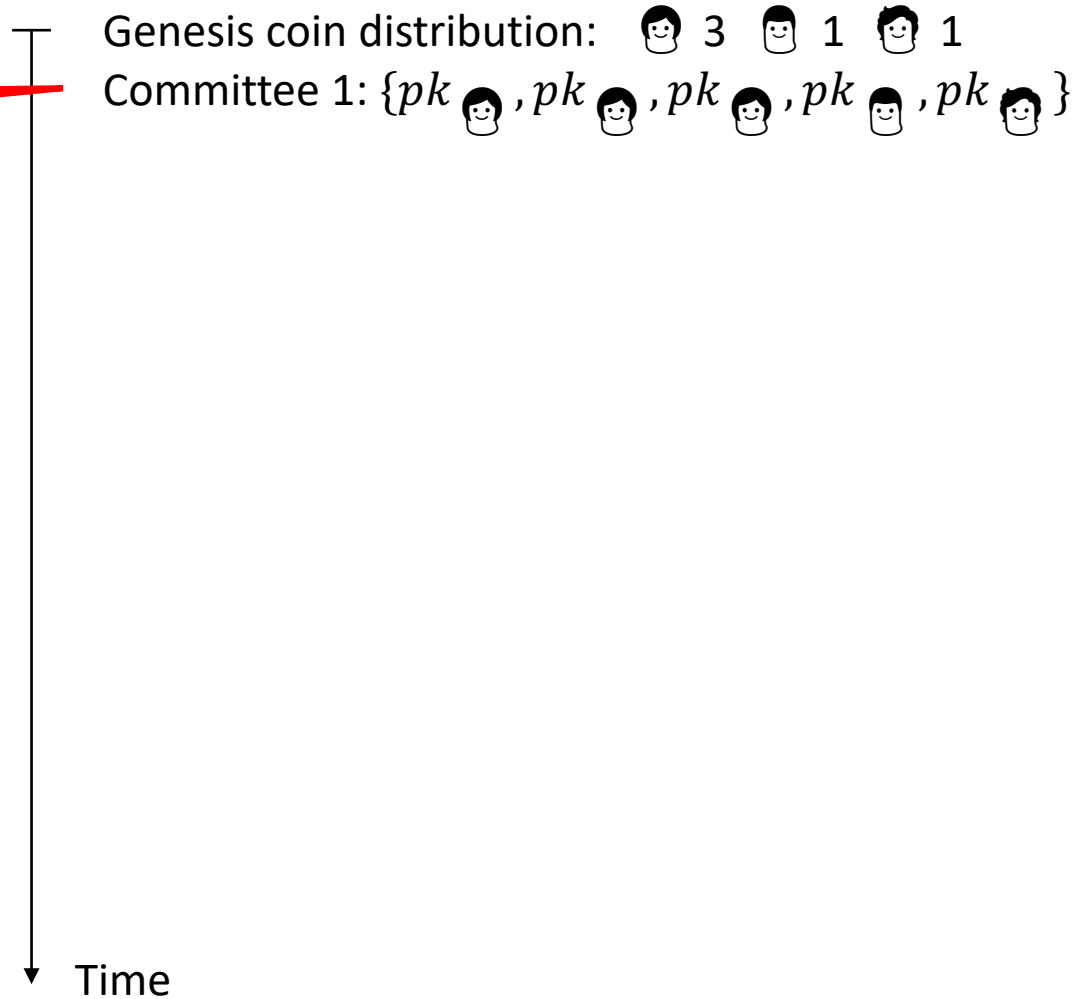
How to construct Π_{PoS} from $\Pi_{\text{permissioned}}$

Subsample committee of consensus nodes from coin holders



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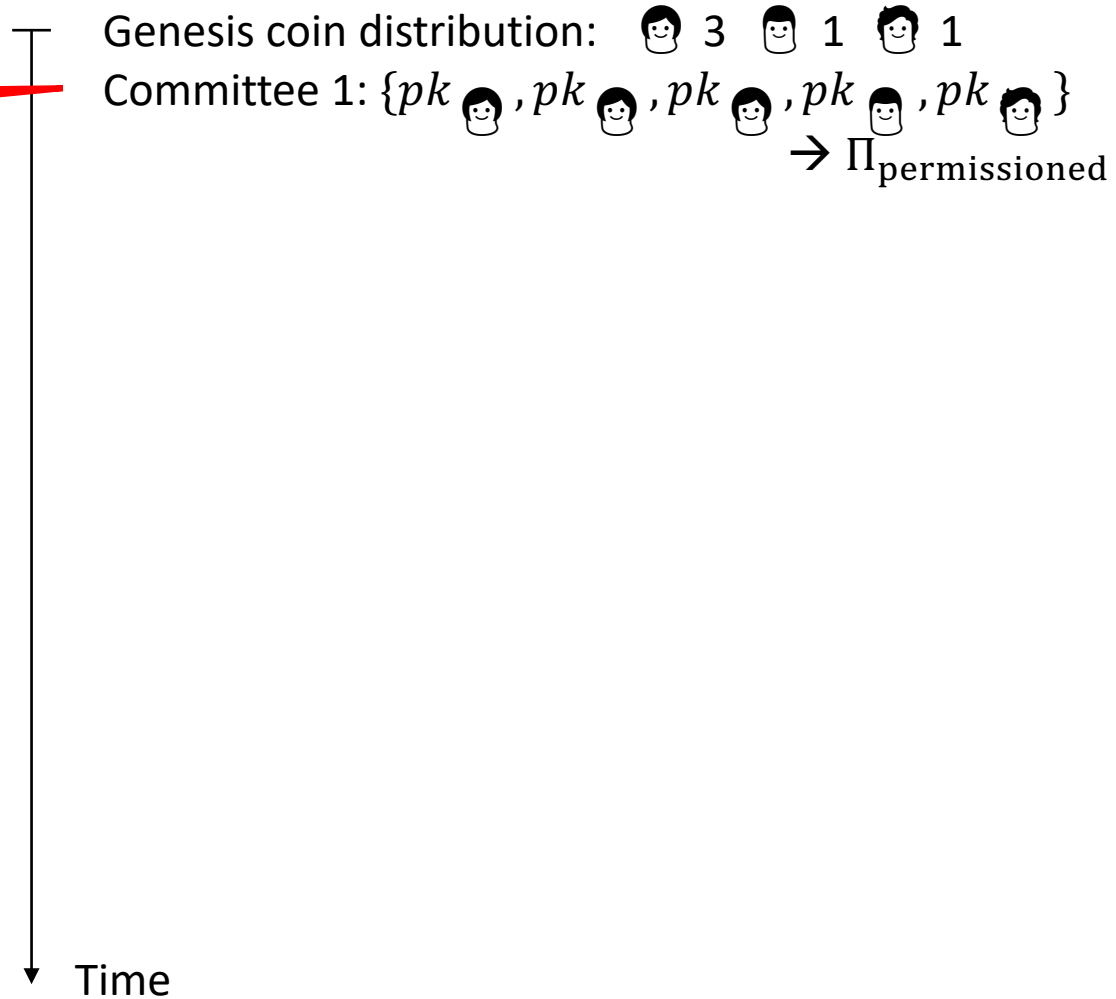

