From Crypto-Paper to Crypto-Currency: the Cardano Consensus Layer

Real-World Crypto Symposium (RWC) 2021

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Well-Typed

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Overview

1. From Theory to Practice
2. Formal Methods and Implementation Correctness
3. What Could Have Gone Wrong
4. Path to Decentralisation

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1. **From Theory to Practice**
2. Formal Methods and Implementation Correctness
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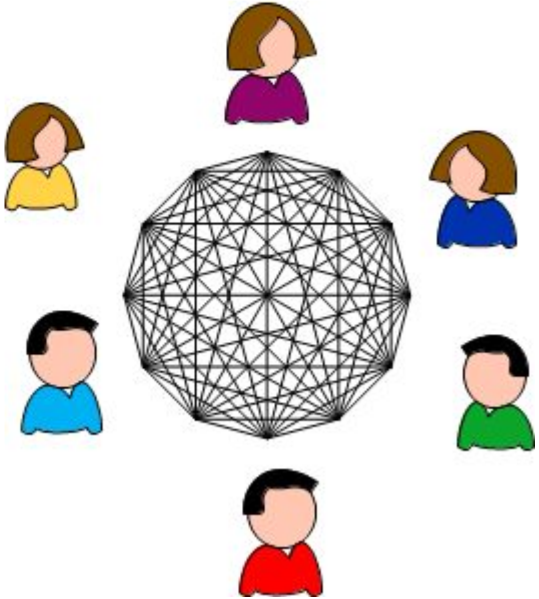
Distributed Computation over a Network



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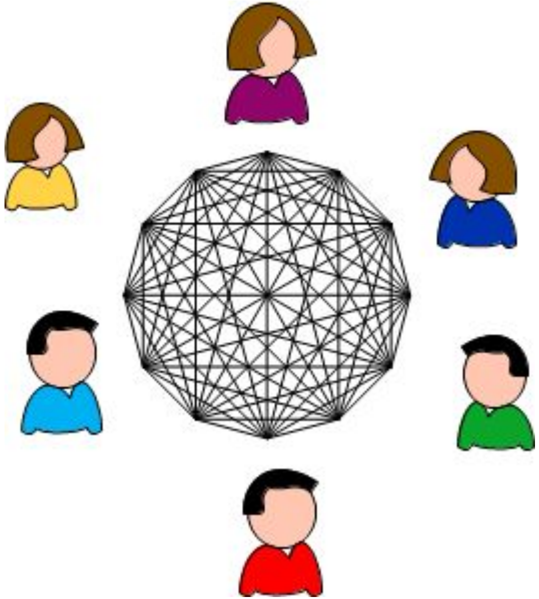
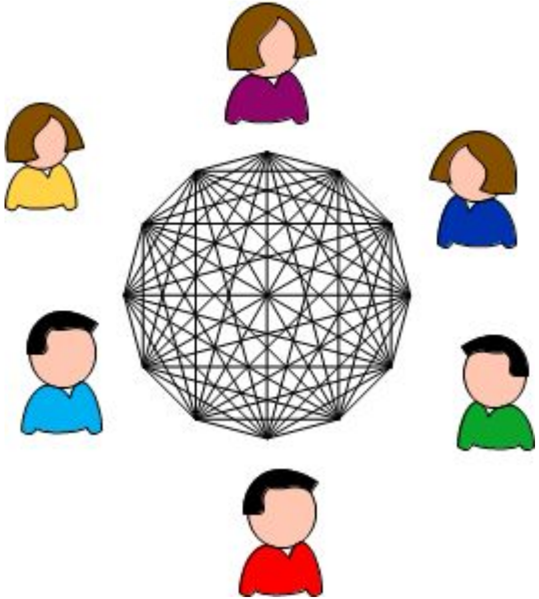


Protocol execution model:

- Interactive machines

Distributed Computation over a Network



Protocol execution model:

- Interactive machines
- **Formalizations of assumed resources (network, clock, random oracle, …)**

