

# Smart Contracts

## IOHK & Cardano

Lars Brünjes



January 6, 2021

# About myself

Dr. Lars Brünjes, Director of Education at IOHK



- PhD in Pure Mathematics from Regensburg University (Germany).
- Postdoc at Cambridge University (UK).
- Ten years working in Software Development prior to joining IOHK.
- Haskell enthusiast for more than 15 years.
- Joined IOHK November 2016.
- Director of Education at IOHK: Haskell courses (Athens, Barbados, Addis Ababa, Ulaanbaatar, . . . ), responsible for internal and external trainings.
- Leading the “Incentives” team.



## Motto

Providing financial services to the three billion people that don't have them.

## Motto

Providing financial services to the three billion people that don't have them.

- Founded 2015 by Charles Hoskinson and Jeremy Wood.

## Motto

Providing financial services to the three billion people that don't have them.

- Founded 2015 by Charles Hoskinson and Jeremy Wood.
- Company building Cardano.

## Motto

Providing financial services to the three billion people that don't have them.

- Founded 2015 by Charles Hoskinson and Jeremy Wood.
- Company building Cardano.
- Distributed around the globe.

## Motto

Providing financial services to the three billion people that don't have them.

- Founded 2015 by Charles Hoskinson and Jeremy Wood.
- Company building Cardano.
- Distributed around the globe.
- Invested in functional programming (Haskell, Scala, ...).



## Motto

Providing financial services to the three billion people that don't have them.

- Founded 2015 by Charles Hoskinson and Jeremy Wood.
- Company building Cardano.
- Distributed around the globe.
- Invested in functional programming (Haskell, Scala, ...).
- Research focused (peer-reviewed research, research centers, ...).

- Proof of Stake blockchain.

# Cardano

- Proof of Stake blockchain.
- Cryptocurrency Ada.

# Cardano

- Proof of Stake blockchain.
- Cryptocurrency Ada.
- Roadmap: <https://cardanoroadmap.com/>.

# Cardano

- Proof of Stake blockchain.
- Cryptocurrency Ada.
- Roadmap: <https://cardanoroadmap.com/>.
- **Smart Contracts:** IELE VM, Solidity, Glow, Plutus, Marlowe.

# Proof of Work versus Proof of Stake

## PoW

Leader selection based on Hashing  
Power: “One CPU, one vote!”.

## PoS

Leader selection based on Stake: “Follow the Satoshi!”

# Proof of Work versus Proof of Stake

## PoW

Leader selection based on Hashing Power: “One CPU, one vote!”.

Huge energy consumption to guarantee security.

## PoS

Leader selection based on Stake: “Follow the Satoshi!”

Consensus is relatively cheap.

# Proof of Work versus Proof of Stake

## PoW

Leader selection based on Hashing Power: “One CPU, one vote!”.

Huge energy consumption to guarantee security.

Well established and provably secure.

## PoS

Leader selection based on Stake: “Follow the Satoshi!”

Consensus is relatively cheap.

Provably secure, but hotly debated.





# Ouroboros

- First provably secure PoS protocol.

# Ouroboros

- First provably secure PoS protocol.
- Elect leader for each time-slot based on stake.

# Ouroboros

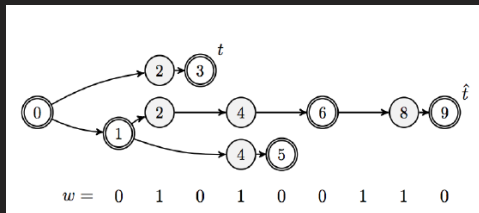
- First provably secure PoS protocol.
- Elect leader for each time-slot based on stake.
- Stakeholders agree on randomness for next epoch.

# Ouroboros

- First provably secure PoS protocol.
- Elect leader for each time-slot based on stake.
- Stakeholders agree on randomness for next epoch.
- Running in production in Cardano since October 2017.

# Ouroboros

- First provably secure PoS protocol.
- Elect leader for each time-slot based on stake.
- Stakeholders agree on randomness for next epoch.
- Running in production in Cardano since October 2017.
- Provably secure against adversary with less than 50% stake.



Adversary	BTC	OB Covert	OB General
0.10	50	3	5
0.15	80	5	8
0.20	110	7	12
0.25	150	11	18
0.30	240	18	31
0.35	410	34	60
0.40	890	78	148
0.45	3400	317	663

# Ouroboros Praos

- Extension of Ouroboros to semi-synchronous setting.

# Ouroboros Praos

- Extension of Ouroboros to semi-synchronous setting.
- Deals gracefully with message delays.



# Ouroboros Genesis

- No checkpointing: New Players can safely join the protocol without any trusted advice.

# Ouroboros Genesis

- No checkpointing: New Players can safely join the protocol without any trusted advice.
- Security Proof in the UC-framework, making it easier to compare with Bitcoin (and other PoW systems).

# Ouroboros Genesis

- No checkpointing: New Players can safely join the protocol without any trusted advice.
- Security Proof in the UC-framework, making it easier to compare with Bitcoin (and other PoW systems).
- Currently being implemented for future versions of Cardano.

# Ouroboros BFT

- **Ouroboros BFT (Byzantine Fault Tolerance)** is a minimal consensus-protocol which is impressively simple.

# Ouroboros BFT

- Ouroboros BFT (Byzantine Fault Tolerance) is a minimal consensus-protocol which is impressively simple.
- It only works for a fixed number  $n$  of nodes.

# Ouroboros BFT

- Ouroboros BFT (Byzantine Fault Tolerance) is a minimal consensus-protocol which is impressively simple.
- It only works for a fixed number  $n$  of nodes.
- It is secure for an honest majority of  $\frac{2}{3}n$  nodes.

# Ouroboros BFT

- Ouroboros BFT (Byzantine Fault Tolerance) is a minimal consensus-protocol which is impressively simple.
- It only works for a fixed number  $n$  of nodes.
- It is secure for an honest majority of  $\frac{2}{3}n$  nodes.
- If dishonest nodes (so-called Byzantine nodes) are not allowed to commit publicly visible protocol violations, only  $\frac{n}{2}$  honest nodes are needed. (This is the so-called Covert Byzantine Setting.)

# Covert Byzantine Setting

- Normal Byzantine nodes can do what they like. They can ignore messages and send misleading messages whenever and however often they want.



# Covert Byzantine Setting

- Normal Byzantine nodes can do what they like. They can ignore messages and send misleading messages whenever and however often they want.
- In the **covert Byzantine setting**, such nodes are still allowed to violate the protocol (for example by being quiet or by ignoring messages from other nodes, pretending to face network problems), but they are not allowed to violate the protocol in a publicly visible way.

