Proof of Stake Blockchain Protocols

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INPUT | OUTPUT

based on joint works with:

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The Ledger Objective

- First formal definition of the objective of a “robust transaction ledger” was formulated by
  Garay, **K**, Leonardos in [GKL15]
  https://eprint.iacr.org/2014/765

  Follow up work refined model and definition:

  [**K**P15] - property definitions
  [PSS17] - partial synchrony / property definitions
  [BMTZ17] - simulation based definition / composition

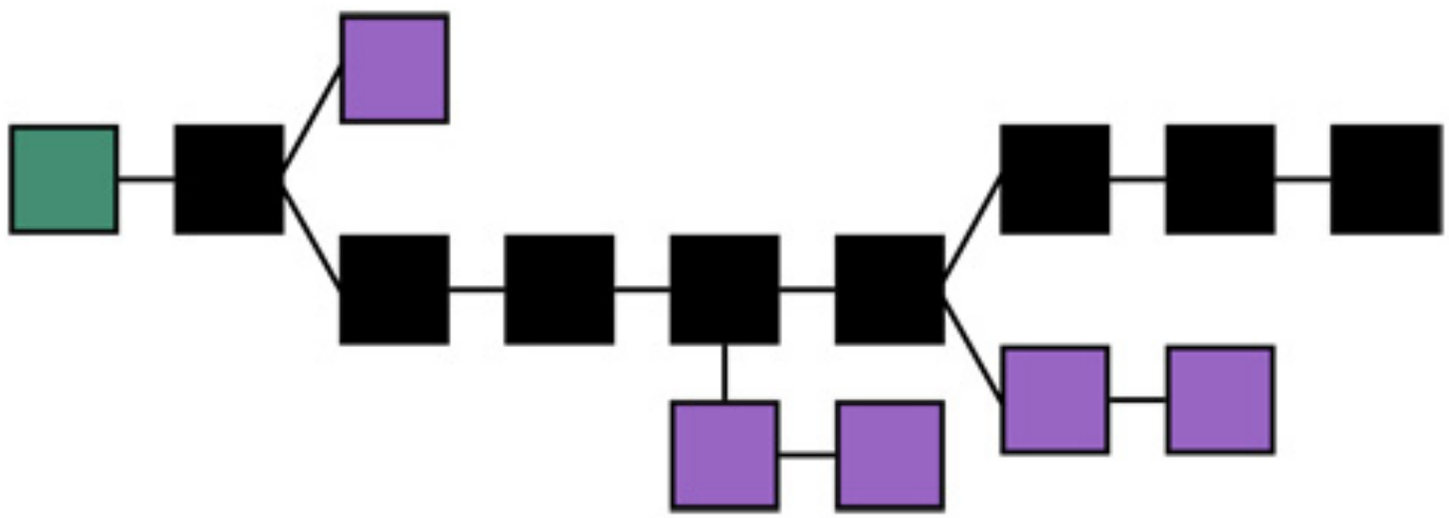
Realizing the Ledger

- The ledger can be realized by bitcoin
- But the protocol exhibits significant **scalability** and **energy efficiency** disadvantages.
- Can we realize it in a more efficient way?

"**Proof-of-Stake**" (PoS) was one alternative that was discussed early on in the bitcoin forum

PoS background

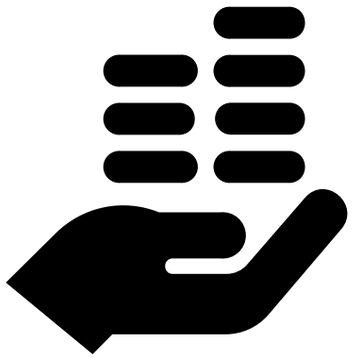
generating the next block in bitcoin is like an election



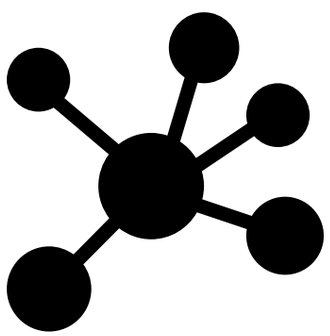
A miner is elected with probability proportional to its hashing power.

Collisions may occur but they can be resolved by the longest chain rule or a similar concept

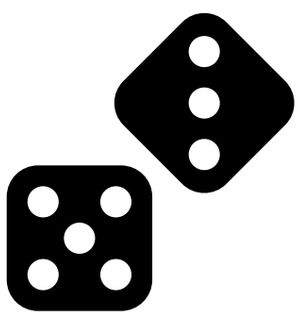
PoS



Use stake instead of hashing power.