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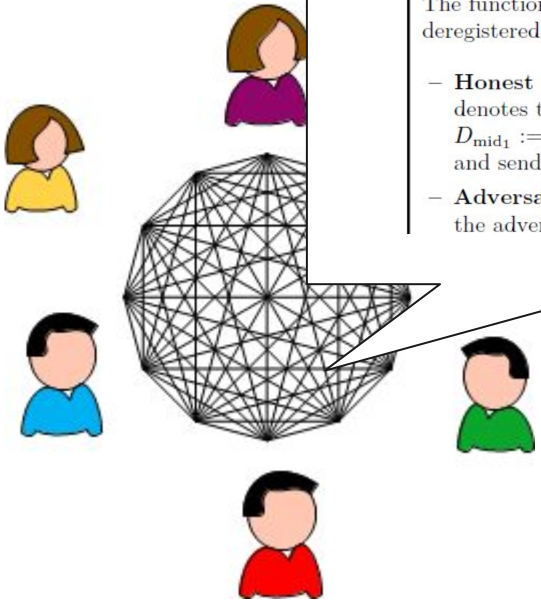

Functionality $\mathcal{F}^{\Delta}_{\text{N-MC}}$

The functionality is parameterized with a set possible send
deregistered) party is added to (resp. deleted from) $\mathcal{P}$.

– **Honest sender multicast.** Upon receiving (MULTICAS
denotes the current party set, choose n new unique mes
$D_{\text{mid}_1} := D^{MAX}_{\text{mid}_1} \ldots := D_{\text{mid}_n} := D^{MAX}_{\text{mid}_n} := 1$, set $\vec{M} :=$
and send $(\text{MULTICAST}, \text{sid}, m, U_p, (U_1, \text{mid}_1), \ldots, (U_n, \text{mi}$

– **Adversarial sender (partial) multicast.** Upon recei
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<u>ution model:</u>

machines

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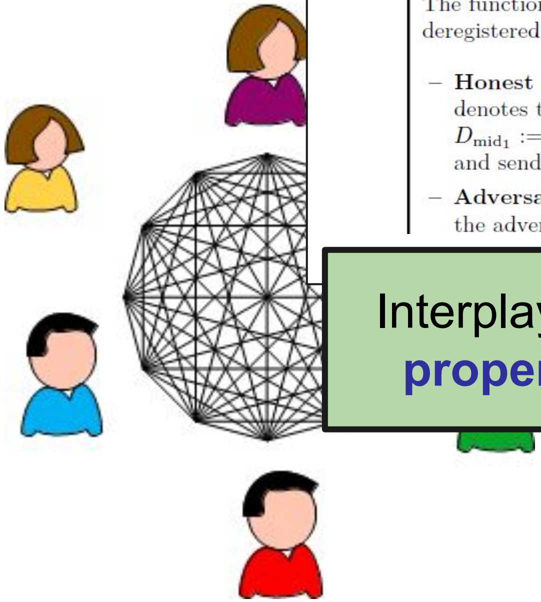