# Covert Byzantine Setting

- Normal Byzantine nodes can do what they like. They can ignore messages and send misleading messages whenever and however often they want.
- In the **covert Byzantine setting**, such nodes are still allowed to violate the protocol (for example by being quiet or by ignoring messages from other nodes, pretending to face network problems), but they are not allowed to violate the protocol in a publicly visible way.
- In particular they cannot create more than one block with the same time stamp and distribute those blocks in the network.

# Covert Byzantine Setting

- Normal Byzantine nodes can do what they like. They can ignore messages and send misleading messages whenever and however often they want.
- In the **covert Byzantine setting**, such nodes are still allowed to violate the protocol (for example by being quiet or by ignoring messages from other nodes, pretending to face network problems), but they are not allowed to violate the protocol in a publicly visible way.
- In particular they cannot create more than one block with the same time stamp and distribute those blocks in the network.
- This is obviously a restriction, which hopefully makes it plausible why in this setting, a majority of 50% honest nodes suffices.

# Covert Byzantine Setting

- Normal Byzantine nodes can do what they like. They can ignore messages and send misleading messages whenever and however often they want.
- In the **covert Byzantine setting**, such nodes are still allowed to violate the protocol (for example by being quiet or by ignoring messages from other nodes, pretending to face network problems), but they are not allowed to violate the protocol in a publicly visible way.
- In particular they cannot create more than one block with the same time stamp and distribute those blocks in the network.
- This is obviously a restriction, which hopefully makes it plausible why in this setting, a majority of 50% honest nodes suffices.
- In practice this setting can be enforced by requiring an upfront deposit of all nodes, which will be forfeit if two blocks with the same time stamp signed by them are discovered.

# The Ouroboros BFT Protocol

- The  $n$  nodes are numbered from 0 to  $(n - 1)$ . Their public keys are fixed and publicly known.

# The Ouroboros BFT Protocol

- The  $n$  nodes are numbered from 0 to  $(n - 1)$ . Their public keys are fixed and publicly known.
- Time is divided into **slots** of a fixed length, slots are numbered starting with 1.

# The Ouroboros BFT Protocol

- The  $n$  nodes are numbered from 0 to  $(n - 1)$ . Their public keys are fixed and publicly known.
- Time is divided into **slots** of a fixed length, slots are numbered starting with 1.
- Newly created blocks contain the current slot-number as a time stamp.

# The Ouroboros BFT Protocol

- The  $n$  nodes are numbered from 0 to  $(n - 1)$ . Their public keys are fixed and publicly known.
- Time is divided into **slots** of a fixed length, slots are numbered starting with 1.
- Newly created blocks contain the current slot-number as a time stamp.
- In slot  $i$ , only node  $k$  with  $k \equiv i \pmod{n}$  has the right to create a block.



# The Ouroboros BFT Protocol

- The  $n$  nodes are numbered from 0 to  $(n - 1)$ . Their public keys are fixed and publicly known.
- Time is divided into **slots** of a fixed length, slots are numbered starting with 1.
- Newly created blocks contain the current slot-number as a time stamp.
- In slot  $i$ , only node  $k$  with  $k \equiv i \pmod{n}$  has the right to create a block.
- A block is valid if
  - Its time stamp is not from the future and
  - it contains the signature of the node associated with the slot.

# Illustration: Ouroboros BFT with Seven Nodes

Nodes	Slots
0	7, 14, 21, 28,...
1	1, 8, 15, 22,...
2	2, 9, 16, 23,...
3	3, 10, 17, 24,...
4	4, 11, 18, 25,...
5	5, 12, 19, 26,...
6	6, 13, 20, 27,...

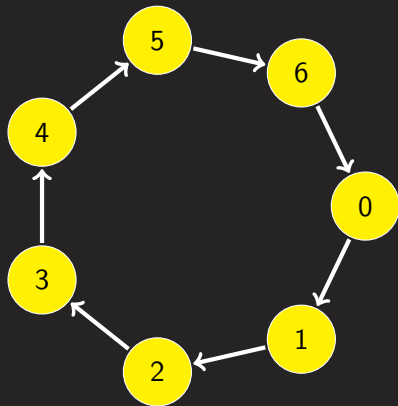


Figure: Ouroboros BFT with seven nodes



## Ouroboros Praos: An adaptively-secure, semi-synchronous proof-of-stake blockchain

Bernardo David\*, Peter Gazi\*\*, Aggelos Kiayias\*\*\*, and Alexander Russell†

October 6, 2017

**Abstract.** We present “Ouroboros Praos”, a proof-of-stake the first time, provides security against *fully-adaptive cor setting*: Specifically, the adversary can corrupt any parts population of stakeholders at any moment as long as the st an honest majority of stake; furthermore, the protocol to b message delivery delay unknown to protocol participants. To achieve these guarantees we formalize and realize in a th suitable form of forward secure digital signatures and a new that maintains unpredictability under malicious key genera a general combinatorial framework for the analysis of sea may be of independent interest. We prove our protocol sea assumptions in the random oracle model.

### Protocol $\pi_{\text{SPoS}}$

The protocol  $\pi_{\text{SPoS}}$  is run by stakeholders  $U_1, \dots, U_n$  interacting among themselves and with ideal functionalities  $\mathcal{F}_{\text{MINT}}, \mathcal{F}_{\text{VRF}}, \mathcal{F}_{\text{KES}}, \mathcal{F}_{\text{DSIG}}, \mathcal{H}$  over a sequence of slots  $S = \{s_1, \dots, s_R\}$ . Define  $T_i \triangleq 2^{\text{ver}} \phi_f(\alpha_i)$  as the threshold for a stakeholder  $U_i$ , where  $\alpha_i$  is the relative stake of  $U_i$ ,  $\ell_{\text{VRF}}$  denotes the output length of  $\mathcal{F}_{\text{VRF}}$ ,  $f$  is the active slots coefficient and  $\phi_f$  is the mapping from Definition 1. Then  $\pi_{\text{SPoS}}$  proceeds as follows:

- Initialization.** The stakeholder  $U_i$  sends  $(\text{KeyGen}, \text{sid}, U_i)$  to  $\mathcal{F}_{\text{VRF}}, \mathcal{F}_{\text{KES}}$  and  $\mathcal{F}_{\text{DSIG}}$ ; receiving  $(\text{VerificationKey}, \text{sid}, v_i^{\text{vrf}})$ ,  $(\text{VerificationKey}, \text{sid}, v_i^{\text{kes}})$  and  $(\text{VerificationKey}, \text{sid}, v_i^{\text{dsig}})$ , respectively. Then, in case it is the first round, it sends  $(\text{ver\_keys}, \text{sid}, U_i, v_i^{\text{vrf}}, v_i^{\text{kes}}, v_i^{\text{dsig}})$  to  $\mathcal{F}_{\text{MINT}}$  (to claim stake from the genesis block). In any case, it terminates the round by returning  $(U_i, v_i^{\text{vrf}}, v_i^{\text{kes}}, v_i^{\text{dsig}})$  to  $\mathcal{Z}$ . In the next round,  $U_i$  sends  $(\text{genblock\_req}, \text{sid}, U_i)$  to  $\mathcal{F}_{\text{MINT}}$ , receiving  $(\text{genblock}, \text{sid}, S_0, \eta)$  as the answer.  $U_i$  sets the local blockchain  $C = B_0 = (S_0, \eta)$  and its initial internal state  $st = H(B_0)$ .
- Chain Extension.** After initialization, for every slot  $sl_j \in S$ , every online stakeholder  $U_i$  performs the following steps:
  - $U_i$  receives from the environment the transaction data  $d \in \{0, 1\}^*$  to be inserted into the blockchain.
  - $U_i$  collects all valid chains received via diffusion into a set  $C$ , pruning blocks belonging to future slots and verifying that for every chain  $C' \in C$  and every block  $B' = (st', d', sl', B', \sigma_{j'}) \in C'$  it holds that the stakeholder who created it is in the slot leader set of slot  $sl'$  (by parsing  $B_{x'}$  as  $(U_i, y', \pi')$  for some  $s$ , verifying that  $\mathcal{F}_{\text{VRF}}$  responds to  $(\text{Verify}, \text{sid}, \eta \parallel sl', y', \pi', v_i^{\text{vrf}})$  by  $(\text{Verified}, \text{sid}, \eta \parallel sl', y', \pi', 1)$ , and that  $y' < T_i$ ), and that  $\mathcal{F}_{\text{KES}}$  responds to  $(\text{Verify}, \text{sid}, (st', d', sl', B'), sl', \sigma_{j'}, v_i^{\text{kes}})$  by  $(\text{Verified}, \text{sid}, (st', d', sl', B'), sl', 1)$ .  $U_i$  computes  $C' = \text{maxvalid}(C, C)$ , sets  $C'$  as the new local chain and sets state  $st = H(\text{head}(C'))$ .
  - $U_i$  sends  $(\text{EvalProve}, \text{sid}, \eta \parallel sl_j)$  to  $\mathcal{F}_{\text{VRF}}$ , receiving  $(\text{Evaluated}, \text{sid}, y, \pi)$ .  $U_i$  checks whether it is in the slot leader set of slot  $sl_j$  by checking that  $y < T_i$ . If yes, it generates a new block  $B = (st, d, sl_j, B_\pi, \sigma)$  where  $st$  is its current state,  $d \in \{0, 1\}^*$  is the transaction data,  $B_\pi = (U_i, y, \pi)$  and  $\sigma$  is a signature obtained by sending  $(\text{USign}, \text{sid}, U_i, (st, d, sl_j, B_\pi), sl_j)$  to  $\mathcal{F}_{\text{KES}}$  and receiving  $(\text{Signature}, \text{sid}, (st, d, sl_j, B_\pi), sl_j, \sigma)$ .  $U_i$  computes  $C' = C \parallel B$ , sets  $C'$  as the new local chain and sets state  $st = H(\text{head}(C'))$ . Finally, if  $U_i$  has generated a block in this step, it diffuses  $C'$ .
- Signing Transactions.** Upon receiving  $(\text{sign\_tx}, \text{sid}', tx)$  from the environment,  $U_i$  sends  $(\text{Sign}, \text{sid}, U_i, tx)$  to  $\mathcal{F}_{\text{DSIG}}$ , receiving  $(\text{Signature}, \text{sid}, tx, \sigma)$ . Then,  $U_i$  sends  $(\text{signed\_tx}, \text{sid}', tx, \sigma)$  back to the environment.

Fig. 4: Protocol  $\pi_{\text{SPoS}}$ .

## Ouroboros Praos: An adaptively-secure, semi-synchronous proof-of-stake blockchain

Bernardo David\*, Peter Gazi\*\*, Aggelos Kiayias\*\*\*, and Alexander Russell†

October 6, 2017

**Abstract.** We present “Ouroboros Praos”, a proof-of-stake the first time, provides security against *fully-adaptive cor setting*: Specifically, the adversary can corrupt any parts population of stakeholders at any moment as long the st an honest majority of stake; furthermore, the protocol to message delivery delay unknown to protocol participants. To achieve these guarantees we formalize and realize in a suitable form of forward secure digital signatures and a new that maintains unpredictability under malicious key genera a general combinatorial framework for the analysis of se may be of independent interest. We prove our protocol se assumptions in the random oracle model.

### Protocol $\pi_{\text{SPoS}}$

The protocol  $\pi_{\text{SPoS}}$  is run by stakeholders  $U_1, \dots, U_n$  interacting among themselves and with ideal functionalities  $\mathcal{F}_{\text{MINT}}, \mathcal{F}_{\text{VRF}}, \mathcal{F}_{\text{KES}}, \mathcal{F}_{\text{DSIG}}, \mathcal{H}$  over a sequence of slots  $S = \{s_1, \dots, s_R\}$ . Define  $T_i \triangleq 2^{\text{ver}} \phi_f(\alpha_i)$  as the threshold for a stakeholder  $U_i$ , where  $\alpha_i$  is the relative stake of  $U_i$ ,  $\ell_{\text{VRF}}$  denotes the output length of  $\mathcal{F}_{\text{VRF}}$ ,  $f$  is the active slots coefficient and  $\phi_f$  is the mapping from Definition 1. Then  $\pi_{\text{SPoS}}$  proceeds as follows:

- Initialization.** The stakeholder  $U_i$  sends  $(\text{KeyGen}, \text{sid}, U_i)$  to  $\mathcal{F}_{\text{VRF}}, \mathcal{F}_{\text{KES}}$  and  $\mathcal{F}_{\text{DSIG}}$ ; receiving  $(\text{VerificationKey}, \text{sid}, v_i^{\text{vrf}})$ ,  $(\text{VerificationKey}, \text{sid}, v_i^{\text{kes}})$  and  $(\text{VerificationKey}, \text{sid}, v_i^{\text{dsig}})$ , respectively. Then, in case it is the first round, it sends  $(\text{ver\_keys}, \text{sid}, U_i, v_i^{\text{vrf}}, v_i^{\text{kes}}, v_i^{\text{dsig}})$  to  $\mathcal{F}_{\text{MINT}}$  (to claim stake from the genesis block). In any case, it terminates the round by returning  $(U_i, v_i^{\text{vrf}}, v_i^{\text{kes}}, v_i^{\text{dsig}})$  to  $\mathcal{Z}$ . In the next round,  $U_i$  sends  $(\text{genblock\_req}, \text{sid}, U_i)$  to  $\mathcal{F}_{\text{MINT}}$ , receiving  $(\text{genblock}, \text{sid}, S_0, \eta)$  as the answer.  $U_i$  sets the local blockchain  $C = B_0 = (S_0, \eta)$  and its initial internal state  $st = H(B_0)$ .
- Chain Extension.** After initialization, for every slot  $sl_j \in S$ , every online stakeholder  $U_i$  performs the following steps:
  - $U_i$  receives from the environment the transaction data  $d \in \{0, 1\}^*$  to be inserted into the blockchain.
  - $U_i$  collects all valid chains received via diffusion into a set  $C$ , pruning blocks belonging to future slots and verifying that for every chain  $C' \in C$  and every block  $B' = (st', d', sl', B', \sigma_j) \in C'$  it holds that the stakeholder who created it is in the slot leader set of slot  $sl'$  (by parsing  $B_{\pi'}$  as  $(U_i, y', \pi')$  for some  $s$ , verifying that  $\mathcal{F}_{\text{VRF}}$  responds to  $(\text{Verify}, \text{sid}, \eta \parallel st', y', \pi', v_i^{\text{vrf}})$  by  $(\text{Verified}, \text{sid}, \eta \parallel st', y', \pi', 1)$ , and that  $y' < T_i$ ), and that  $\mathcal{F}_{\text{KES}}$  responds to  $(\text{Verify}, \text{sid}, (st', d', sl', B'), st', \sigma_j, v_i^{\text{kes}})$  by  $(\text{Verified}, \text{sid}, (st', d', sl', B'), st', 1)$ .  $U_i$  computes  $C' = \text{maxvalid}(C, C)$ , sets  $C'$  as the new local chain and sets state  $st = H(\text{head}(C'))$ .
  - $U_i$  sends  $(\text{EvalProve}, \text{sid}, \eta \parallel sl_j)$  to  $\mathcal{F}_{\text{VRF}}$ , receiving  $(\text{Evaluated}, \text{sid}, y, \pi)$ .  $U_i$  checks whether it is in the slot leader set of slot  $sl_j$  by checking that  $y < T_i$ . If yes, it generates a new block  $B = (st, d, sl_j, B_{\pi}, \sigma)$  where  $st$  is its current state,  $d \in \{0, 1\}^*$  is the transaction data,  $B_{\pi} = (U_i, y, \pi)$  and  $\sigma$  is a signature obtained by sending  $(\text{USign}, \text{sid}, U_i, (st, d, sl_j, B_{\pi}), sl_j)$  to  $\mathcal{F}_{\text{KES}}$  and receiving  $(\text{Signature}, \text{sid}, (st, d, sl_j, B_{\pi}), sl_j, \sigma)$ .  $U_i$  computes  $C' = C \parallel B$ , sets  $C'$  as the new local chain and sets state  $st = H(\text{head}(C'))$ . Finally, if  $U_i$  has generated a block in this step, it diffuses  $C'$ .
- Signing Transactions.** Upon receiving  $(\text{sign\_tx}, \text{sid}', tx)$  from the environment,  $U_i$  sends  $(\text{Sign}, \text{sid}, U_i, tx)$  to  $\mathcal{F}_{\text{DSIG}}$ , receiving  $(\text{Signature}, \text{sid}, tx, \sigma)$ . Then,  $U_i$  sends  $(\text{signed\_tx}, \text{sid}', tx, \sigma)$  back to the environment.

Fig. 4: Protocol  $\pi_{\text{SPoS}}$ .

• Written in English.

# From Mathematical Paper...

## Ouroboros Praos: An adaptively-secure, semi-synchronous proof-of-stake blockchain

Bernardo David\*, Peter Gaži\*\*, Aggelos Kiayias\*\*\*, and Alexander Russell†

October 6, 2017

**Abstract.** We present “Ouroboros Praos”, a proof-of-stake the first time, provides security against *fully-adaptive cor setting*: Specifically, the adversary can corrupt any parts population of stakeholders at any moment as long as the st an honest majority of stake; furthermore, the protocol to message delivery delay unknown to protocol participants. To achieve these guarantees we formalize and realize in a th suitable form of forward secure digital signatures and a new that maintains unpredictability under malicious key genera a general combinatorial framework for the analysis of se may be of independent interest. We prove our protocol se assumptions in the random oracle model.

### Protocol $\pi_{\text{SPoS}}$

The protocol  $\pi_{\text{SPoS}}$  is run by stakeholders  $U_1, \dots, U_n$  interacting among themselves and with ideal functionalities  $\mathcal{F}_{\text{MINT}}, \mathcal{F}_{\text{VRF}}, \mathcal{F}_{\text{KES}}, \mathcal{F}_{\text{DSIG}}, \mathcal{H}$  over a sequence of slots  $S = \{s_1, \dots, s_R\}$ . Define  $T_i \triangleq 2^{\text{ver}} \phi_f(\alpha_i)$  as the threshold for a stakeholder  $U_i$ , where  $\alpha_i$  is the relative stake of  $U_i$ ,  $\ell_{\text{VRF}}$  denotes the output length of  $\mathcal{F}_{\text{VRF}}$ ,  $f$  is the active slots coefficient and  $\phi_f$  is the mapping from Definition 1. Then  $\pi_{\text{SPoS}}$  proceeds as follows:

- Initialization.** The stakeholder  $U_i$  sends  $(\text{KeyGen}, \text{sid}, U_i)$  to  $\mathcal{F}_{\text{VRF}}, \mathcal{F}_{\text{KES}}$  and  $\mathcal{F}_{\text{DSIG}}$ ; receiving  $(\text{VerificationKey}, \text{sid}, v_i^{\text{vrf}})$ ,  $(\text{VerificationKey}, \text{sid}, v_i^{\text{kes}})$  and  $(\text{VerificationKey}, \text{sid}, v_i^{\text{dsig}})$ , respectively. Then, in case it is the first round, it sends  $(\text{ver\_keys}, \text{sid}, U_i, v_i^{\text{vrf}}, v_i^{\text{kes}}, v_i^{\text{dsig}})$  to  $\mathcal{F}_{\text{MINT}}$  (to claim stake from the genesis block). In any case, it terminates the round by returning  $(U_i, v_i^{\text{vrf}}, v_i^{\text{kes}}, v_i^{\text{dsig}})$  to  $\mathcal{Z}$ . In the next round,  $U_i$  sends  $(\text{genblock\_req}, \text{sid}, U_i)$  to  $\mathcal{F}_{\text{MINT}}$ , receiving  $(\text{genblock}, \text{sid}, S_0, \eta)$  as the answer.  $U_i$  sets the local blockchain  $C = B_0 = (S_0, \eta)$  and its initial internal state  $st = H(B_0)$ .
- Chain Extension.** After initialization, for every slot  $sl_j \in S$ , every online stakeholder  $U_i$  performs the following steps:
  - $U_i$  receives from the environment the transaction data  $d \in \{0, 1\}^*$  to be inserted into the blockchain.
  - $U_i$  collects all valid chains received via diffusion into a set  $C$ , pruning blocks belonging to future slots and verifying that for every chain  $C' \in C$  and every block  $B' = (st', d', sl', B', \sigma_{j'}) \in C'$  it holds that the stakeholder who created it is in the slot leader set of slot  $sl'$  (by parsing  $B_{x'}$  as  $(U_i, y', \pi')$  for some  $s$ , verifying that  $\mathcal{F}_{\text{VRF}}$  responds to  $(\text{Verify}, \text{sid}, \eta \parallel st', y', \pi', v_i^{\text{vrf}})$  by  $(\text{Verified}, \text{sid}, \eta \parallel st', y', \pi', 1)$ , and that  $y' < T_i$ ), and that  $\mathcal{F}_{\text{KES}}$  responds to  $(\text{Verify}, \text{sid}, (st', d', sl', B'), st', \sigma_{j'}, v_i^{\text{kes}})$  by  $(\text{Verified}, \text{sid}, (st', d', sl', B'), st', 1)$ .  $U_i$  computes  $C' = \text{maxvalid}(C, C)$ , sets  $C'$  as the new local chain and sets state  $st = H(\text{head}(C'))$ .
  - $U_i$  sends  $(\text{EvalProve}, \text{sid}, \eta \parallel sl_j)$  to  $\mathcal{F}_{\text{VRF}}$ , receiving  $(\text{Evaluated}, \text{sid}, y, \pi)$ .  $U_i$  checks whether it is in the slot leader set of slot  $sl_j$  by checking that  $y < T_i$ . If yes, it generates a new block  $B = (st, d, sl_j, B_\pi, \sigma)$  where  $st$  is its current state,  $d \in \{0, 1\}^*$  is the transaction data,  $B_\pi = (U_i, y, \pi)$  and  $\sigma$  is a signature obtained by sending  $(\text{USign}, \text{sid}, U_i, (st, d, sl_j, B_\pi), sl_j)$  to  $\mathcal{F}_{\text{KES}}$  and receiving  $(\text{Signature}, \text{sid}, (st, d, sl_j, B_\pi), sl_j, \sigma)$ .  $U_i$  computes  $C' = C \parallel B$ , sets  $C'$  as the new local chain and sets state  $st = H(\text{head}(C'))$ . Finally, if  $U_i$  has generated a block in this step, it diffuses  $C'$ .
- Signing Transactions.** Upon receiving  $(\text{sign\_tx}, \text{sid}', tx)$  from the environment,  $U_i$  sends  $(\text{Sign}, \text{sid}, U_i, tx)$  to  $\mathcal{F}_{\text{DSIG}}$ , receiving  $(\text{Signature}, \text{sid}, tx, \sigma)$ . Then,  $U_i$  sends  $(\text{signed\_tx}, \text{sid}', tx, \sigma)$  back to the environment.

Fig. 4: Protocol  $\pi_{\text{SPoS}}$ .

- Written in English.
- Written by mathematicians.

# From Mathematical Paper...

## Ouroboros Praos: An adaptively-secure, semi-synchronous proof-of-stake blockchain

Bernardo David\*, Peter Gazi\*\*, Aggelos Kiayias\*\*\*, and Alexander Russell†

October 6, 2017

**Abstract.** We present “Ouroboros Praos”, a proof-of-stake the first time, provides security against *fully-adaptive cor setting*: Specifically, the adversary can corrupt any parts population of stakeholders at any moment as long the st an honest majority of stake; furthermore, the protocol to message delivery delay unknown to protocol participants. To achieve these guarantees we formalize and realize in a new suitable form of forward secure digital signatures and a new that maintains unpredictability under malicious key genera a general combinatorial framework for the analysis of se may be of independent interest. We prove our protocol se assumptions in the random oracle model.

### Protocol $\pi_{\text{SPoS}}$

The protocol  $\pi_{\text{SPoS}}$  is run by stakeholders  $U_1, \dots, U_n$  interacting among themselves and with ideal functionalities  $\mathcal{F}_{\text{MINT}}, \mathcal{F}_{\text{VRF}}, \mathcal{F}_{\text{KES}}, \mathcal{F}_{\text{DSIG}}, \mathcal{H}$  over a sequence of slots  $S = \{s_1, \dots, s_R\}$ . Define  $T_i \triangleq 2^{\text{ver}} \phi_f(\alpha_i)$  as the threshold for a stakeholder  $U_i$ , where  $\alpha_i$  is the relative stake of  $U_i$ ,  $\ell_{\text{VRF}}$  denotes the output length of  $\mathcal{F}_{\text{VRF}}$ ,  $f$  is the active slots coefficient and  $\phi_f$  is the mapping from Definition 1. Then  $\pi_{\text{SPoS}}$  proceeds as follows:

- Initialization.** The stakeholder  $U_i$  sends  $(\text{KeyGen}, \text{sid}, U_i)$  to  $\mathcal{F}_{\text{VRF}}, \mathcal{F}_{\text{KES}}$  and  $\mathcal{F}_{\text{DSIG}}$ ; receiving  $(\text{VerificationKey}, \text{sid}, v_i^{\text{vrf}})$ ,  $(\text{VerificationKey}, \text{sid}, v_i^{\text{kes}})$  and  $(\text{VerificationKey}, \text{sid}, v_i^{\text{dsig}})$ , respectively. Then, in case it is the first round, it sends  $(\text{ver\_keys}, \text{sid}, U_i, v_i^{\text{vrf}}, v_i^{\text{kes}}, v_i^{\text{dsig}})$  to  $\mathcal{F}_{\text{MINT}}$  (to claim stake from the genesis block). In any case, it terminates the round by returning  $(U_i, v_i^{\text{vrf}}, v_i^{\text{kes}}, v_i^{\text{dsig}})$  to  $\mathcal{Z}$ . In the next round,  $U_i$  sends  $(\text{genblock\_req}, \text{sid}, U_i)$  to  $\mathcal{F}_{\text{MINT}}$ , receiving  $(\text{genblock}, \text{sid}, S_0, \eta)$  as the answer.  $U_i$  sets the local blockchain  $C = B_0 = (S_0, \eta)$  and its initial internal state  $st = H(B_0)$ .
- Chain Extension.** After initialization, for every slot  $sl_j \in S$ , every online stakeholder  $U_i$  performs the following steps:
  - $U_i$  receives from the environment the transaction data  $d \in \{0, 1\}^*$  to be inserted into the blockchain.
  - $U_i$  collects all valid chains received via diffusion into a set  $C$ , pruning blocks belonging to future slots and verifying that for every chain  $C' \in C$  and every block  $B' = (st', d', sl', B', \sigma_{j'}) \in C'$  it holds that the stakeholder who created it is in the slot leader set of slot  $sl'$  (by parsing  $B_{x'}$  as  $(U_i, y', \pi')$  for some  $s$ , verifying that  $\mathcal{F}_{\text{VRF}}$  responds to  $(\text{Verify}, \text{sid}, \eta \parallel st', y', \pi', v_i^{\text{vrf}})$  by  $(\text{Verified}, \text{sid}, \eta \parallel st', y', \pi', 1)$ , and that  $y' < T_i$ ), and that  $\mathcal{F}_{\text{KES}}$  responds to  $(\text{Verify}, \text{sid}, (st', d', sl', B'), st', \sigma_{j'}, v_i^{\text{kes}})$  by  $(\text{Verified}, \text{sid}, (st', d', sl', B'), st', 1)$ .  $U_i$  computes  $C' = \text{maxvalid}(C, C)$ , sets  $C'$  as the new local chain and sets state  $st = H(\text{head}(C'))$ .
  - $U_i$  sends  $(\text{EvalProve}, \text{sid}, \eta \parallel sl_j)$  to  $\mathcal{F}_{\text{VRF}}$ , receiving  $(\text{Evaluated}, \text{sid}, y, \pi)$ .  $U_i$  checks whether it is in the slot leader set of slot  $sl_j$  by checking that  $y < T_i$ . If yes, it generates a new block  $B = (st, d, sl_j, B_\pi, \sigma)$  where  $st$  is its current state,  $d \in \{0, 1\}^*$  is the transaction data,  $B_\pi = (U_i, y, \pi)$  and  $\sigma$  is a signature obtained by sending  $(\text{USign}, \text{sid}, U_i, (st, d, sl_j, B_\pi), sl_j)$  to  $\mathcal{F}_{\text{KES}}$  and receiving  $(\text{Signature}, \text{sid}, (st, d, sl_j, B_\pi), sl_j, \sigma)$ .  $U_i$  computes  $C' = C \parallel B$ , sets  $C'$  as the new local chain and sets state  $st = H(\text{head}(C'))$ . Finally, if  $U_i$  has generated a block in this step, it diffuses  $C'$ .
- Signing Transactions.** Upon receiving  $(\text{sign\_tx}, \text{sid}', tx)$  from the environment,  $U_i$  sends  $(\text{Sign}, \text{sid}, U_i, tx)$  to  $\mathcal{F}_{\text{DSIG}}$ , receiving  $(\text{Signature}, \text{sid}, tx, \sigma)$ . Then,  $U_i$  sends  $(\text{signed\_tx}, \text{sid}', tx, \sigma)$  back to the environment.

Fig. 4: Protocol  $\pi_{\text{SPoS}}$ .

- Written in English.
- Written by mathematicians.
- Very abstract.

## ... To Efficient Code

```
235 -- CHECK: @verifyEncShare
236 -- | Verify encrypted shares
237 verifyEncShares
238   :: MonadRandom m
239   => SecretProof
240   -> Scrape.Threshold
241   -> [(VssPublicKey, EncShare)]
242   -> m Bool
243 verifyEncShares SecretProof{..} threshold (sortWith fst -> pairs)
244   | threshold <= 1      = error "verifyEncShares: threshold must be > 1"
245   | threshold >= n - 1 = error "verifyEncShares: threshold must be < n-1"
246   | otherwise =
247       Scrape.verifyEncryptedShares
248         spExtraGen
249         threshold
250         spCommitments
251         spParallelProofs
252         (coerce $ map snd pairs) -- shares
253         (coerce $ map fst pairs) -- participants
254   where
255     n = fromIntegral (length pairs)
```



## ... To Efficient Code

- Written in Haskell.

```
235 -- CHECK: @verifyEncShare
236 -- | Verify encrypted shares
237 verifyEncShares
238     :: MonadRandom m
239     => SecretProof
240     -> Scrape.Threshold
241     -> [(VssPublicKey, EncShare)]
242     -> m Bool
243 verifyEncShares SecretProof{..} threshold (sortWith fst -> pairs)
244     | threshold <= 1      = error "verifyEncShares: threshold must be > 1"
245     | threshold >= n - 1 = error "verifyEncShares: threshold must be < n-1"
246     | otherwise =
247         Scrape.verifyEncryptedShares
248             spExtraGen
249             threshold
250             spCommitments
251             spParallelProofs
252             (coerce $ map snd pairs) -- shares
253             (coerce $ map fst pairs) -- participants
254     where
255         n = fromIntegral (length pairs)
```

## ... To Efficient Code

- Written in Haskell.
- Written by Software Engineers.

```
235 -- CHECK: @verifyEncShare
236 -- | Verify encrypted shares
237 verifyEncShares
238     :: MonadRandom m
239     => SecretProof
240     -> Scrape.Threshold
241     -> [(VssPublicKey, EncShare)]
242     -> m Bool
243 verifyEncShares SecretProof{..} threshold (sortWith fst -> pairs)
244     | threshold <= 1      = error "verifyEncShares: threshold must be > 1"
245     | threshold >= n - 1 = error "verifyEncShares: threshold must be < n-1"
246     | otherwise =
247         Scrape.verifyEncryptedShares
248             spExtraGen
249             threshold
250             spCommitments
251             spParallelProofs
252             (coerce $ map snd pairs) -- shares
253             (coerce $ map fst pairs) -- participants
254     where
255         n = fromIntegral (length pairs)
```

## ... To Efficient Code

- Written in Haskell.
- Written by Software Engineers.
- Efficient code.

```
235 -- CHECK: @verifyEncShare
236 -- | Verify encrypted shares
237 verifyEncShares
238   :: MonadRandom m
239   => SecretProof
240   -> Scrape.Threshold
241   -> [(VssPublicKey, EncShare)]
242   -> m Bool
243 verifyEncShares SecretProof{..} threshold (sortWith fst -> pairs)
244   | threshold <= 1      = error "verifyEncShares: threshold must be > 1"
245   | threshold >= n - 1 = error "verifyEncShares: threshold must be < n-1"
246   | otherwise =
247       Scrape.verifyEncryptedShares
248         spExtraGen
249         threshold
250         spCommitments
251         spParallelProofs
252         (coerce $ map snd pairs) -- shares
253         (coerce $ map fst pairs) -- participants
254 where
255     n = fromIntegral (length pairs)
```

# The Problem

- We start from a **mathematical** paper written by **mathematicians**.