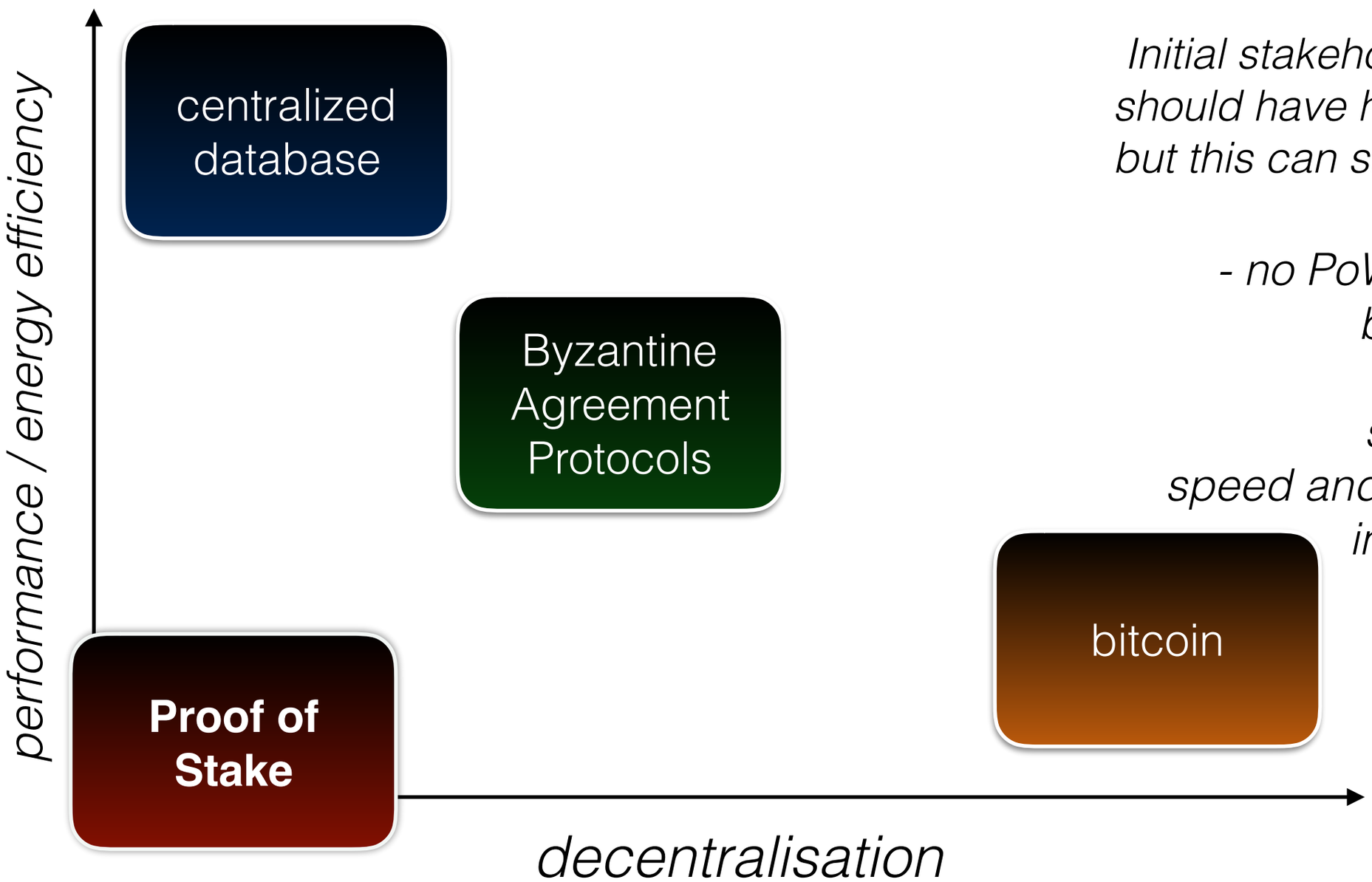


Define the set of miners to be the set of all stakeholders, as reported in the ledger.



Use a **randomised process** that takes the current stake into account to elect the next miner eligible to produce a block.

Performance vs. Decentralization



Initial stakeholder distribution should have honest majority, but this can shift over time

- no PoW requirement - blockchain runs at maximum synchronization speed and scales without increasing costs

Design Challenges Specific to PoS

- **Grinding attacks.** The adversary may try to bias the random election process in its favor, trading hashing power for a more favorable protocol execution.

- **Nothing-at-stake.** the adversary may try multiple alternative histories (even from any point in the past).

- **Circularity**. if injecting fresh randomness is done via the blockchain - how can we avoid circularity in the security argument? (*blockchain is secure b/c of randomness, and randomness is unbiased b/c of blockchain*).

The Ouroboros PoS Protocols

- **Ouroboros**: synchronous setting, corruptions with delay, slow & clean beacon implementation (PVSS-based).
- **Ouroboros Praos**: semi-synchronous setting, fully adaptive corruptions, fast & dirty beacon implementation (hash-based).

Design Methodology

- **Stage 1. Static State.** Assume that initial stakeholder distribution remains the root of trust of the system.

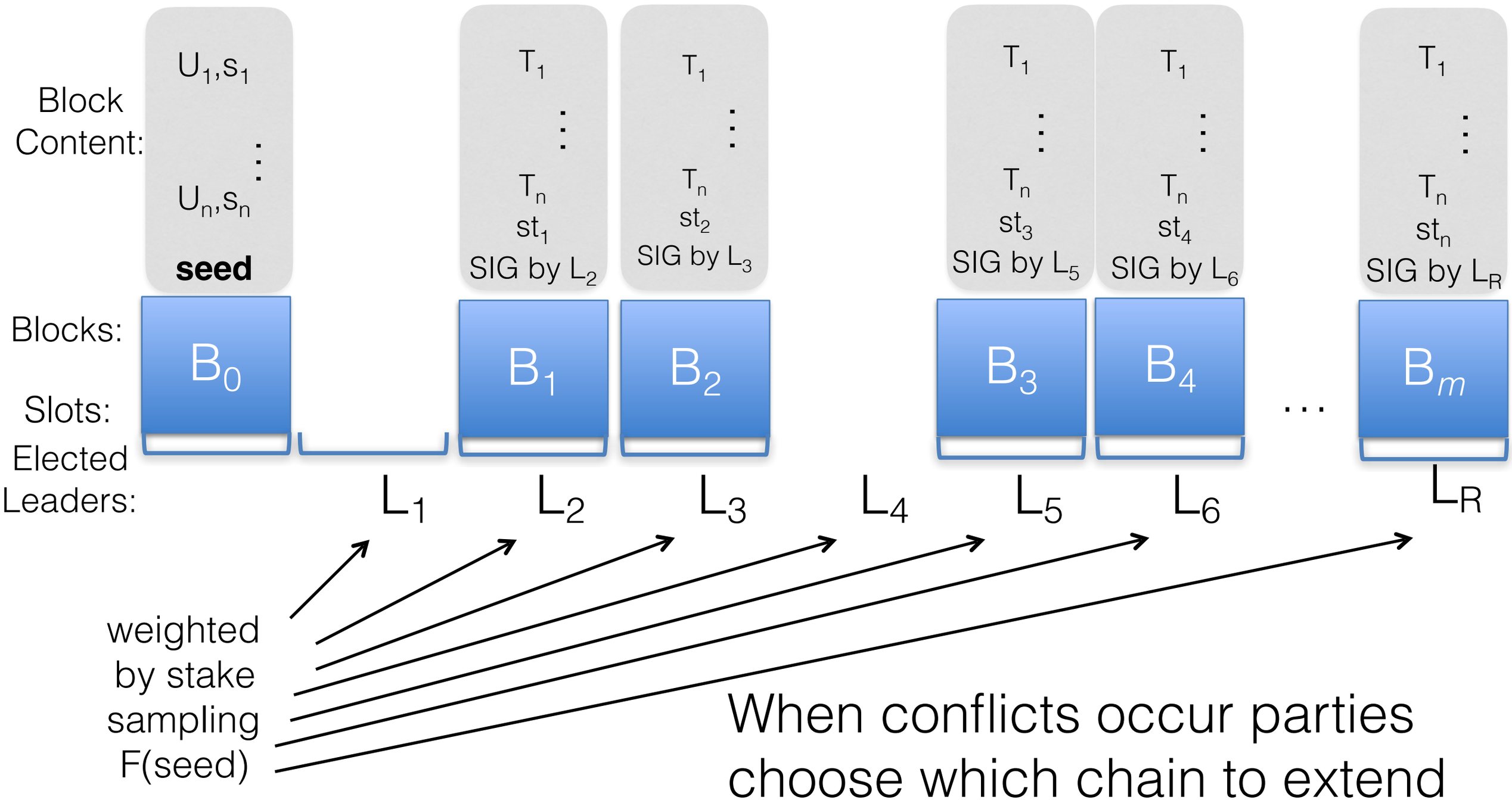
- **Stage 2. Using a semi-trusted beacon (some leakage / adversarial control)** Assume a randomness beacon emits a seed in regular intervals and show how this can be utilized to let the roof to trust stakeholder distribution evolve.