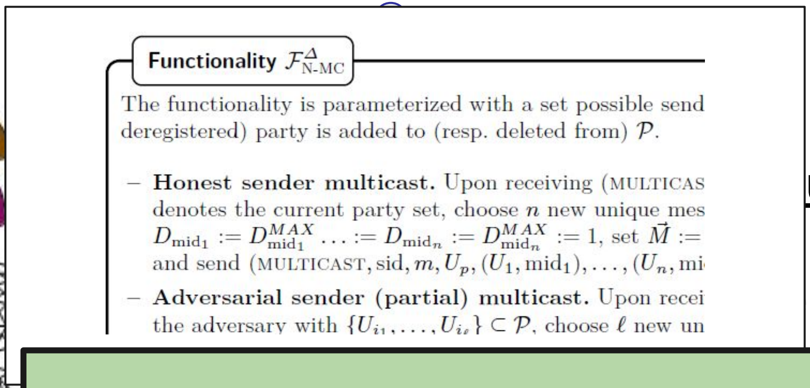

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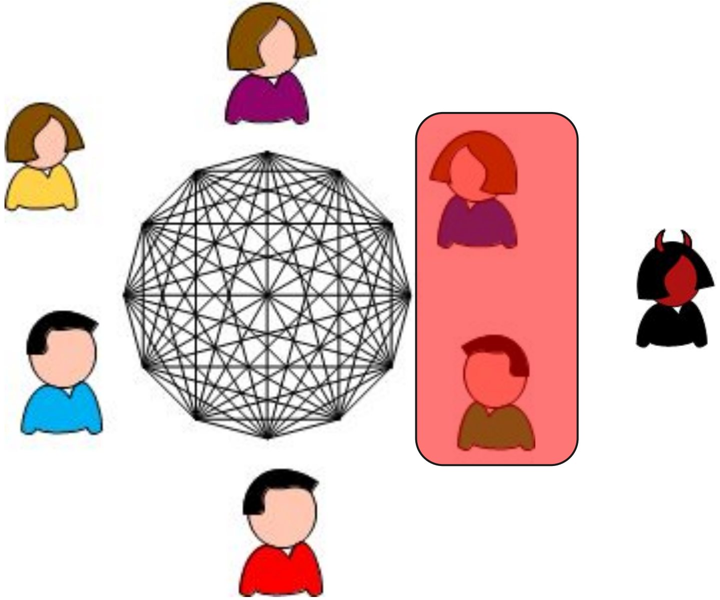
<u>ution model:</u>

machines

Interplay between theory and engineering: **relevant properties must be captured** by the abstraction

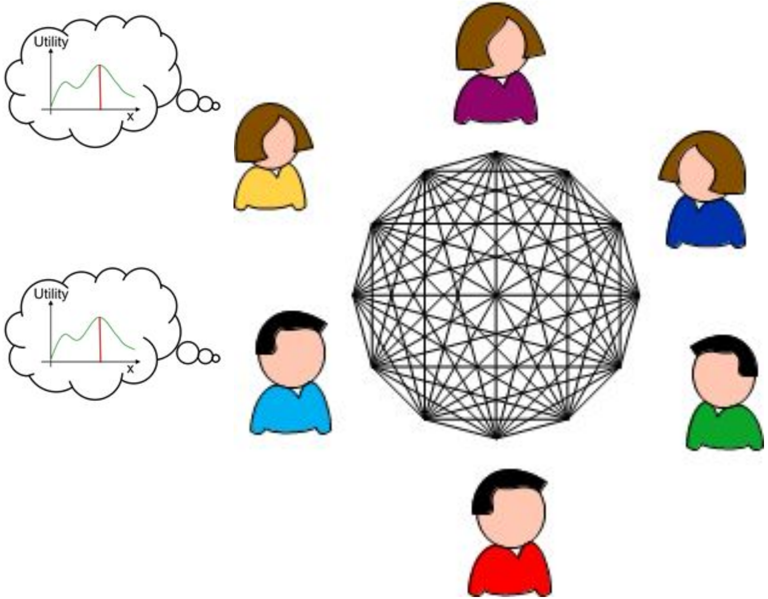
Distributed Computation over a Network



Protocol execution model:

- Interactive machines
- Formalizations of assumed resources (network, clock, random oracle, …)
- **Byzantine behavior**

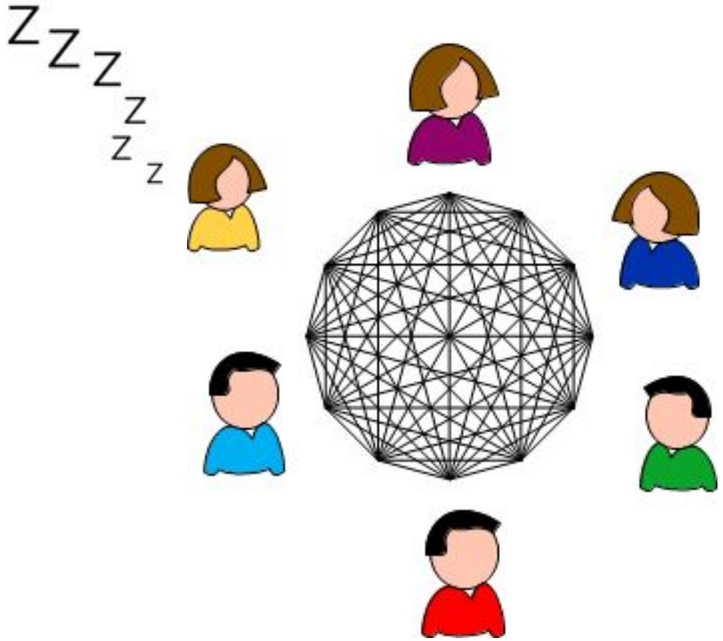
Distributed Computation over a Network



Protocol execution model:

- Interactive machines
- Formalizations of assumed resources (network, clock, random oracle, …)
- Byzantine behavior
- **Rational behavior**

Distributed Computation over a Network



Protocol execution model:

- Interactive machines
- Formalizations of assumed resources (network, clock, random oracle, …)
- Byzantine behavior
- Rational behavior
- **Machine failures**

Distributed Computation over a Network

Fine-Grained security model

+ **Security under composition:**
  Each external input might depend on the entire view of this and other protocols

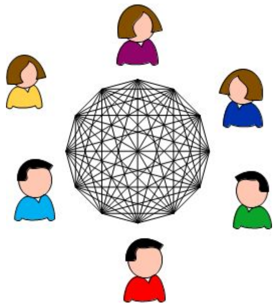
⇒ **A security proof is meaningful to practice.**

Protocol execution model:

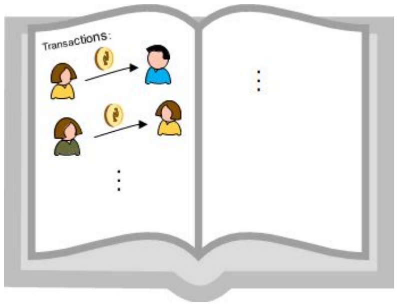
- Interactive machines
- Formalizations of assumed resources (network, clock, random oracle, …)
- Byzantine behavior
- Rational behavior
- Machine failures

Consensus Layer of Cardano

Goal:



Realize



<u>Ledger:</u>

- Persistence
- Liveness

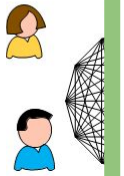
(Consensus on ledger state)

Result:

<u>Ouroboros:</u>

A Nakamoto-style **Proof-of-Stake Blockchain Protocol** realizing a ledger

Goal:



Nakamoto-Style Blockchain:

B_0

Genesis
Block

Result:

Ouroboros:

A Nakamoto-style **Proof-of-Stake Blockchain Protocol** realizing a ledger

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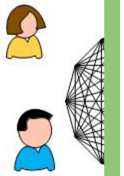

Nakamoto-Style Blockchain:

Genesis Block

- Lottery on next block proposer(s).
- Proposers elected proportional to owned stake.

Result:

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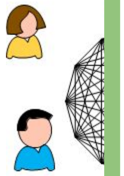
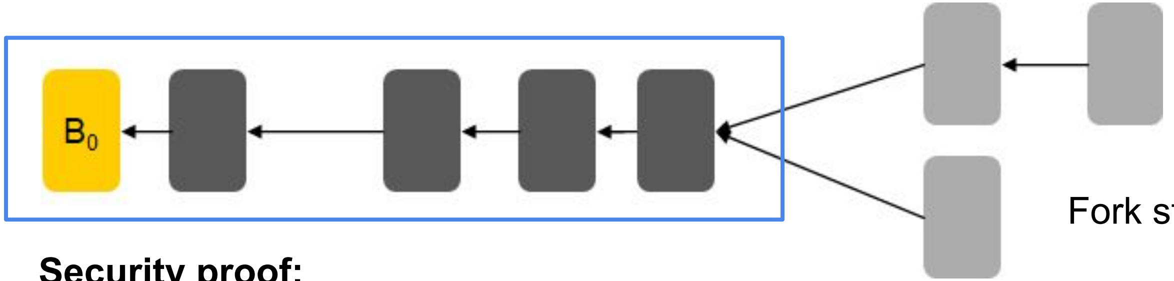
A Nakamoto-style **Proof-of-Stake Blockchain Protocol** realizing a ledger

Goal:



Result:

Nakamoto-Style Blockchain:

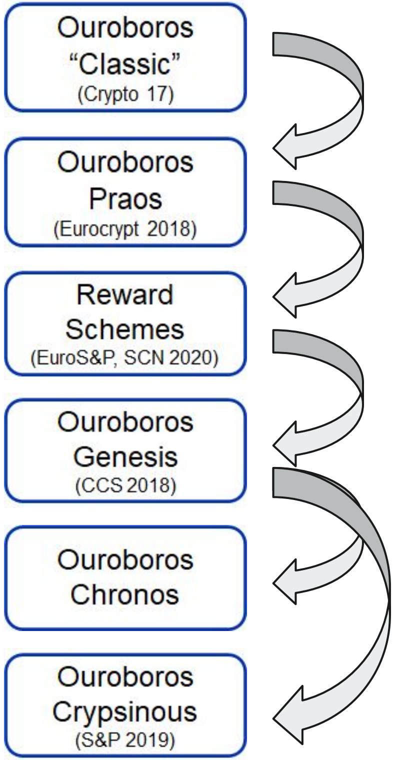


Security proof:
Establish **common-prefix, chain-growth, chain-quality** properties (under honest majority of stake assumption).