# The Problem

- We start from a **mathematical** paper written by **mathematicians**.
- The paper will undergo rigid **peer review** and contain mathematical **proofs of correctness**.

# The Problem

- We start from a **mathematical** paper written by **mathematicians**.
- The paper will undergo rigid **peer review** and contain mathematical **proofs of correctness**.
- The outcome should be **correct** and **efficient** Haskell code.

# The Problem

- We start from a **mathematical** paper written by **mathematicians**.
- The paper will undergo rigid **peer review** and contain mathematical **proofs of correctness**.
- The outcome should be **correct** and **efficient** Haskell code.
- Our mathematicians do not know Haskell, our engineers do not know cryptography.

# The Problem

- We start from a **mathematical** paper written by **mathematicians**.
- The paper will undergo rigid **peer review** and contain mathematical **proofs of correctness**.
- The outcome should be **correct** and **efficient** Haskell code.
- Our mathematicians do not know Haskell, our engineers do not know cryptography.
- How can we guarantee we deploy code that faithfully implements the original paper?



# Why does it matter?

- We are very proud of the quality of our research branch. We want to ensure this quality translates into equal quality of our software.

# Why does it matter?

- We are very proud of the quality of our research branch. We want to ensure this quality translates into equal quality of our software.
- Literally billions of dollars are managed by our code. A single mistake can be extremely costly.

# Why does it matter?

- We are very proud of the quality of our research branch. We want to ensure this quality translates into equal quality of our software.
- Literally billions of dollars are managed by our code. A single mistake can be extremely costly.
- We are interested in developing best practices that can be applied to a wide range of domains, pushing the envelope of what is possible and practicable.

# The Solution: Formal Methods

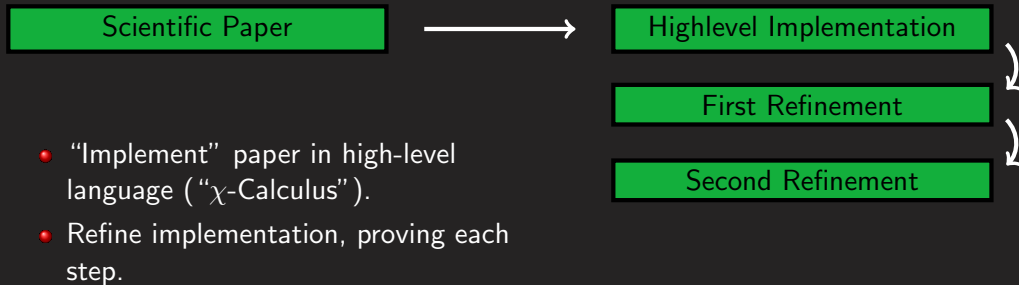
Scientific Paper

# The Solution: Formal Methods

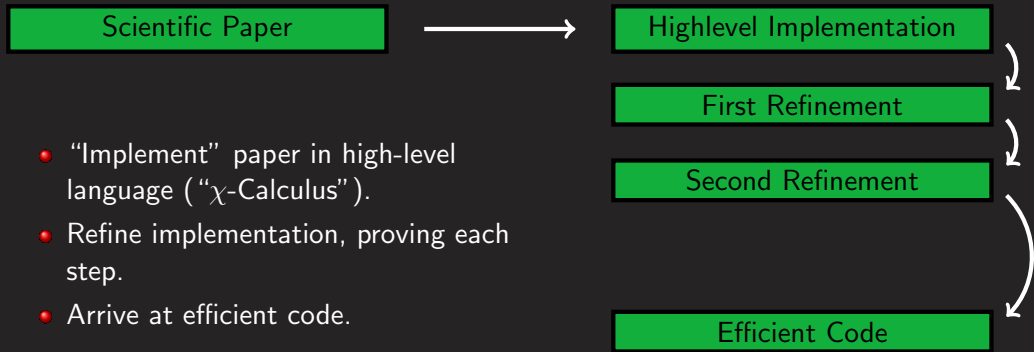


- “Implement” paper in high-level language (“ $\chi$ -Calculus”).

# The Solution: Formal Methods



# The Solution: Formal Methods



- Our version of the  $\pi$ - (or  $\psi$ -) Calculus (like  $\lambda$ -Calculus, but for concurrent systems).

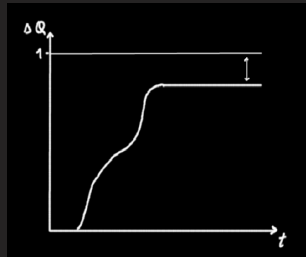


- Our version of the  $\pi$ - (or  $\psi$ -) Calculus (like  $\lambda$ -Calculus, but for concurrent systems).
- Can be embedded in Haskell and then...

- Our version of the  $\pi$ - (or  $\psi$ -) Calculus (like  $\lambda$ -Calculus, but for concurrent systems).
- Can be embedded in Haskell and then...
  - ...be executed.

- Our version of the  $\pi$ - (or  $\psi$ -) Calculus (like  $\lambda$ -Calculus, but for concurrent systems).
- Can be embedded in Haskell and then...
  - ...be executed.
  - ...be exported to a proof assistant.

- Our version of the  $\pi$ - (or  $\psi$ -) Calculus (like  $\lambda$ -Calculus, but for concurrent systems).
- Can be embedded in Haskell and then...
  - ...be executed.
  - ...be exported to a proof assistant.
  - ...be analyzed for performance ( $\Delta Q$ ).





# The people doing all the hard work...



Prof. Aggelos Kiayias, University of Edinburgh (UK), Chief Scientist at IOHK.



Prof. Elias Koutsoupias, University of Oxford (UK), Senior Research Fellow at IOHK.



Aikaterini-Panagiota Stouka, University of Edinburgh (UK), Researcher at IOHK.

# What are Incentives?

- Incentives in the context of a cryptocurrency are ways of encouraging people to participate in the protocol and to follow it faithfully.

# What are Incentives?

- Incentives in the context of a cryptocurrency are ways of encouraging people to participate in the protocol and to follow it faithfully.
- In the case of Bitcoin, this means mining blocks and including as many valid transactions in those blocks as possible.



# What are Incentives?

- Incentives in the context of a cryptocurrency are ways of encouraging people to participate in the protocol and to follow it faithfully.
- In the case of Bitcoin, this means mining blocks and including as many valid transactions in those blocks as possible.
- In the case of Cardano, it means being online and creating a block when they have been elected slot leader and to participate in the election process.