- **Stage 3. Implement the beacon via protocol that uses the blockchain.** remove the trusted beacon by having the elected subset of stakeholders simulate it cryptographically.

Synchronous Setting

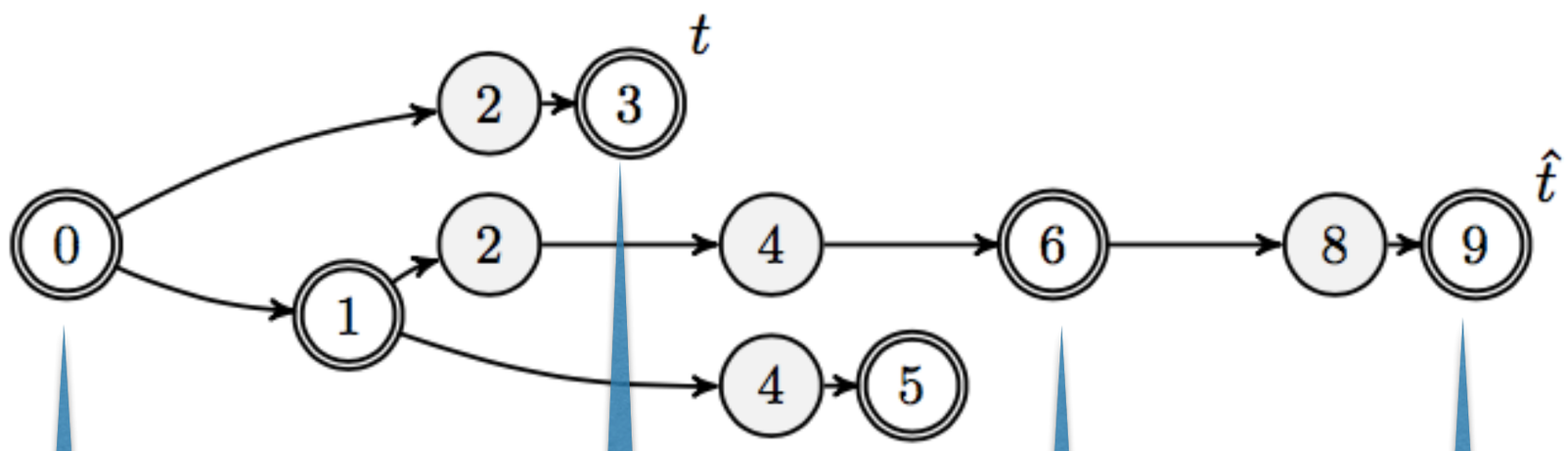
- Time is divided in rounds (we will call them ***slots***)
- messages are sent through a “diffusion” mechanism
- The adversary is rushing and may :
  1. spoof messages
  2. inject messages
  3. reorder messages

Ouroboros : Static Stake



When conflicts occur parties choose which chain to extend based on **longest chain rule**

Forks and Protocol Executions



Characteristic string $w = 0\ 1\ 0\ 1\ 0\ 0\ 1\ 1\ 0$

$$w_i = \begin{cases} 0 & i\text{-th slot belongs to an honest party} \\ 1 & i\text{-th slot belongs to a malicious coalition} \end{cases}$$

Genesis

honest party produce block 1

adversary serves block 2 to honest party

adversary serves block 4 to honest party

adversary serves new block 2,4 to honest party

adversary serves block 8 to honest party

Analysis

- The adversary is at a **much better position** in this protocol execution compared to Bitcoin's PoW-based execution.

  - it can **see** ahead of time how stakeholders are activated.

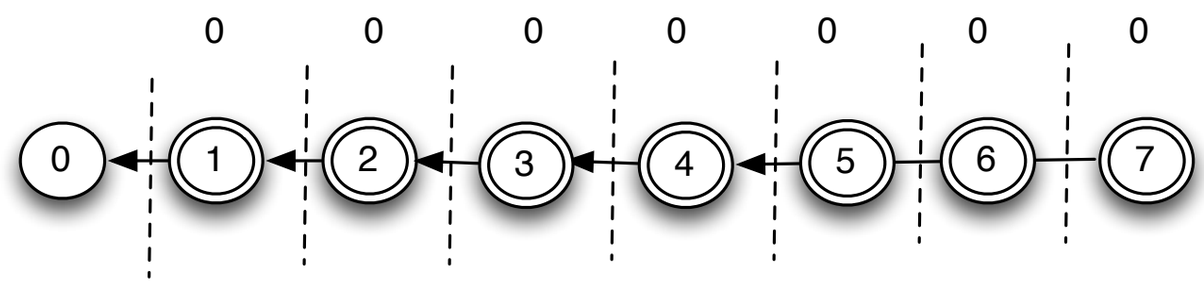
  - it can **generate multiple** different blocks for the **same slot** at any time **without cost**.

  - it can **wait** and act just before an honest party comes online.