Ouroboros:

A Nakamoto-style **Proof-of-Stake Blockchain Protocol** realizing a ledger

Theory + Practice Interplay



- Series of results to overcome specific design challenges

- **Theoretical papers** live in an **abstract, proof-oriented world:**
  - Abstraction of components
  - Pseudocode
  - Asymptotic statements
  - Not usually implementation friendly

Theory + Practice Interplay

Ouroboros "Classic" (Crypto 17)

Ouroboros Praos (Eurocrypt 2018)

Reward Schemes (EuroS&P, SCN 2020)

Ouroboros Genesis (CCS 2018)

Ouroboros Chronos

Ouroboros Crypsinous (S&P 2019)

Synchronous model of computation and static corruption

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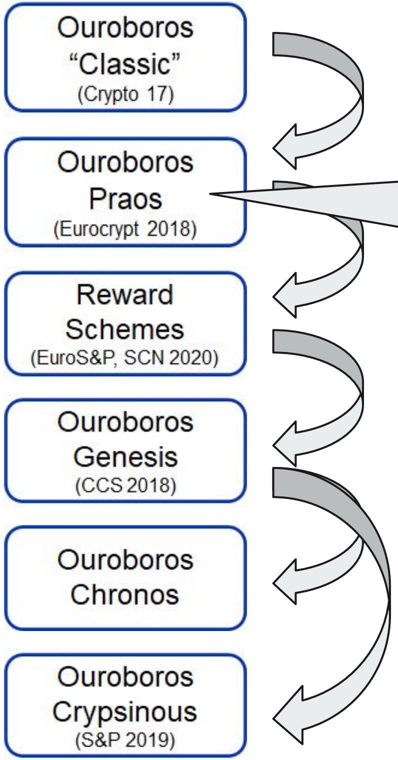
Theory + Practice Interplay



- Series of results to overcome specific design

Remove rigid message-passing round structure and tolerate adaptive corruptions

proof-oriented world:

- Abstraction of components
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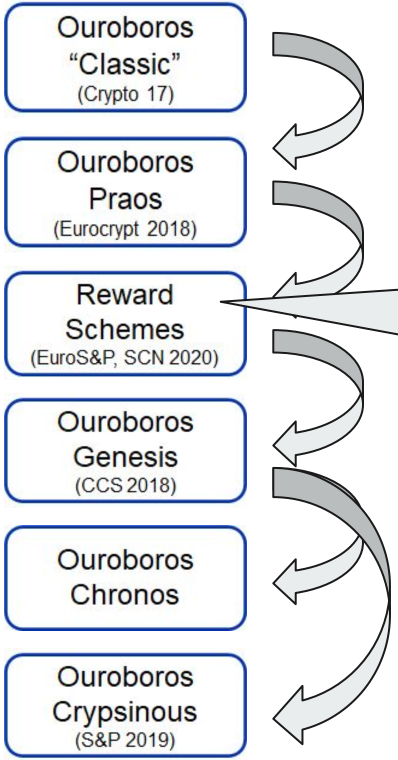
Theory + Practice Interplay