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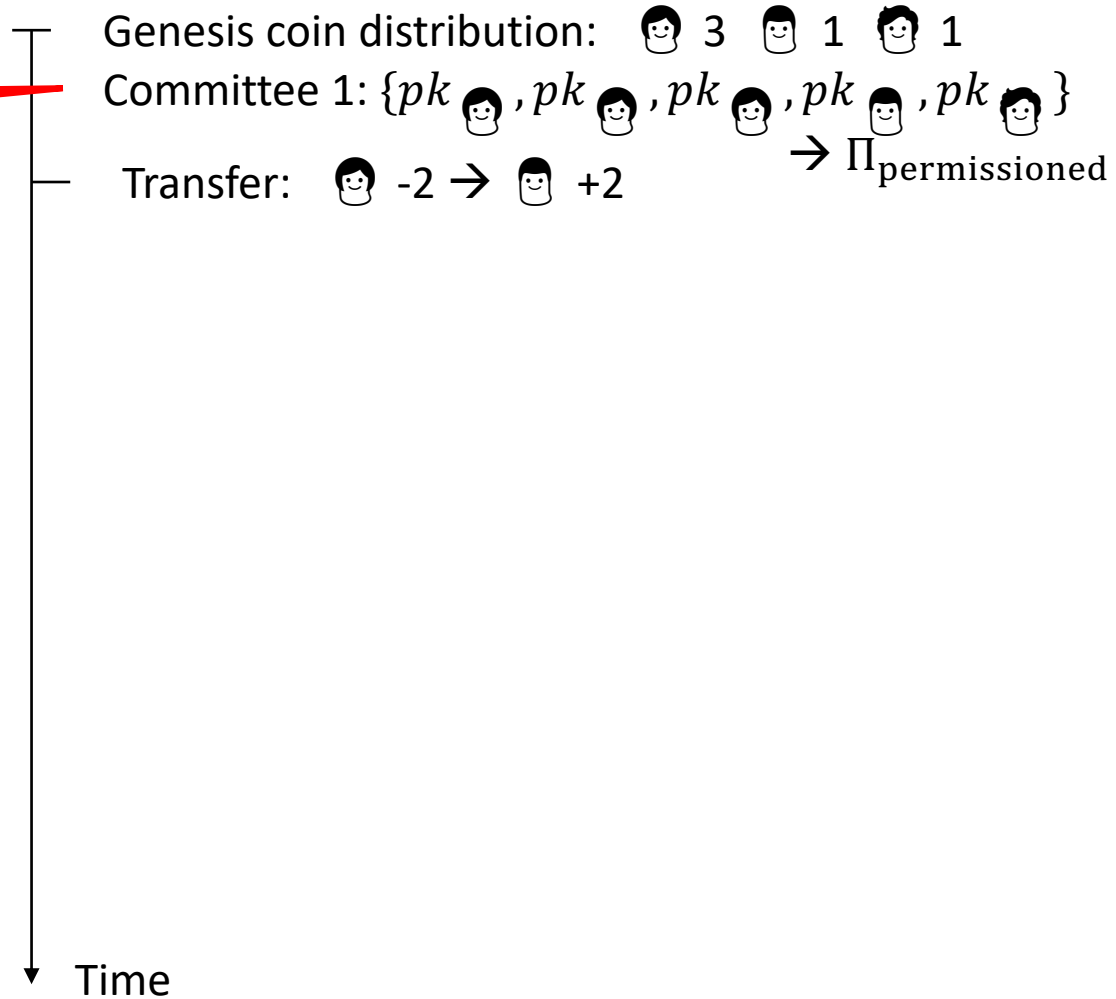

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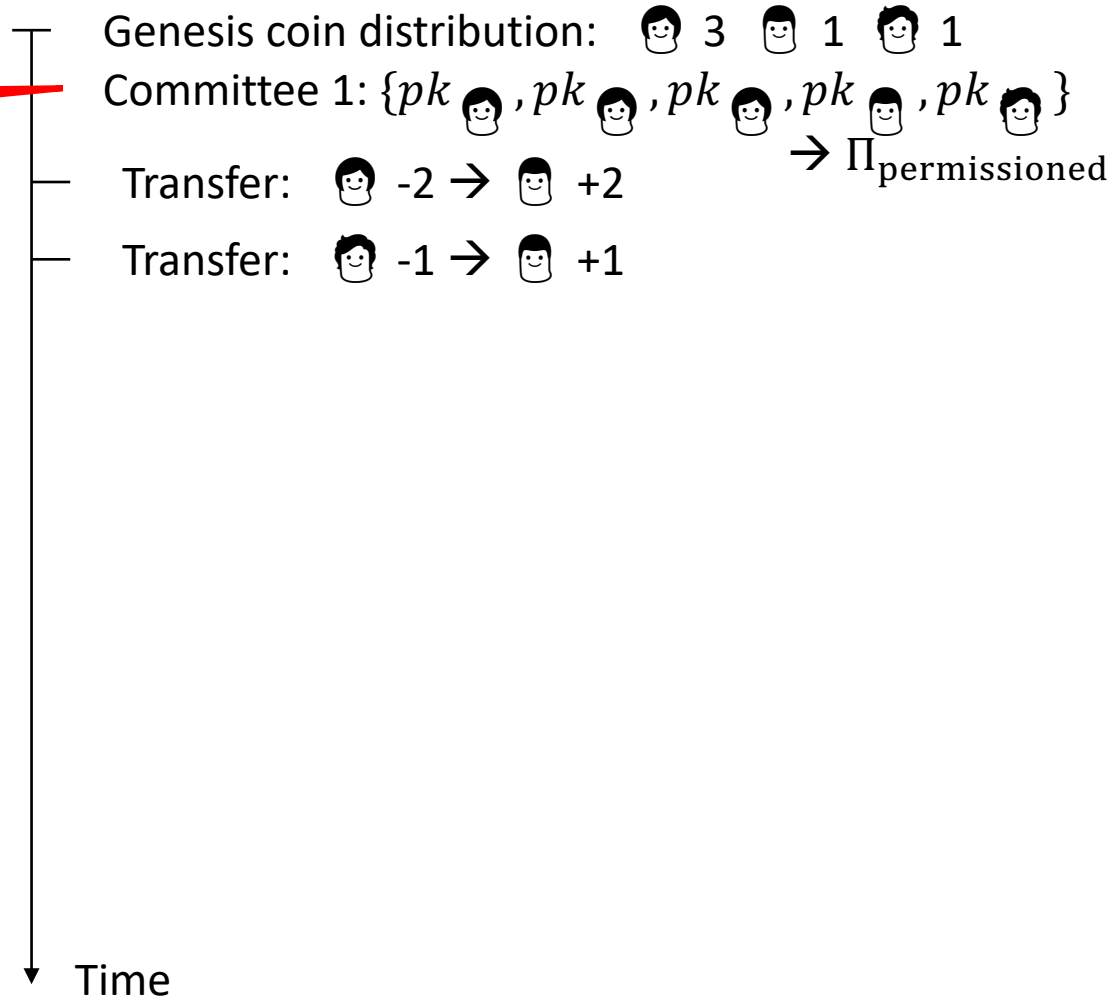