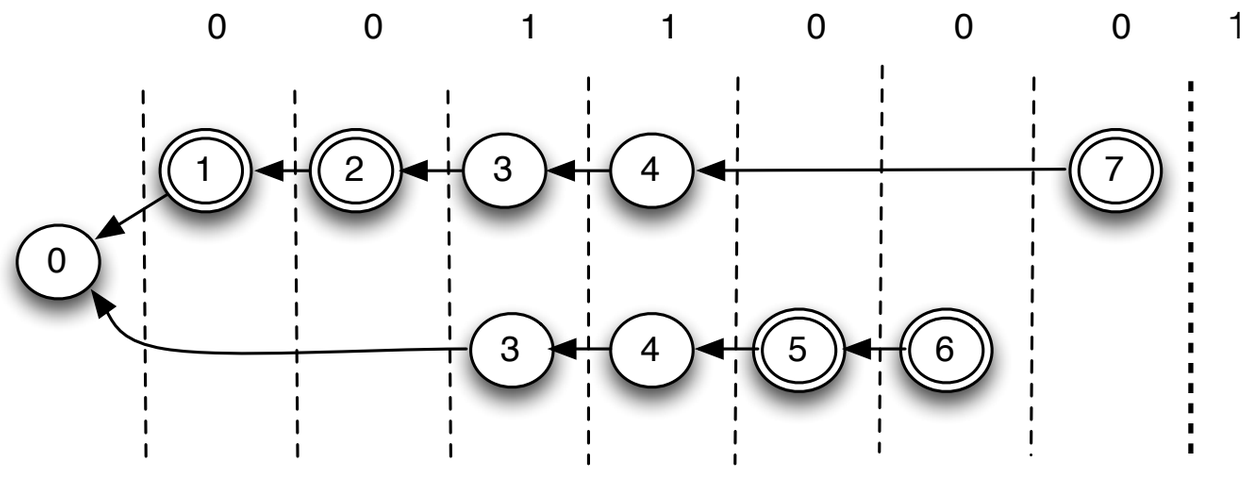
Forkable Strings

The characteristic strings the adversary prefers!

Not Forkable!

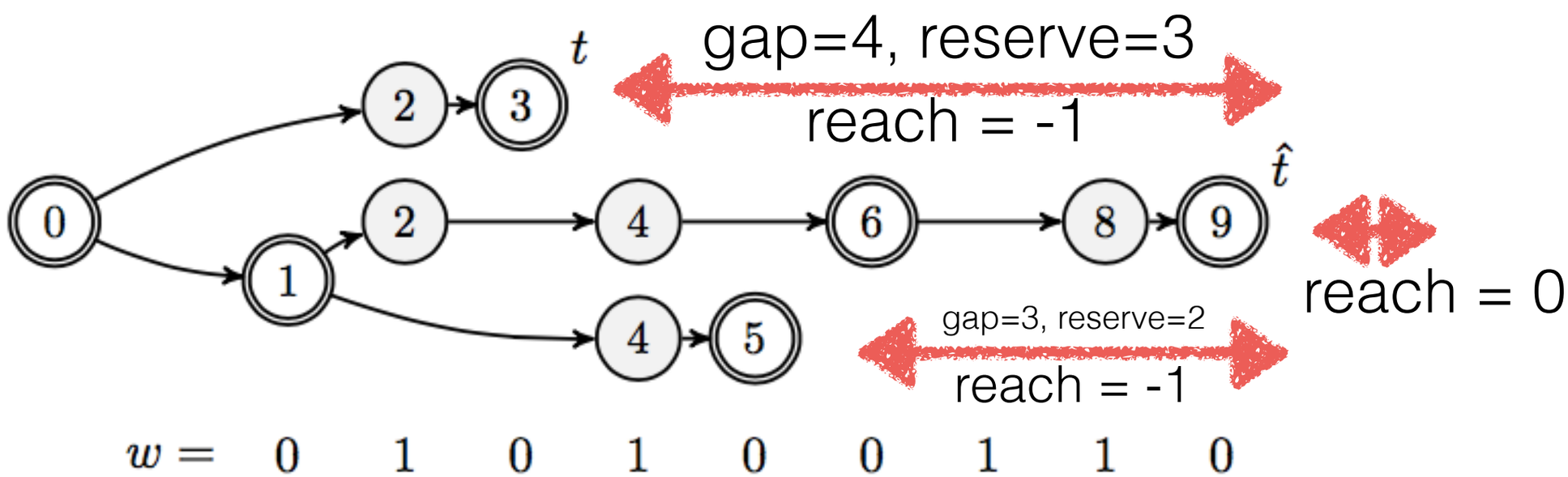


Forkable!



Reach/Margin of Closed Forks

closed fork: ends only in honest leaves



Reach : maximum *reach* across all tines

Margin : the penultimate *reach* across edge-disjoint tines

Theorem : A string is forkable iff for some closed fork it holds that *margin* is >=0

Recursive Formula for Reach & Margin

$$[\rho(w1), \mu(w1)] = [\rho(w) + 1, \mu(w) + 1]$$

$$[\rho(w0), \mu(w0)] = \begin{cases} [\rho(w) - 1, 0] & \rho(w) > \mu(w) = 0 \\ [0, \mu(w) - 1] & \rho(w) = 0 \\ [\rho(w) - 1, \mu(w) - 1] & \text{otherwise} \end{cases}$$

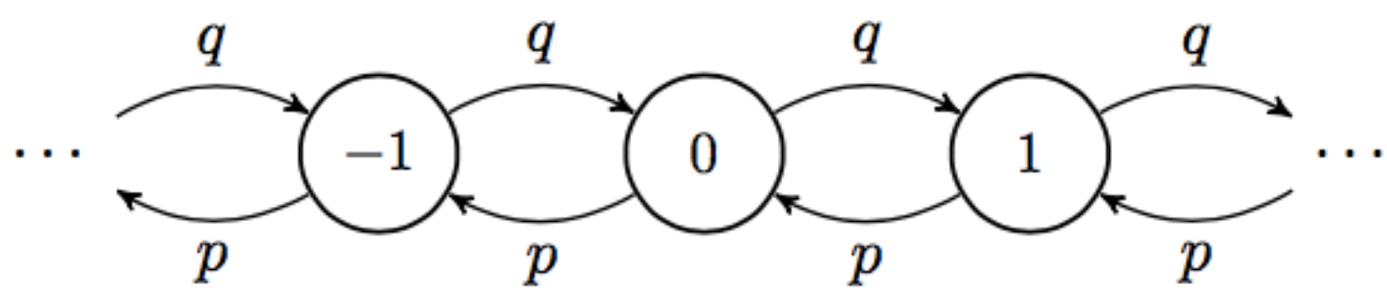
it is possible for the adversary to compensate for *margin*, by spending *reach*

reach never drops below 0

reach and *margin* decrement

2D Random Walk

1D …



Start at 0, flip a biased coin: right for “1” and left for “0”