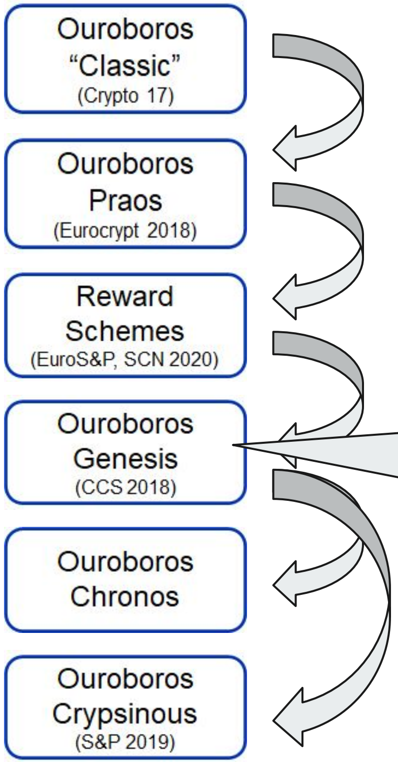


- Series of results to overcome specific design challenges

Reward sharing scheme for stake pools to establish an equilibrium with a large number of pools with high commitment to the system

- Pseudocode
- Asymptotic statements
- Not usually implementation friendly

Theory + Practice Interplay



- Series of results to overcome specific design challenges
- **Theoretical papers** live in an **abstract, proof-oriented world:**
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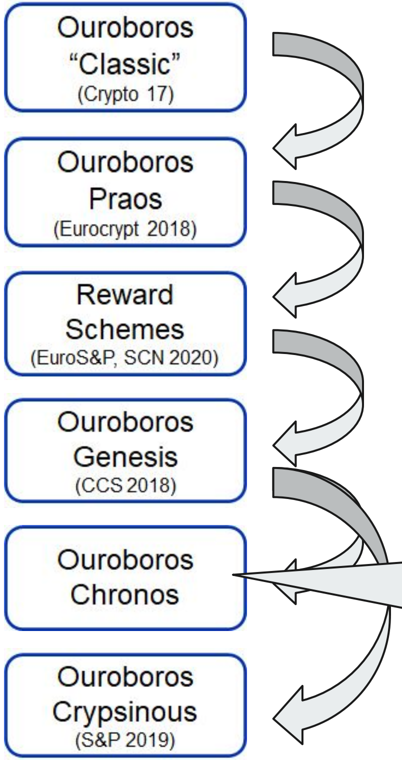
Dealing with fluctuating participation, joining after disconnection in a decentralized manner

Theory + Practice Interplay



- Series of results to overcome specific design challenges

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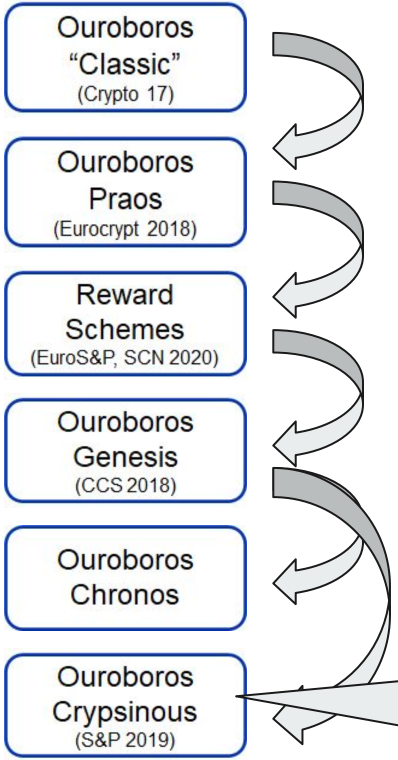
More resilience by less dependency on external timing services

