Smart Contracts

IOHK & Cardano

Lars Brünjes

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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, ...), responsible for internal and external trainings.
- Leading the "Incentives" team.

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- Smart Contracts: IELE VM, Plutus, Marlowe.

Proof of Work versus Proof of Stake

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Well established and provably secure.	Provably secure, but hotly debated.

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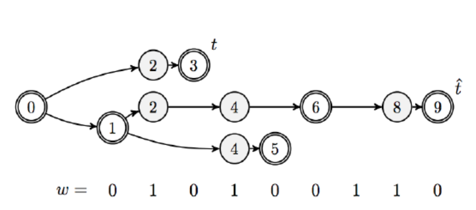
- Running in production in Cardano since October 2017.
- Provably secure against adversary with less than 50% stake.



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

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- Currently being implemented for future versions of Cardano.

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- Security Proof in the UC-framework, making it easier to compare with Bitcoin (and other PoW systems).

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- 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.)

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- 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.

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- 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,...

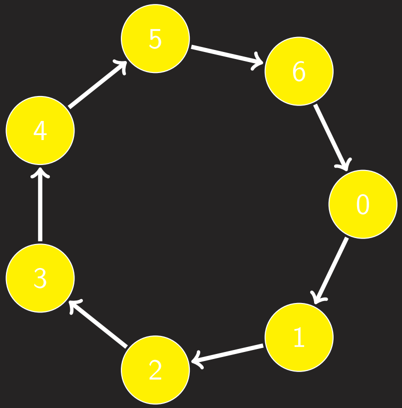

Figure: Ouroboros BFT with seven nodes

Formal Methods

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

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Protocol π_{SPoS}

The protocol π_{SPoS} is run by stakeholders $U_1, \ldots, U_n$ interacting among themselves and with ideal functionalities $\mathcal{F}_{\mathsf{INIT}}, \mathcal{F}_{\mathsf{VRF}}, \mathcal{F}_{\mathsf{KES}}, \mathcal{F}_{\mathsf{DSIG}}, \mathsf{H}$ over a sequence of slots $S = \{sl_1, \ldots, sl_R\}$. Define $T_i \triangleq 2^{\ell_{\mathsf{VRF}}} \phi_f(\alpha_i)$ as the threshold for a stakeholder U_i, where α_i is the relative stake of U_i, ℓ_{VRF} denotes the output length of $\mathcal{F}_{\mathsf{VRF}}$, f is the active slots coefficient and ϕ_f is the mapping from Definition 1. Then π_{SPoS} proceeds as follows:

1. **Initialization.** The stakeholder U_i sends $(\mathsf{KeyGen}, sid, U_i)$ to $\mathcal{F}_{\mathsf{VRF}}$, $\mathcal{F}_{\mathsf{KES}}$ and $\mathcal{F}_{\mathsf{DSIG}}$; receiving $(\mathsf{VerificationKey}, sid, v_i^{\mathrm{vrf}})$, $(\mathsf{VerificationKey}, sid, v_i^{\mathrm{kes}})$ and $(\mathsf{VerificationKey}, sid, v_i^{\mathrm{dsig}})$, respectively. Then, in case it is the first round, it sends $(\mathsf{ver\_keys}, sid, U_i, v_i^{\mathrm{vrf}}, v_i^{\mathrm{kes}}, v_i^{\mathrm{dsig}})$ to $\mathcal{F}_{\mathsf{INIT}}$ (to claim stake from the genesis block). In any case, it terminates the round by returning $(U_i, v_i^{\mathrm{vrf}}, v_i^{\mathrm{kes}}, v_i^{\mathrm{dsig}})$ to $\mathcal{Z}$. In the next round, U_i sends $(\mathsf{genblock\_req}, sid, U_i)$ to $\mathcal{F}_{\mathsf{INIT}}$, receiving $(\mathsf{genblock}, sid, \mathbb{S}_0, \eta)$ as the answer. U_i sets the local blockchain $\mathcal{C} = B_0 = (\mathbb{S}_0, \eta)$ and its initial internal state $st = H(B_0)$.
2. **Chain Extension.** After initialization, for every slot $sl_j \in S$, every online stakeholder U_i performs the following steps:
   (a) U_i receives from the environment the transaction data $d \in \{0,1\}^*$ to be inserted into the blockchain.
   (b) U_i collects all valid chains received via diffusion into a set $\mathbb{C}$, pruning blocks belonging to future slots and verifying that for every chain $\mathcal{C}' \in \mathbb{C}$ and every block $B' = (st', d', sl', B_\pi{}', \sigma_{j'}) \in \mathcal{C}'$ it holds that the stakeholder who created it is in the slot leader set of slot sl' (by parsing $B_\pi{}'$ as (U_s, y', π') for some s, verifying that $\mathcal{F}_{\mathsf{VRF}}$ responds to $(\mathsf{Verify}, sid, \eta \,\|\, sl', y', \pi', v_s^{\mathrm{vrf}})$ by $(\mathsf{Verified}, sid, \eta \,\|\, sl', y', \pi', 1)$, and that $y' < T_s$), and that $\mathcal{F}_{\mathsf{KES}}$ responds to $(\mathsf{Verify}, sid, (st', d', sl', B_\pi{}'), sl', \sigma_{j'}, v_s^{\mathrm{kes}})$ by $(\mathsf{Verified}, sid, (st', d', sl', B_\pi{}'), sl', 1)$. U_i computes $\mathcal{C}' = \mathsf{maxvalid}(\mathcal{C}, \mathbb{C})$, sets $\mathcal{C}'$ as the new local chain and sets state $st = H(\mathrm{head}(\mathcal{C}'))$.
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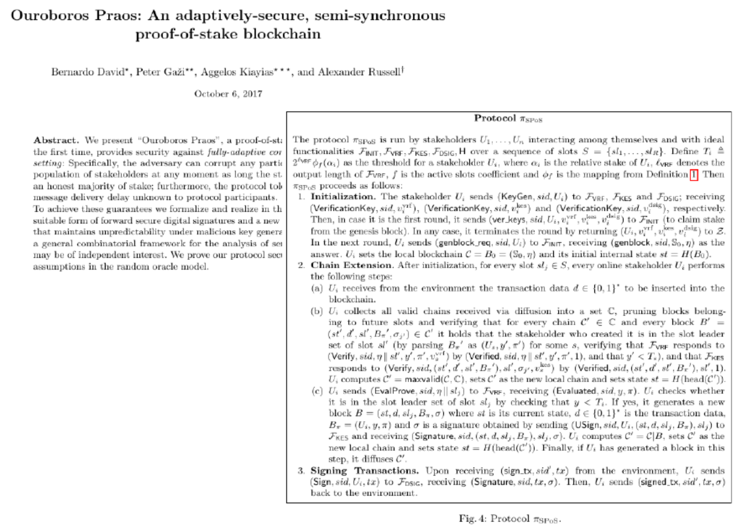