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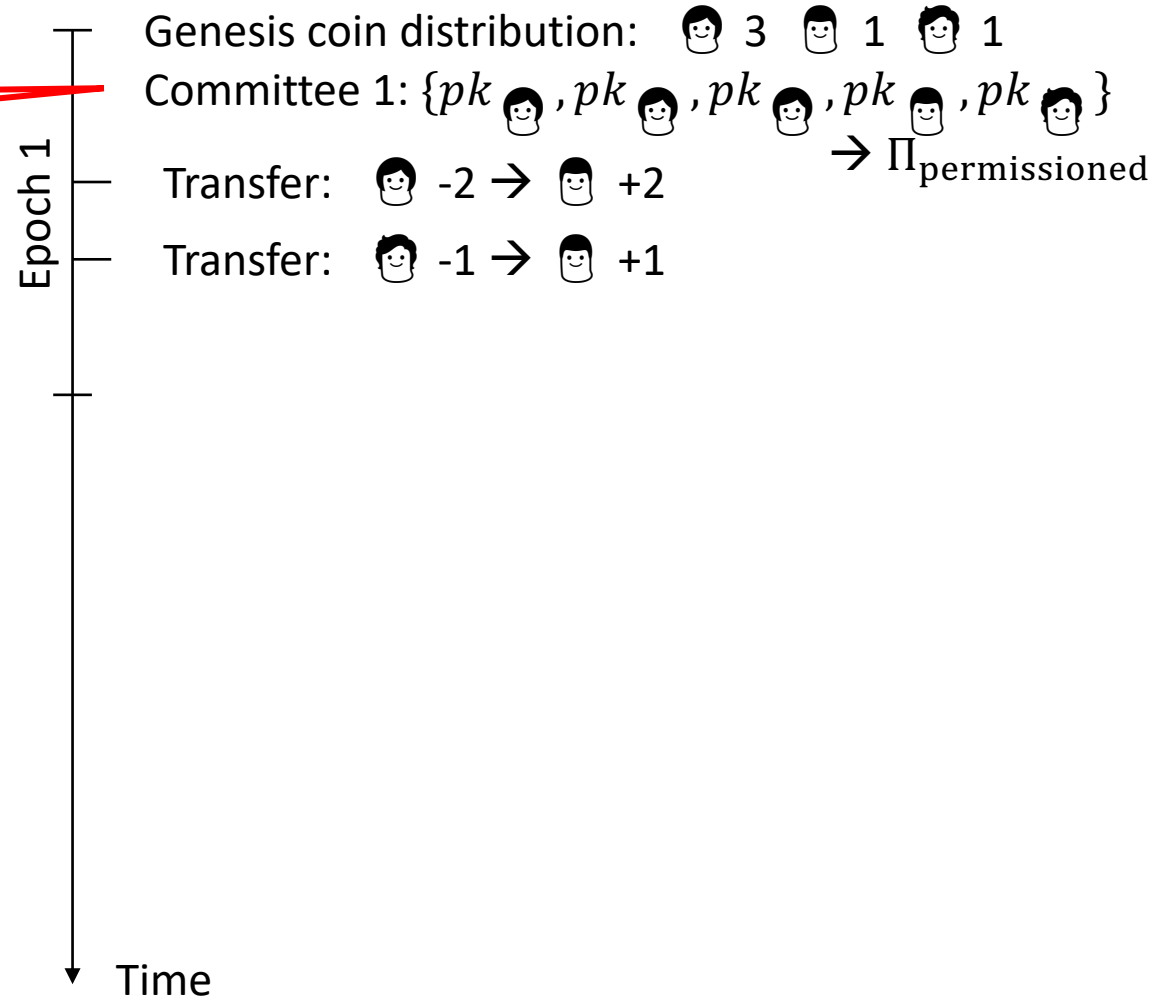

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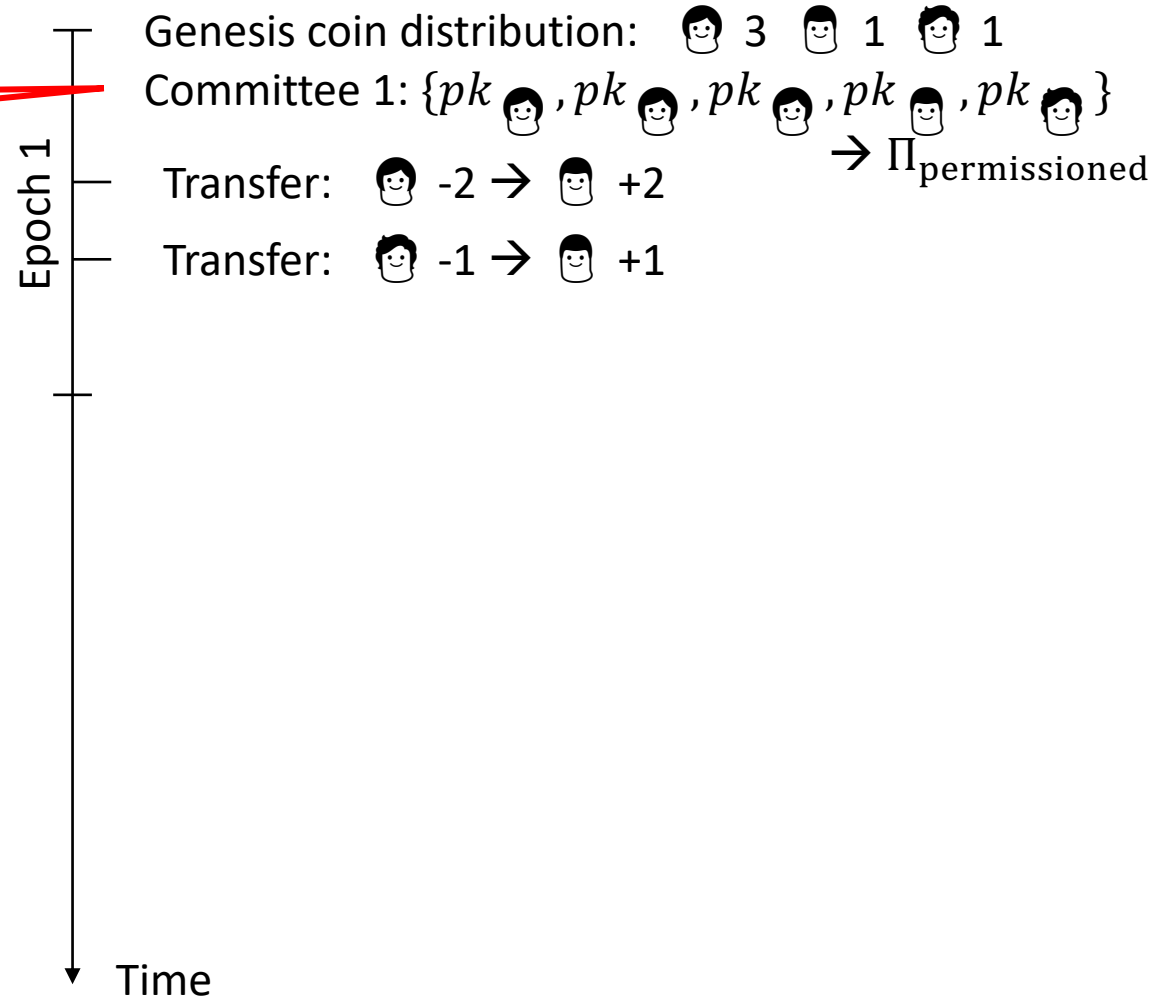
Subsample committee of consensus nodes from coin holders