Theory + Practice Interplay



- Series of results to overcome specific design challenges

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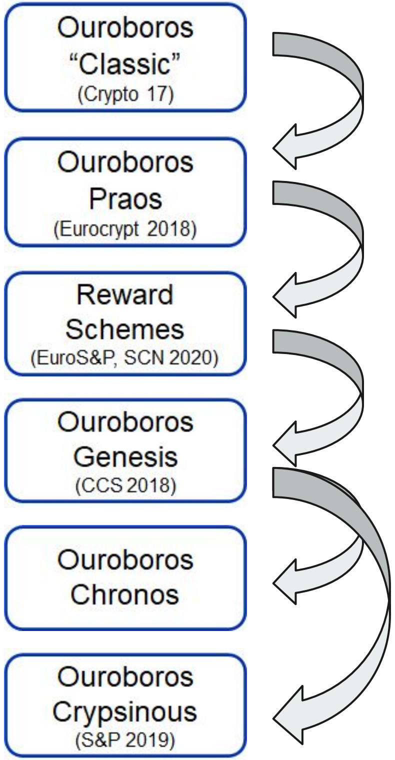
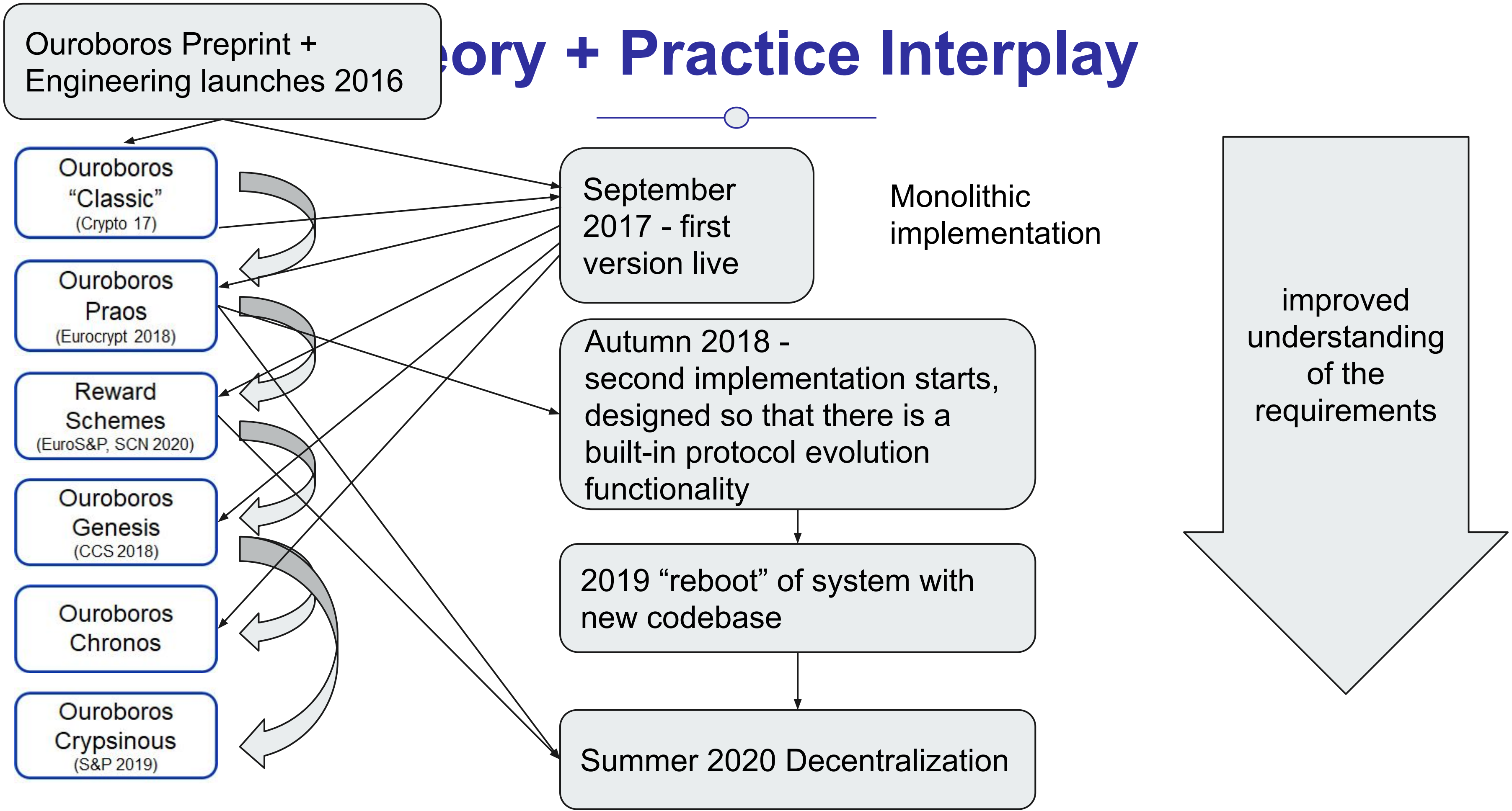
More functionality by privacy

Theory + Practice Interplay



Everything so ordered ...