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Protocol π_{SPoS}

The protocol π_{SPoS} is run by stakeholders $U_1, \ldots, U_n$ interacting among themselves and with ideal functionalities $\mathcal{F}_{\mathsf{INIT}}, \mathcal{F}_{\mathsf{VRF}}, \mathcal{F}_{\mathsf{KES}}, \mathcal{F}_{\mathsf{DSIG}}, \mathsf{H}$ over a sequence of slots $S = \{sl_1, \ldots, sl_R\}$. Define $T_i \triangleq 2^{\ell_{\mathsf{VRF}}} \phi_f(\alpha_i)$ as the threshold for a stakeholder U_i, where α_i is the relative stake of U_i, ℓ_{VRF} denotes the output length of $\mathcal{F}_{\mathsf{VRF}}$, f is the active slots coefficient and ϕ_f is the mapping from Definition 1. Then π_{SPoS} proceeds as follows:

1. **Initialization.** The stakeholder U_i sends $(\mathsf{KeyGen}, sid, U_i)$ to $\mathcal{F}_{\mathsf{VRF}}$, $\mathcal{F}_{\mathsf{KES}}$ and $\mathcal{F}_{\mathsf{DSIG}}$; receiving $(\mathsf{VerificationKey}, sid, v_i^{\mathrm{vrf}})$, $(\mathsf{VerificationKey}, sid, v_i^{\mathrm{kes}})$ and $(\mathsf{VerificationKey}, sid, v_i^{\mathrm{dsig}})$, respectively. Then, in case it is the first round, it sends $(\mathsf{ver\_keys}, sid, U_i, v_i^{\mathrm{vrf}}, v_i^{\mathrm{kes}}, v_i^{\mathrm{dsig}})$ to $\mathcal{F}_{\mathsf{INIT}}$ (to claim stake from the genesis block). In any case, it terminates the round by returning $(U_i, v_i^{\mathrm{vrf}}, v_i^{\mathrm{kes}}, v_i^{\mathrm{dsig}})$ to $\mathcal{Z}$. In the next round, U_i sends $(\mathsf{genblock\_req}, sid, U_i)$ to $\mathcal{F}_{\mathsf{INIT}}$, receiving $(\mathsf{genblock}, sid, \mathbb{S}_0, \eta)$ as the answer. U_i sets the local blockchain $\mathcal{C} = B_0 = (\mathbb{S}_0, \eta)$ and its initial internal state $st = H(B_0)$.
2. **Chain Extension.** After initialization, for every slot $sl_j \in S$, every online stakeholder U_i performs the following steps:
   (a) U_i receives from the environment the transaction data $d \in \{0,1\}^*$ to be inserted into the blockchain.
   (b) U_i collects all valid chains received via diffusion into a set $\mathbb{C}$, pruning blocks belonging to future slots and verifying that for every chain $\mathcal{C}' \in \mathbb{C}$ and every block $B' = (st', d', sl', B_\pi{}', \sigma_{j'}) \in \mathcal{C}'$ it holds that the stakeholder who created it is in the slot leader set of slot sl' (by parsing $B_\pi{}'$ as (U_s, y', π') for some s, verifying that $\mathcal{F}_{\mathsf{VRF}}$ responds to $(\mathsf{Verify}, sid, \eta \,\|\, sl', y', \pi', v_s^{\mathrm{vrf}})$ by $(\mathsf{Verified}, sid, \eta \,\|\, sl', y', \pi', 1)$, and that $y' < T_s$), and that $\mathcal{F}_{\mathsf{KES}}$ responds to $(\mathsf{Verify}, sid, (st', d', sl', B_\pi{}'), sl', \sigma_{j'}, v_s^{\mathrm{kes}})$ by $(\mathsf{Verified}, sid, (st', d', sl', B_\pi{}'), sl', 1)$. U_i computes $\mathcal{C}' = \mathsf{maxvalid}(\mathcal{C}, \mathbb{C})$, sets $\mathcal{C}'$ as the new local chain and sets state $st = H(\mathrm{head}(\mathcal{C}'))$.
   (c) U_i sends $(\mathsf{EvalProve}, sid, \eta \,\|\, sl_j)$ to $\mathcal{F}_{\mathsf{VRF}}$, receiving $(\mathsf{Evaluated}, sid, y, \pi)$. 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 σ is a signature obtained by sending $(\mathsf{USign}, sid, U_i, (st, d, sl_j, B_\pi), sl_j)$ to $\mathcal{F}_{\mathsf{KES}}$ and receiving $(\mathsf{Signature}, sid, (st, d, sl_j, B_\pi), sl_j, \sigma)$. U_i computes $\mathcal{C}' = \mathcal{C}|B$, sets $\mathcal{C}'$ as the new local chain and sets state $st = H(\mathrm{head}(\mathcal{C}'))$. Finally, if U_i has generated a block in this step, it diffuses $\mathcal{C}'$.