Systems differ in length of epochs



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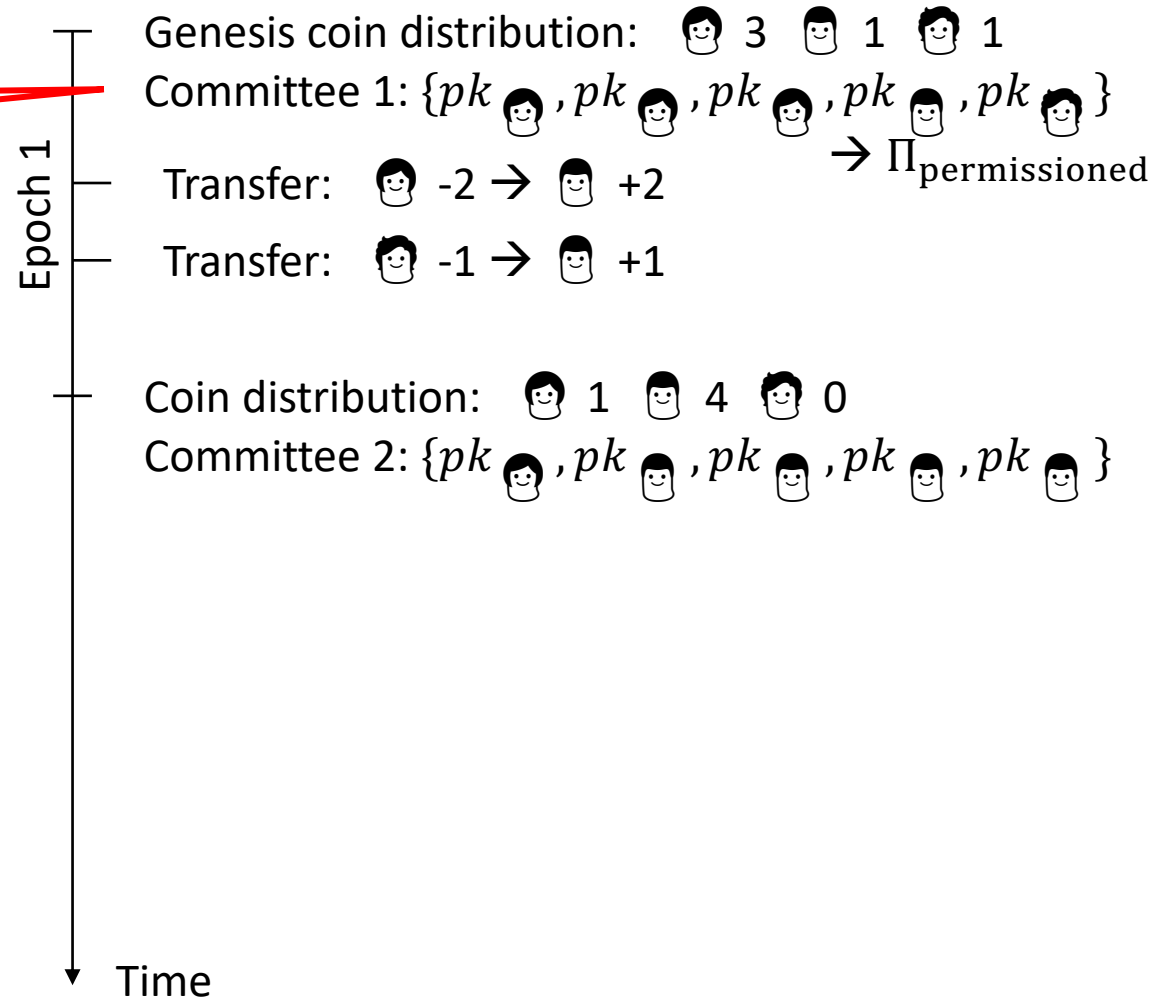

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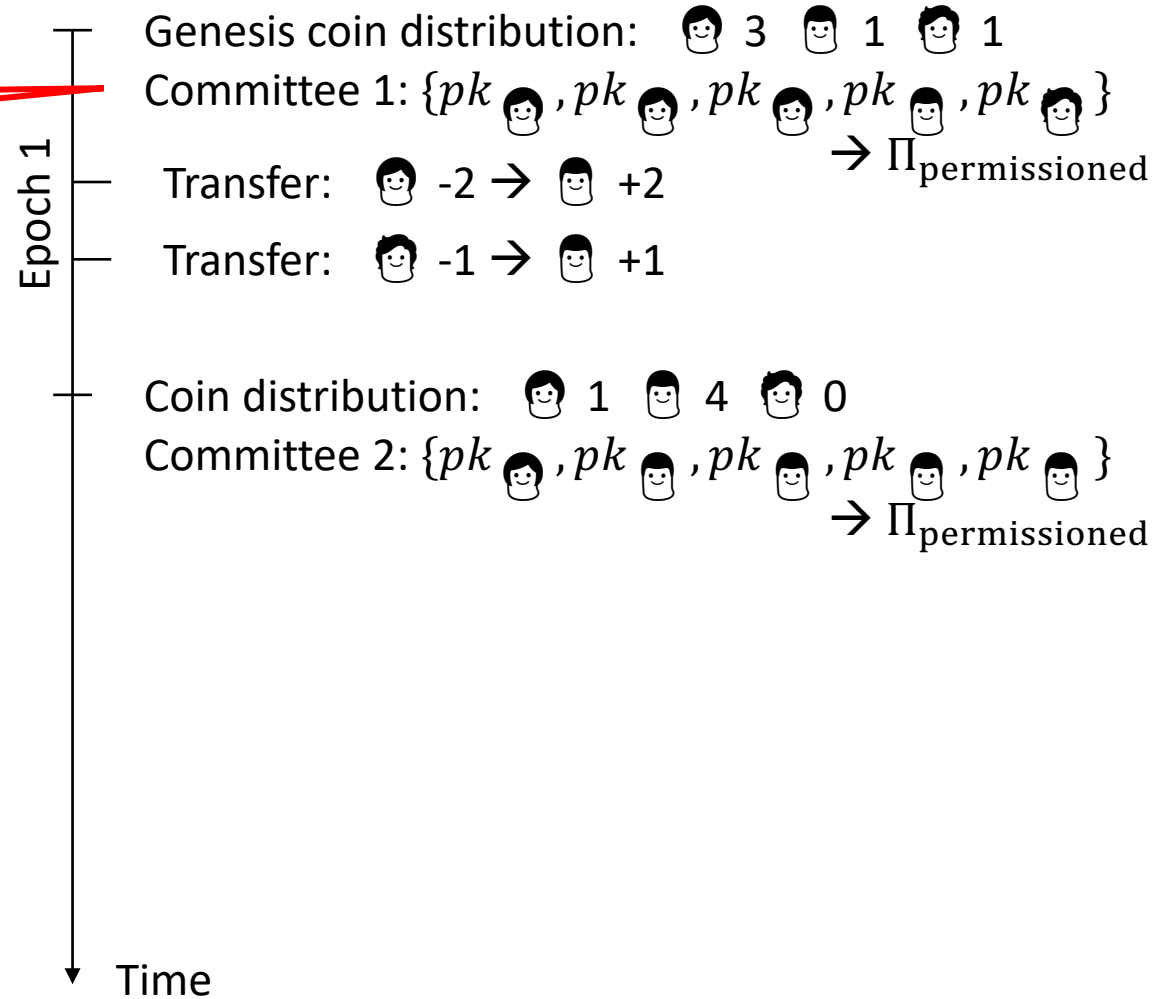