Variable **reach** performs a 1D random walk when positive

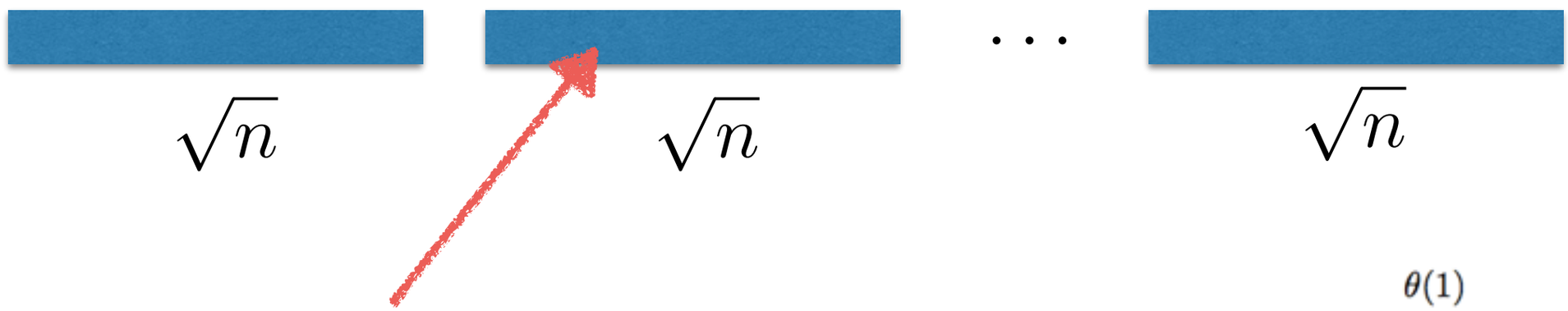
Variable **margin** performs a 1D random walk when negative

Variable **margin** sticks to 0 when **reach** is positive

Forkable strings are rare!

partition string in equal segments

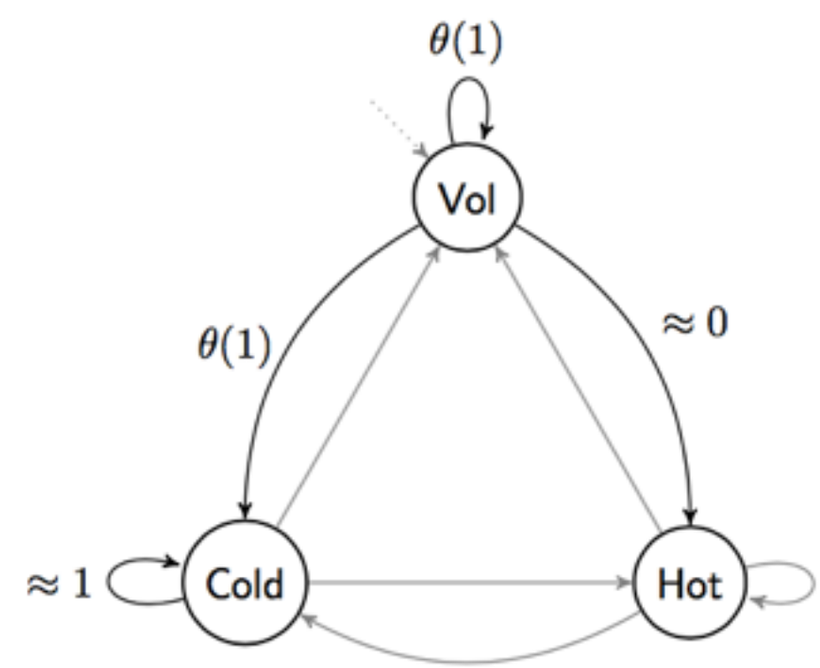
$w = 0101\ldots \qquad \ldots 0101$



$(\rho \geq \delta\sqrt{n}) \wedge (\mu \geq -\delta\sqrt{n})$ **Hot**

$-\delta\sqrt{n} \leq \mu \leq \rho < \delta\sqrt{n}$ **Volatile**

$\mu < -\delta\sqrt{n}$ **Cold**



density is $2^{-\Omega(\sqrt{n})}$

error is $2^{-\sqrt{n}}$

Divergence

- Given a string & a pair of viable tines for it, their **divergence** is the # of blocks after the two tines fork.

- The divergence of a string is the maximum divergence over all possible tines.

- **Theorem.** (informal) The divergence of any string, is realized by a specific forkable substring of length at least as large as the divergence.

  - **Corollary.** Forkable strings are rare, thus the divergence of a string length *R* is bounded by *k*<<*R* with error $\exp(-\Omega(\sqrt{k}) + \log R)$ assuming adversarial stake ratio at most $(1-\epsilon)/2$

Semi-Synchronous Setting

- Time is divided in **slots** — as before.
- messages are sent through a **diffusion** mechanism + the adversary is rushing — as before.
- Messages can be **delayed** by Δ slots, an unknown to the honest parties parameter, which is only determined at execution time.

Ouroboros Praos

- Designate periods of **silence** to allow the opportunity to parties to synchronize in the semi-synchronous setting.

- Determine slot leader eligibility **independently** via a private test based on a VRF, to prevent the adversary from learning the slot leader schedule ahead of time.

- Use a key-evolving signature to **protect** past slots that were assigned to honest parties.

Analysis Approach

- Realize key-evolving signature and VRF with *malicious key generation*, in the UC setting.
- Analyze combinatorially, using a generalization of forkable strings, the hybrid protocol.

Crypto Primitives

- Universally Composable Key-evolving signature; we prove it can be derived by a game based key-evolving signature.