3. **Signing Transactions.** Upon receiving $(\mathsf{sign\_tx}, sid', tx)$ from the environment, U_i sends $(\mathsf{Sign}, sid, U_i, tx)$ to $\mathcal{F}_{\mathsf{DSIG}}$, receiving $(\mathsf{Signature}, sid, tx, \sigma)$. Then, U_i sends $(\mathsf{signed\_tx}, sid', tx, \sigma)$ back to the environment.

Fig. 4: Protocol π_{SPoS}.

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

. . . To Efficient Code

```haskell
-- CHECK: @verifyEncShare
-- | Verify encrypted shares
verifyEncShares
    :: MonadRandom m
    => SecretProof
    -> Scrape.Threshold
    -> [(VssPublicKey, EncShare)]
    -> m Bool
verifyEncShares SecretProof{..} threshold (sortWith fst -> pairs)
    | threshold <= 1     = error "verifyEncShares: threshold must be > 1"
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    | otherwise =
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- 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?

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- 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

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Scientific Paper $\longrightarrow$ Highlevel Implementation

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Efficient Code

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- Arrive at efficient code.

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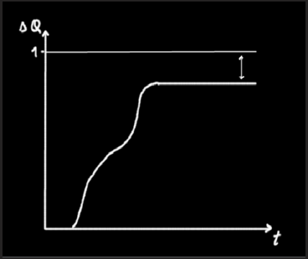

Incentives

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.

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- 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

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- Ideally, monetary and moral incentives should align perfectly.

Incentives in Cardano

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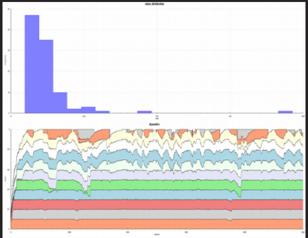
- The above example shows that in Bitcoin, this ideal is not always achieved. Sometimes people have to choose between doing the morally right thing and pursuing their financial gain.
- In Cardano, we strive for perfect alignment of incentives.
- We use Game Theory and Simulations to develop and test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



Smart Contracts

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.

Plutus

- 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.

Haskell

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- 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

```haskell
-- | 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)
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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

```haskell
type Slot      = Int
type NodeIndex = Int

data Block = Block
    { blSlot      :: !Slot
    , blNodeIndex :: !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

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

slotLeader :: Int -> Slot -> NodeIndex
slotLeader nodeCount s = 1 + mod (s - 1) nodeCount

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

Ouroboros BFT in Haskell — Ticker

```haskell
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

```haskell
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