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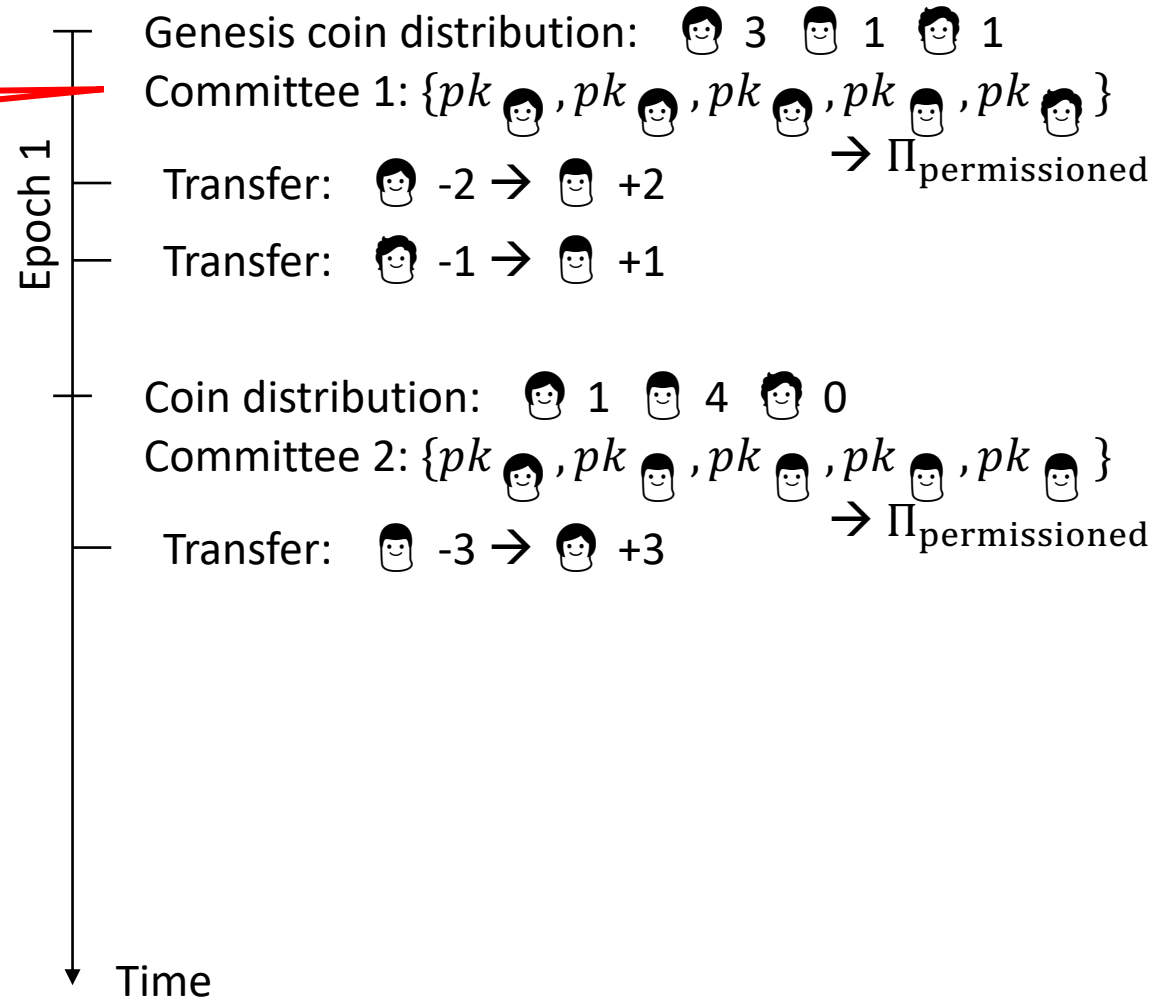