- Universally Composable VRF (that retains randomness even under malicious key generation): we prove a construction in the RO model based on 2Hash-DH construction [JKK14].

$$x \mapsto H(x, H(m)^k)$$

public-key $y = g^k$ $\quad \mathrm{EQDL}(k : u = H(m)^k \wedge y = g^k)$

Praos Slot Leader Selection

Rule. you are a slot leader if

$$H(rnd, slot, H(rnd, slot)^k) < T_{\mathsf{stk}}$$

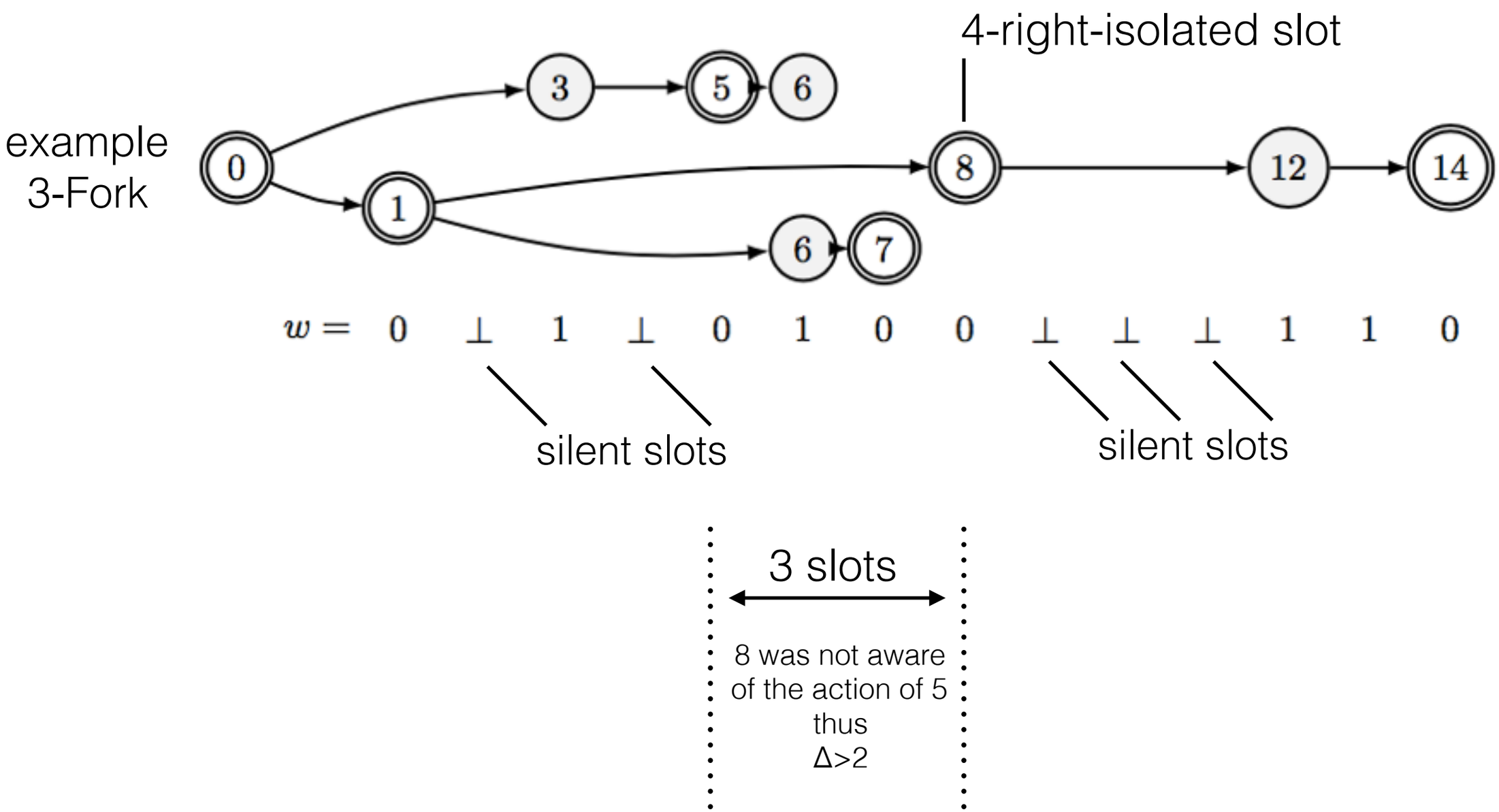
public-key $y = g^k$

Calibrate the target so that a party with relative stake α will succeed with probability $1 - (1 - f)^\alpha$

f is a protocol parameter = rate of non-silent slots

Δ-Forks

If two honest slots *i, j* satisfy $i+\Delta<j$ then the *j* player should be aware of the actions of *i* player



Δ-Divergence

- Δ-Divergence of a string is the corresponding notion of divergence but now taking Δ delays into account.
- Objective (as before): show that Δ-Divergence of the protocol execution is small.

Semi-Synchronous to Synchronous Reduction

$$\rho_\Delta(\varepsilon) = \varepsilon,\ \rho_\Delta(\perp \| w') = \rho_\Delta(w'),$$

$$\rho_\Delta(1 \| w') = 1 \| \rho_\Delta(w'),$$

$$\rho_\Delta(0 \| w') = \begin{cases} 0 \| \rho_\Delta(w') & \textit{if } w' \in \perp^{\Delta-1} \| \{0,1,\perp\}^*, \\ 1 \| \rho_\Delta(w') & \textit{otherwise.} \end{cases}$$

Lemma *Let* $w \in \{0,1,\perp\}^*$. *Then* $\mathrm{div}_\Delta(w) \leq \mathrm{div}_0(\rho_\Delta(w))$.

Note however that forkable string density does not imply immediately (as before) small divergence as the reduction mangles the underlying distribution

Dominant Distribution

relative honest stake = α

$$\mathbf{Pr}[w_i = \perp] = 1 - f$$

$$\mathbf{Pr}[w_i = 0] = (1-f)(1-(1-f)^{\alpha})$$

$$\mathbf{Pr}[w_i = 1] = f - (1-f)(1-(1-f)^{\alpha})$$

Theorem : the dominant distribution
via $\rho_{\Delta}(\cdot)$

still yields a sequence of Bernoulli trials
with honest slot probability >= $\alpha(1-f)^{\Delta}$