## (Non-) Monetary Incentives

- When the Bitcoin mining pool Ghash.io accumulated 42% of total mining power, people voluntarily started leaving the pool and brought it down to 38% in only two days. (CoinDesk, 2014-01-09)

## (Non-) Monetary Incentives

- When the Bitcoin mining pool Ghash.io accumulated 42% of total mining power, people voluntarily started leaving the pool and brought it down to 38% in only two days. (CoinDesk, 2014-01-09)
- The people who left Ghash.io did not receive any Bitcoin for leaving. Rather, they believed that concentrating too much mining power was bad and that leaving was the right thing to do.

## (Non-) Monetary Incentives

- When the Bitcoin mining pool Ghash.io accumulated 42% of total mining power, people voluntarily started leaving the pool and brought it down to 38% in only two days. (CoinDesk, 2014-01-09)
- The people who left Ghash.io did not receive any Bitcoin for leaving. Rather, they believed that concentrating too much mining power was bad and that leaving was the right thing to do.
- Ideally, monetary and moral incentives should align perfectly.

# Incentives in Cardano

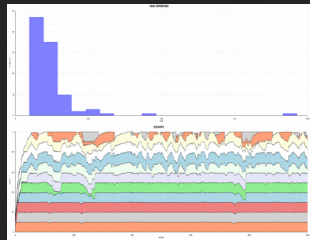
- The above example shows that in Bitcoin, this ideal is not always achieved. Sometimes people have to choose between doing the morally right thing and pursuing their financial gain.

# Incentives in Cardano

- The above example shows that in Bitcoin, this ideal is not always achieved. Sometimes people have to choose between doing the morally right thing and pursuing their financial gain.
- In Cardano, we strive for perfect alignment of incentives.

# Incentives in Cardano

- The above example shows that in Bitcoin, this ideal is not always achieved. Sometimes people have to choose between doing the morally right thing and pursuing their financial gain.
- In Cardano, we strive for perfect alignment of incentives.
- We use **Game Theory** and **Simulations** to develop and test our model.







# IELE and K-Framework



- Prof. Grigore Roşu, University of Illinois in Urbana-Champaign (US), CEO of Runtime Verification.
- K-Framework: meta framework for specifying formal semantics of programming languages.
- IELE: formally specified smart-contract language.



- Prof. Phil Wadler, University of Edinburgh (UK), Senior Research Fellow and Area Leader Programming Languages at IOHK.



- Dr. Manuel Chakravarty, Language Architect at IOHK.
- Plutus: newly developed smart-contract language heavily inspired by Haskell.



- Prof. Simon Thompson, University of Canterbury (UK), Senior Research Fellow at IOHK.
- Marlowe: newly developed smart-contract language for financial contracts.



- Statically typed: Every expression has a type at compile time.

# Haskell

- Statically typed: Every expression has a type at compile time.
- Lazy: Expressions are evaluated only when needed.

# Haskell

- Statically typed: Every expression has a type at compile time.
- Lazy: Expressions are evaluated only when needed.
- Pure: Side effects (I/O) are visible in the types.

# Haskell

- Statically typed: Every expression has a type at compile time.
- Lazy: Expressions are evaluated only when needed.
- Pure: Side effects (I/O) are visible in the types.
- Extremely expressive type system.



# Ouroboros BFT in Haskell — Commands

-- | Used to specify the length of a 'Delay'.

**type Seconds** = Double

-- | 'Command' is a simple DSL for the description of processes that can

-- communicate with each other via /broadcast/.

**data Command** =

Stop

| Delay **Seconds Command**

| Broadcast **String Command**

| Receive (**String** -> **Command**)

| Say **String Command**

# Ouroboros BFT in Haskell — Commands

*-- | Used to specify the length of a 'Delay'.*

**type Seconds** = Double

*-- | 'Command' is a simple DSL for the description of processes that can*

*-- communicate with each other via /broadcast/.*

**data Command** =

**Stop**

| **Delay Seconds Command**

| **Broadcast String Command**

| **Receive (String -> Command)**

| **Say String Command**

## Remark

The abstract `Command` type allows writing the protocol as a pure value in an ordinary Haskell data type. This can then later be interpreted in different ways.

# Ouroboros BFT in Haskell — Supporting Types

```
type Slot = Int
type NodeIndex = Int

data Block = Block
  { bISlot      :: !Slot
  , bINodeIndex :: !NodeIndex
  } deriving (Show, Read)
```

```
infixl 5 :>
```

```
data Chain =
  Genesis
  | Chain :> Block
  deriving (Show, Read)
```

```
data Message =
  Tick Int
  | NewChain Chain
  deriving (Show, Read)
```

# Ouroboros BFT in Haskell — Helper Functions

```
chainLength :: Chain -> Int
chainLength Genesis = 0
chainLength (c :> _) = 1 + chainLength c
```

```
slotLeader :: Int -> Slot -> NodeIndex
slotLeader nodeCount s = mod s nodeCount
```

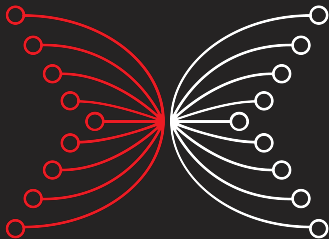
```
isValidChain :: Int -> Slot -> Chain -> Bool
isValidChain _ Genesis = True
isValidChain nodeCount s (c :> b) =
    (bSlot b <= s)
    && (bSlot b >= 1)
    && (slotLeader nodeCount (bSlot b) == bNodeIndex b)
    && (isValidChain nodeCount (bSlot b - 1) c)
```

# Ouroboros BFT in Haskell — Ticker

```
ticker :: Seconds -> Command
ticker interval = go 0
  where
    go :: Int -> Command
    go i =
      let j    = i + 1
          msg = show $ Tick j
      in Delay interval $ Broadcast msg $ Say ("tick " ++ show j) $ go j
```

# Ouroboros BFT in Haskell — The Protocol

```
bft :: Int -> NodeIndex -> Command
bft nodeCount i = go Genesis 0
  where
    go :: Chain -> Slot -> Command
    go c s = Receive $ \msg -> case read msg of
      Tick s'
        | s' > s ->
          Say ("entered slot " ++ show s') $
            if slotLeader nodeCount s' == i -- Am I leader?
              then let b    = Block s' i
                     c'    = c :> b
                     msg' = show $ NewChain c'
                   in Say ("created " ++ show c') $ Broadcast msg' $ go c' s'
              else go c s'
      NewChain c'
        | (isValidChain nodeCount s c') && (chainLength c' > chainLength c) ->
          Say ("adopted chain " ++ show c') $ go c' s
        | chainLength c' <= chainLength c ->
          Say "rejected chain — too short" $ go c s
        | otherwise ->
          Say "rejected chain — invalid" $ go c s
    - -> go c s
```



INPUT | OUTPUT