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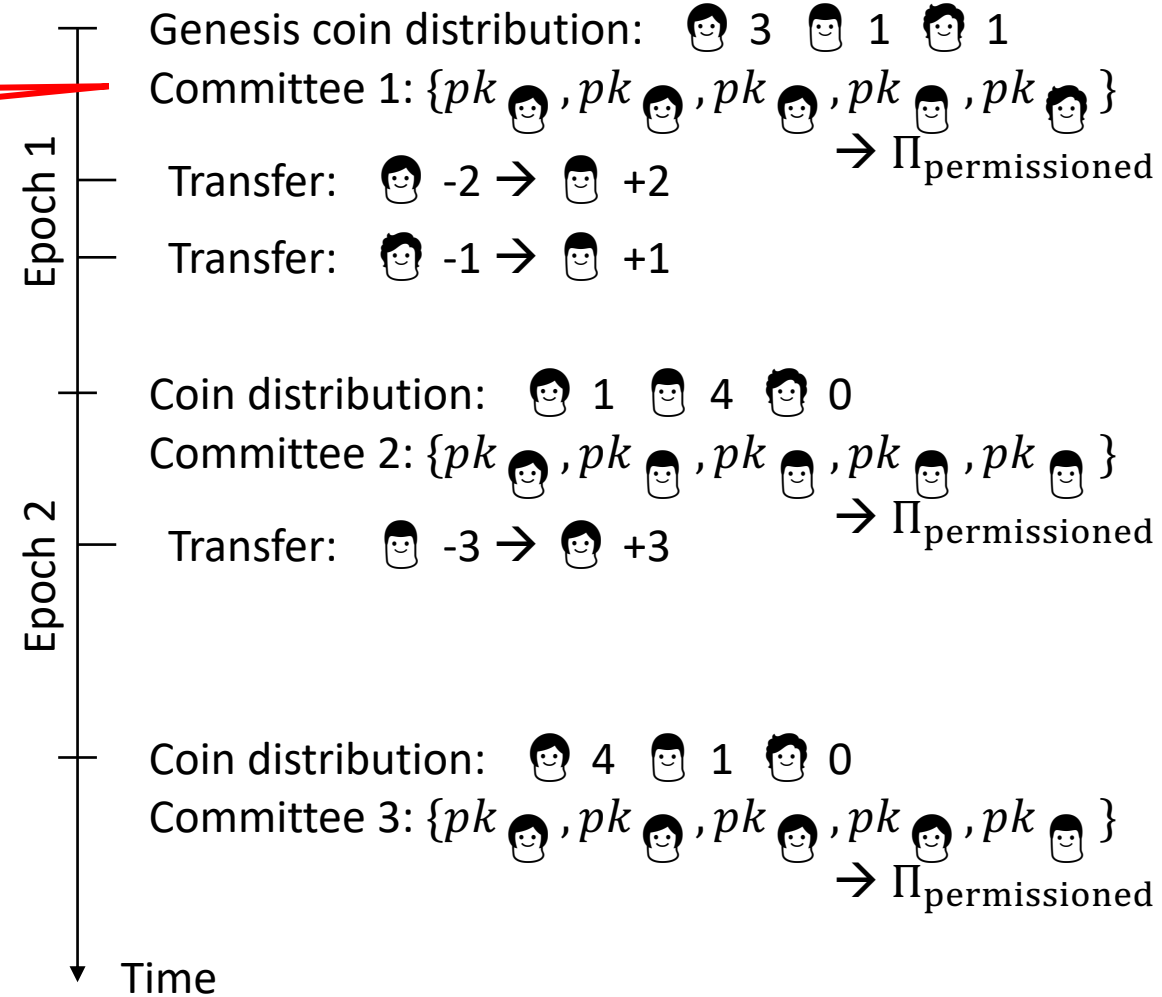

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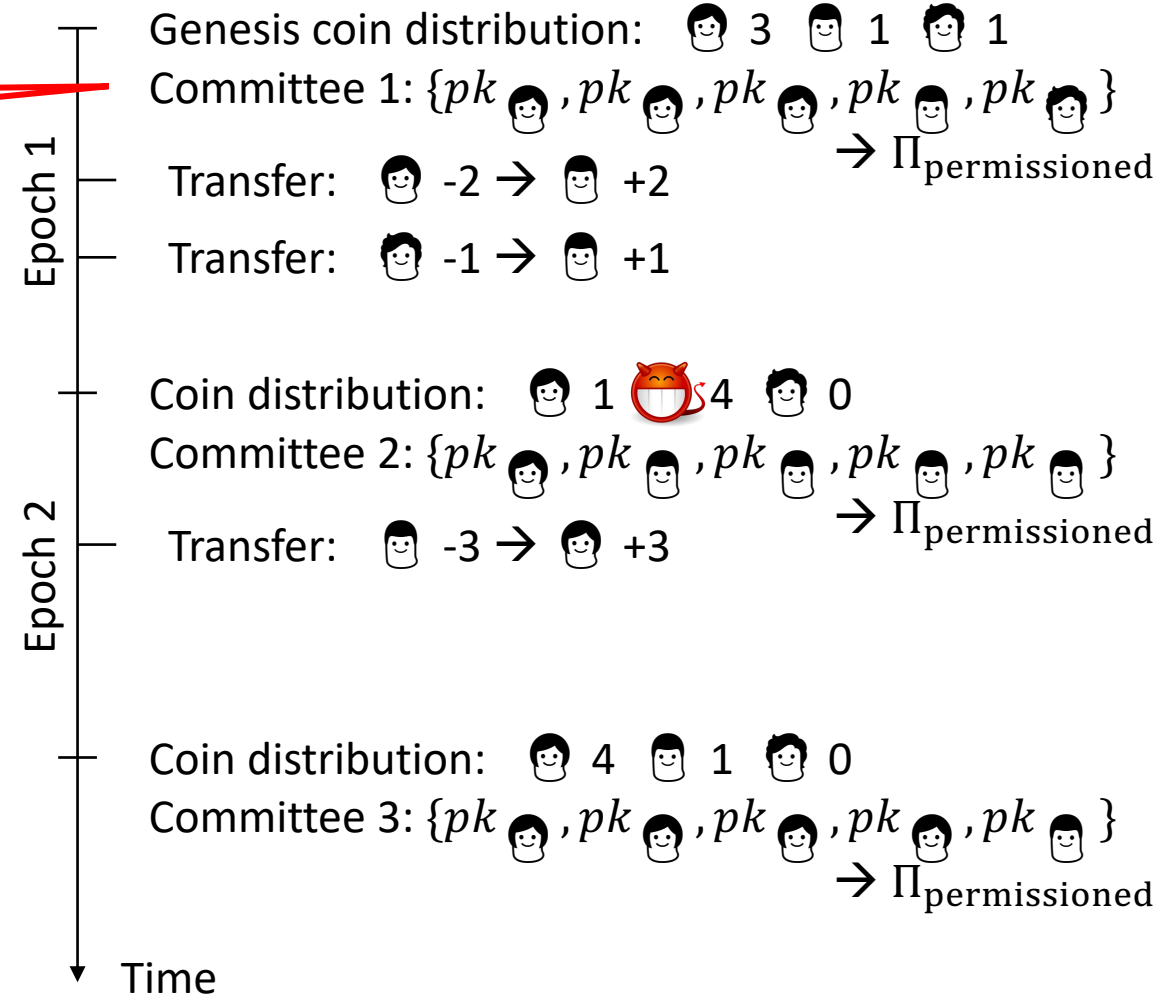
Subsample committee of consensus nodes from coin holders