- Δ-divergence of a string length *R* is bounded by *k*<<*R*

with error $\exp(-\Omega(\sqrt{k}) + \log R)$

assuming

$$\alpha(1-f)^{\Delta} \geq (1+\epsilon)/2$$

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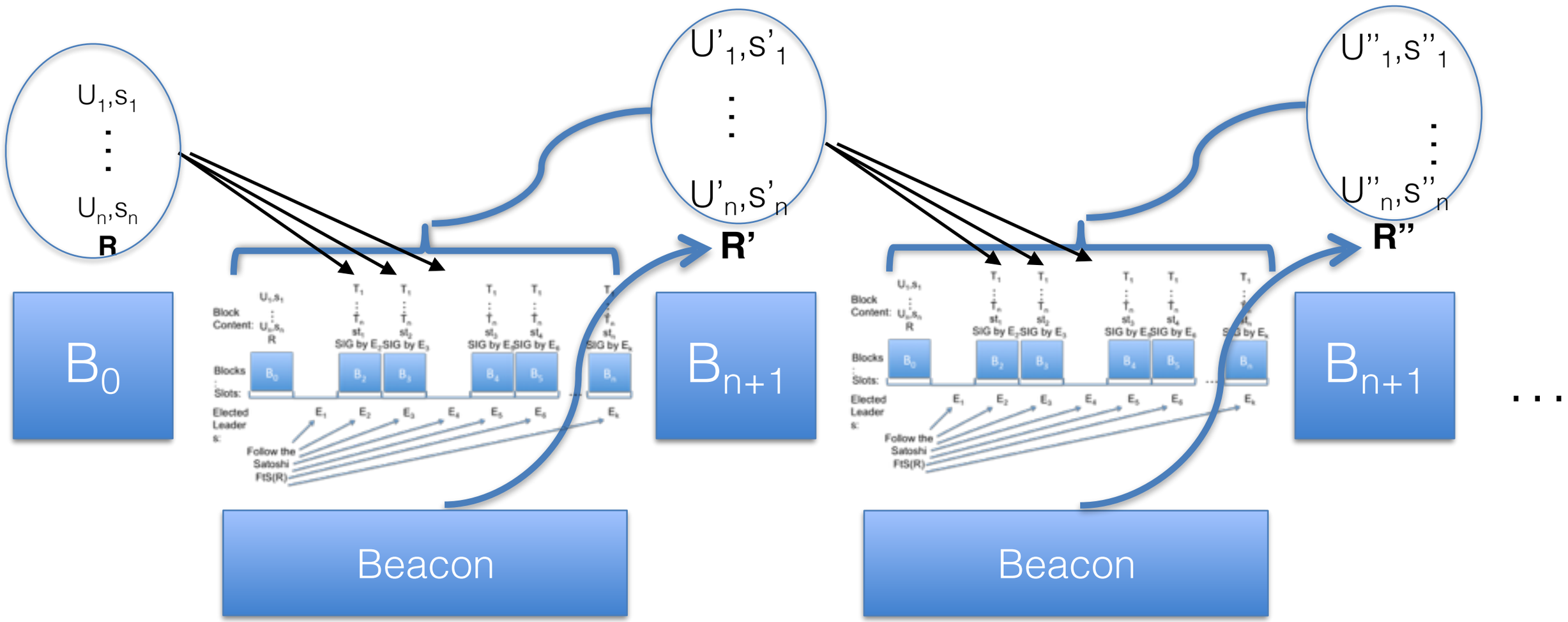
Dynamic Stake



R **R'** **R''**

randomness beacon

Leakage/Adversarial Control

- [Ouroboros] Adversary is allowed to **learn** the beacon value ahead of time.
- [Ouroboros Praos] Adversary is additionally allowed to **reset** the value of the beacon a number of times.

Design Methodology

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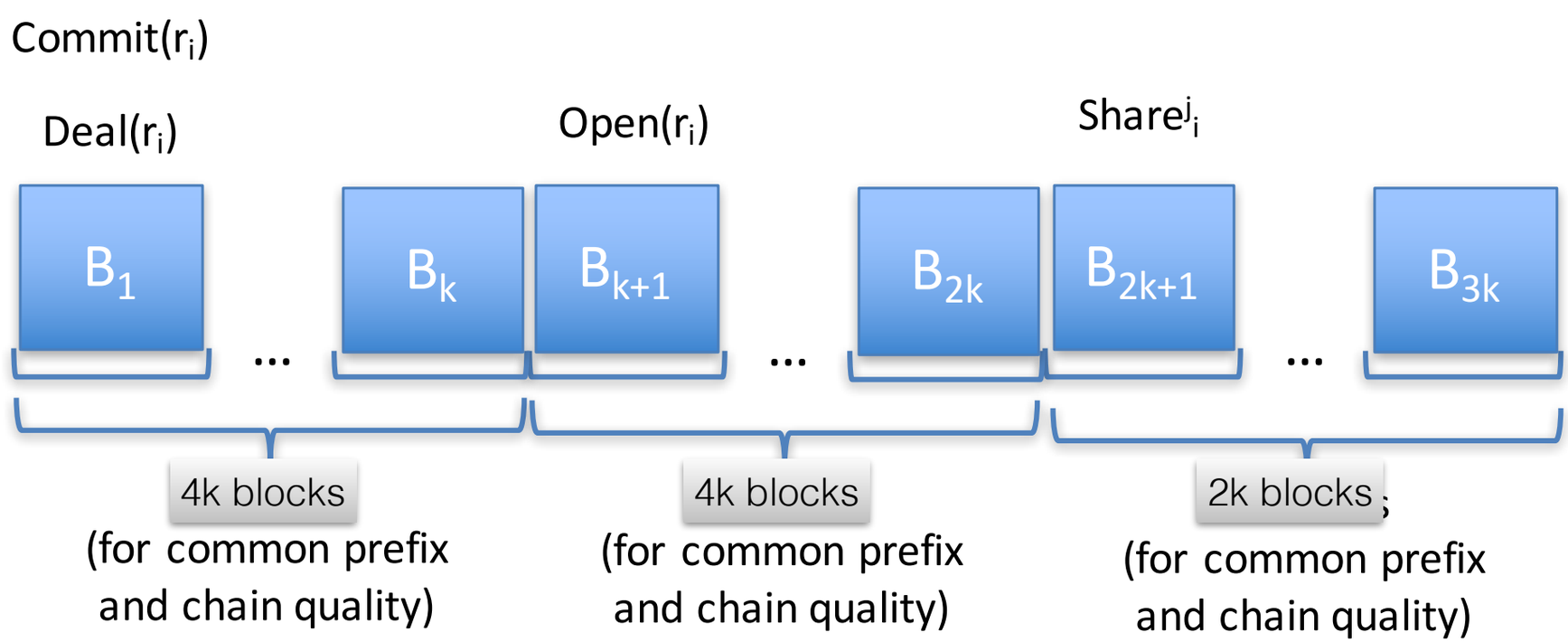
Ouroboros: GOD coin tossing

- For every stakeholder when each epoch starts:

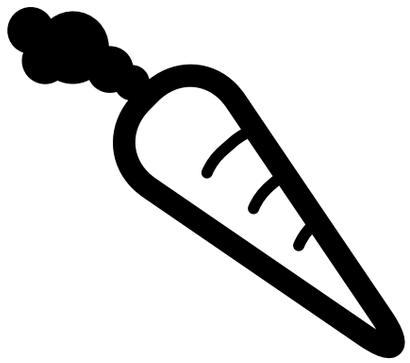


Use publicly verifiable secret-sharing (PVSS) for distributing commitment openings

Ouroboros-Praos: Hash-based Beacon

- Collect a vector of the VRF values inserted by each slot leader in a block.
- Set the beacon value to the hash of the VRF values.
- **Grinding** becomes possible, but can be controlled by using the [GKL15] *q*-bounded model (the adversary has a quota of hashing queries per slot).

Incentive Structure



How to **incentivise** parties to execute the protocol?

We introduce the concept of "**Input-Endorsers**"

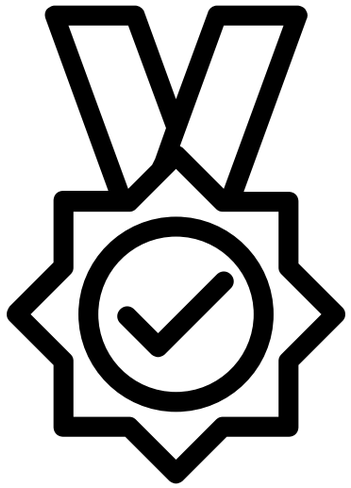
A sequence of transactions need to be **endorsed** in order to be included in a block.

Endorsed sequence can be included **in any upcoming block** up to *2k* slots in the future (inclusive).

Assumptions about protocol costs

- Our Assumptions :
  - Issuing blocks is **easy** (blocks contain only endorsed sequences of transactions, hence effort to verify transactions is passed to the endorsers).
- **Expensive actions** are:
  - Running the GOD protocol to simulate the randomness beacon. (need to issue commitments and open them)
  - Endorsing sets of transactions (need to verify them)

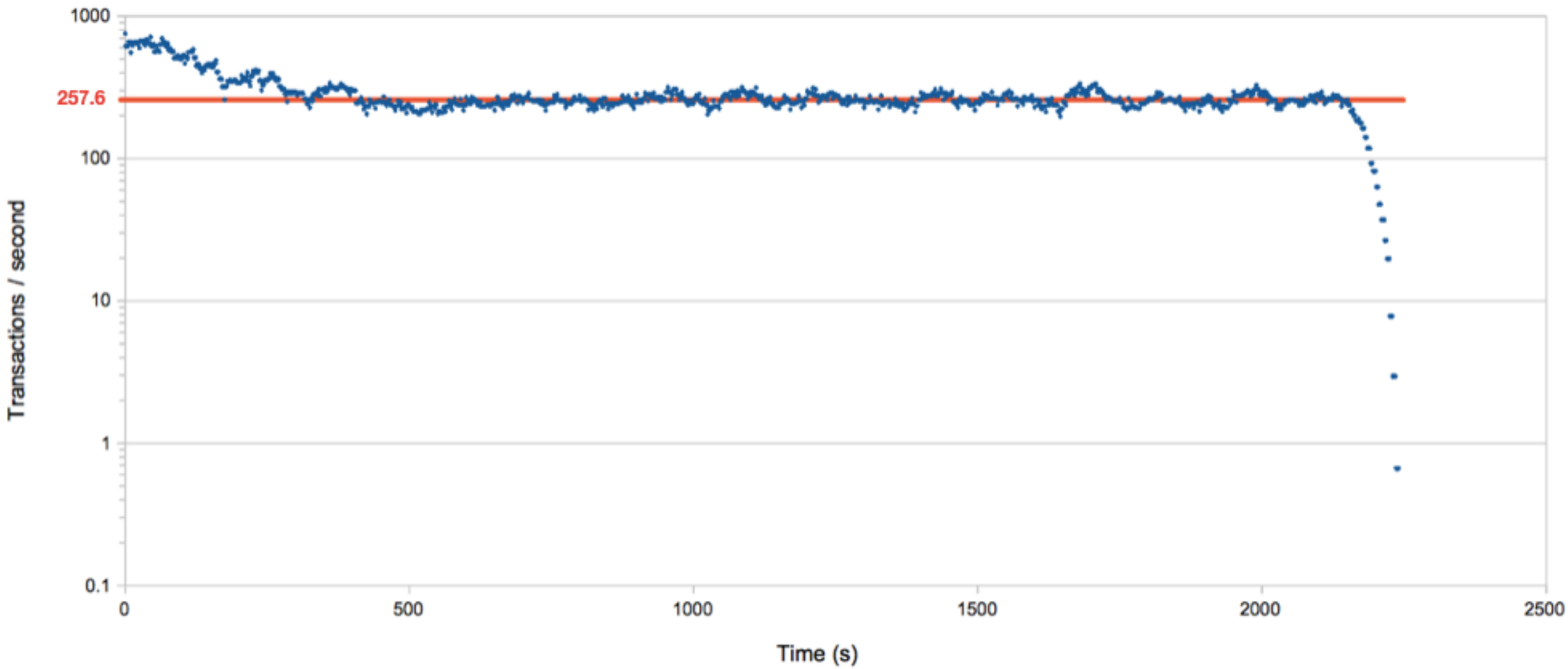
Reward Mechanism



- Epoch based.
  - After each epoch stabilizes, provide rewards for the following acts:
    1) (just) being a slot leader.
    2) endorsing a set of inputs.
    3) sending messages for the MPC protocol.

Theorem. Ouroboros is an **approximate Nash equilibrium**.

Ouroboros Performance



Implementation : Parity Rust-based Extensible Ethereum

40 nodes in Amazon Cloud, Slot length = 5s

median TPS = 257.6

Related Works

- NXT, PeerCoin
- Cryptocurrencies w/o PoW, Bentov, Gabizon, Mizrahi
- Algorand by Jing Chen and S. Micali
- Snow White by P. Daian, R. Pass and E. Shi
- Sleepy consensus by R. Pass and E. Shi.
- Fruitchain by R. Pass and E. Shi

Reading

- Ouroboros: A Provably Secure Proof-of-Stake Blockchain Protocol. https://eprint.iacr.org/2016/889

- Forkable Strings are Rare. https://eprint.iacr.org/2017/241

- Ouroboros Praos: An adaptively-secure, semi-synchronous proof-of-stake protocol. https://eprint.iacr.org/2017/573

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