Systems differ in length of epochs



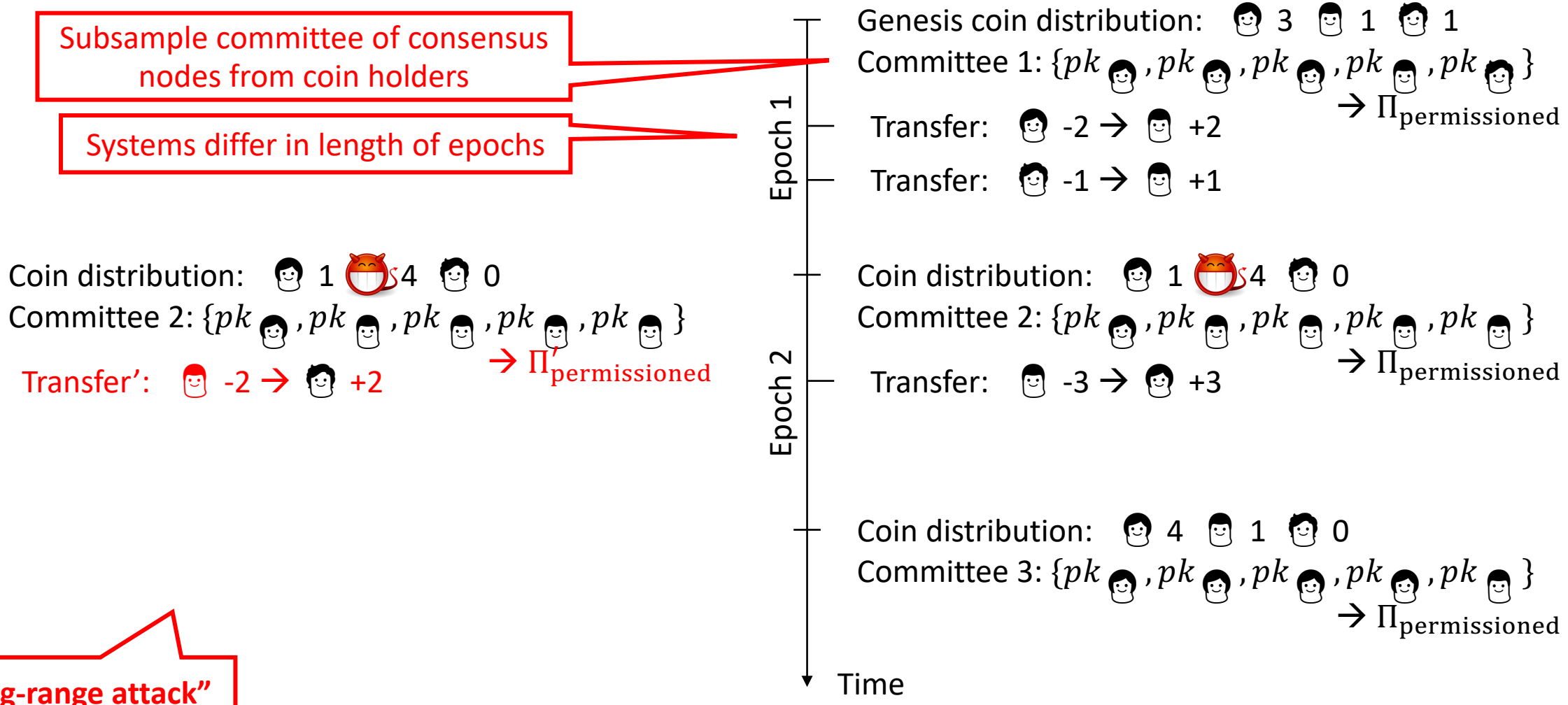
"Long-range attack"

Proof-of-Stake

How to construct Π_{PoS} from $\Pi_{\text{permissioned}}$

Subsample committee of consensus nodes from coin holders

Systems differ in length of epochs



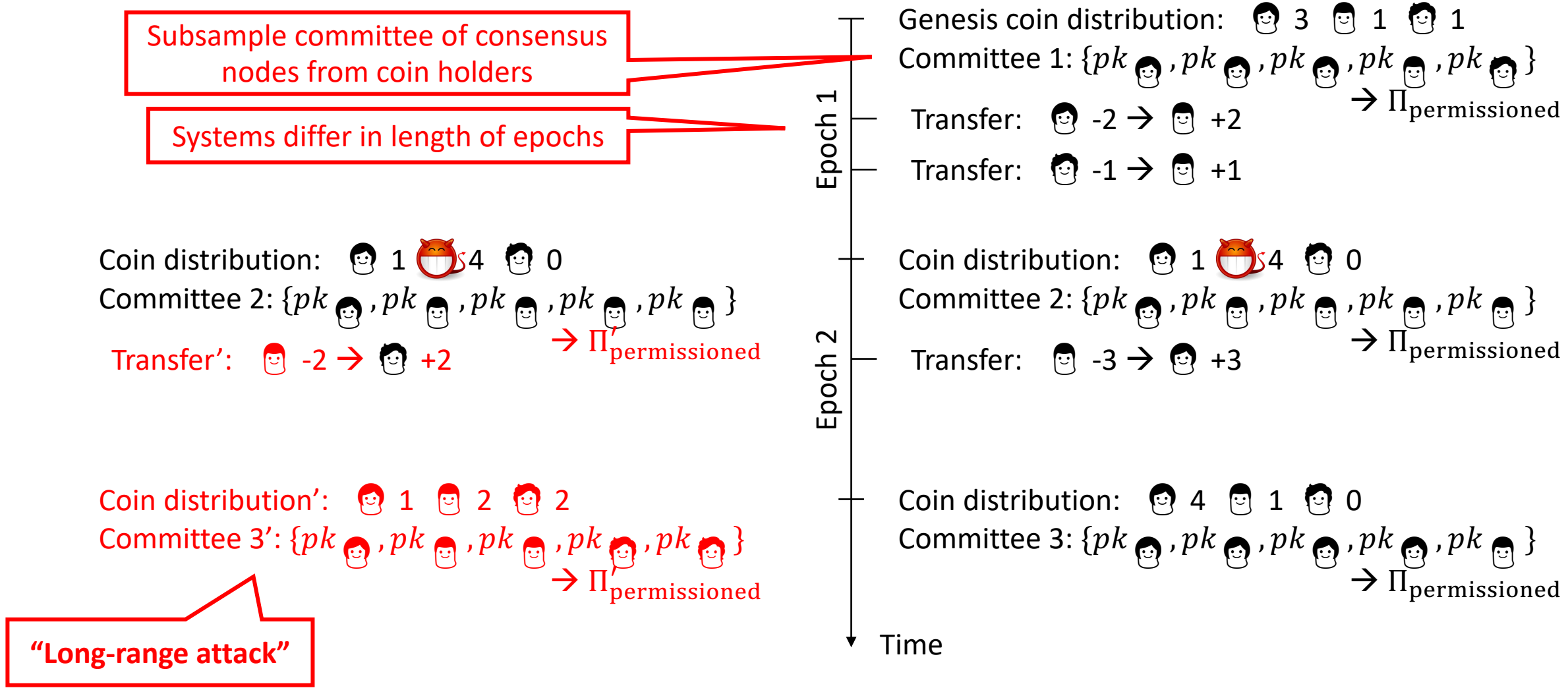
Coin distribution: 1 4 0
Committee 2: $\{pk, pk, pk, pk, pk\}$
→ $\Pi'_{\text{permissioned}}$

Transfer': -2 → +2

"Long-range attack"

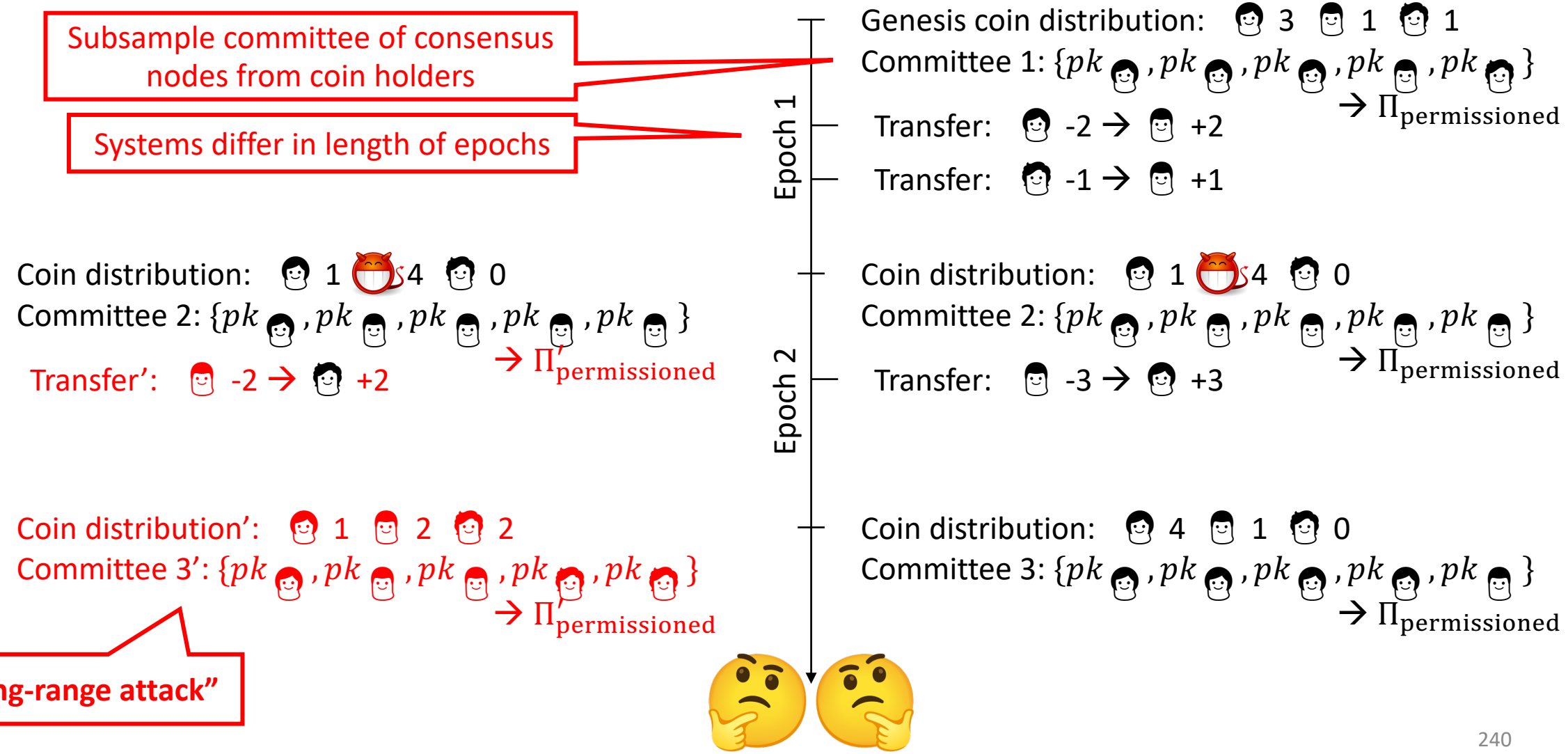
Proof-of-Stake

How to construct Π_{PoS} from $\Pi_{\text{permissioned}}$



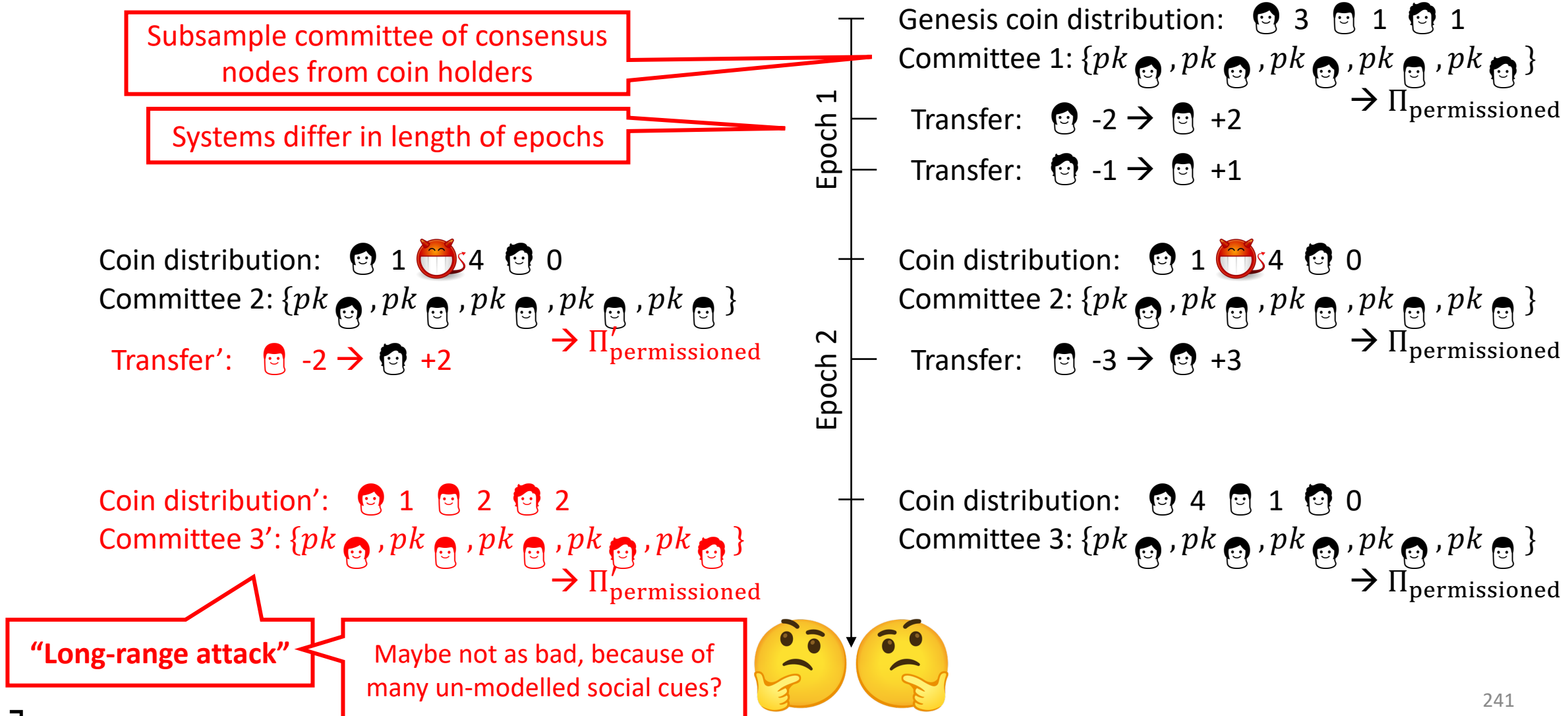
Proof-of-Stake

How to construct Π_{PoS} from $\Pi_{\text{permissioned}}$



Proof-of-Stake

How to construct Π_{PoS} from $\Pi_{\text{permissioned}}$



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