eory + Practice Interplay



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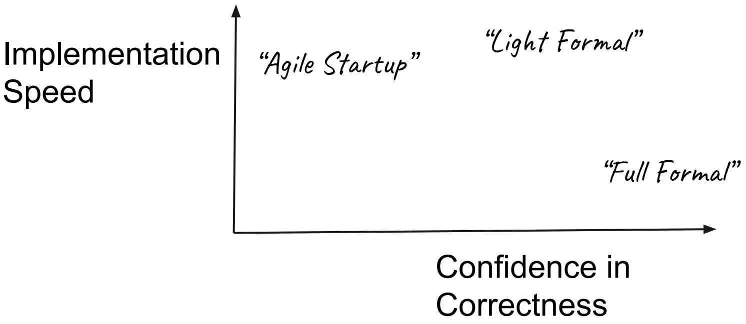
Implementing Correctly ~~or~~ and Quickly?

Questions before implementation

- Required level of confidence?
- Time available?
- Requirements fixed?
- Difficulty of Problem?



Correctness Toolbox

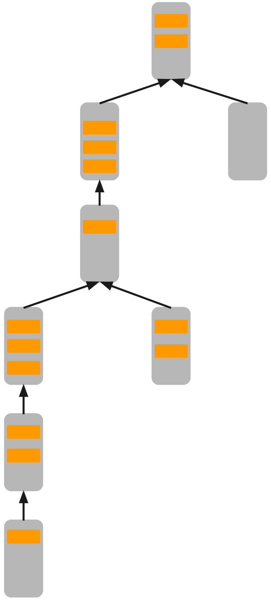
Variety of Tools

- Formal specifications
- Proofs (machine verifiable or manual)
- Model checking
- Property-based tests

System Properties

- Determinism?
- Concurrency?
- Finite state space?

Separating the Concerns

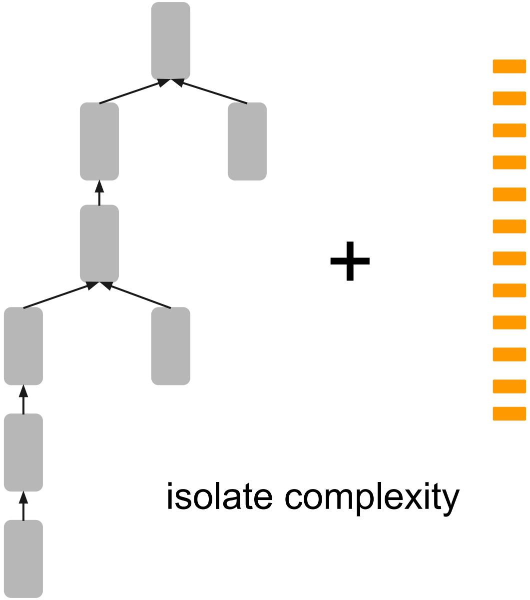


Blockchains are messy

- Forks,
  eventual consistency
- Distributed system,
  concurrency

Ledger can be simple

- Single, linear view
  of history



isolate complexity

Transaction Ledger

$$\frac{\text{txins}\ tx \subseteq \text{dom}\ utxo \qquad \text{minfee}\ pc\ tx \leqslant \text{txfee}\ tx \\ \text{balance (txouts}\ tx) + \text{txfee}\ tx = \text{balance (txins}\ tx \lhd utxo)}{pc \vdash utxo \xrightarrow[\text{UTXO}]{tx} (\text{txins}\ tx \not\lhd utxo) \cup \text{txouts}\ tx}$$

```
Rule
  [Predicate $ λ(_, utxo, tx) →
     txins tx ‘Set.isSubsetOf‘ dom utxo ?! BadInputs
  , Predicate $ λ(pc, _, tx) →
     pcMinFee pc tx ⩽ txfee tx            ?! FeeTooLow
  , Predicate $ λ(_, utxo, tx) →
        balance (txouts tx) <> txfee tx
      ≡ balance (txins tx ◁ utxo)          ?! IncreasedTotalBalance
  ]
  (Extension ∘ Transition $
     λ(pc, utxo, tx) → (txins tx ⋪ utxo) ∪ txouts tx)
```

Formal/executable specifications

- Describe microscopic behaviour
  “small step operational semantics”

Correctness:

- Formulate macroscopic properties
  “money is conserved”
- Property-based testing
  `QuickCheck`
- Prove them (manually, assisted)

Consensus and Networking

Harder: Concurrency, Distributed Computing

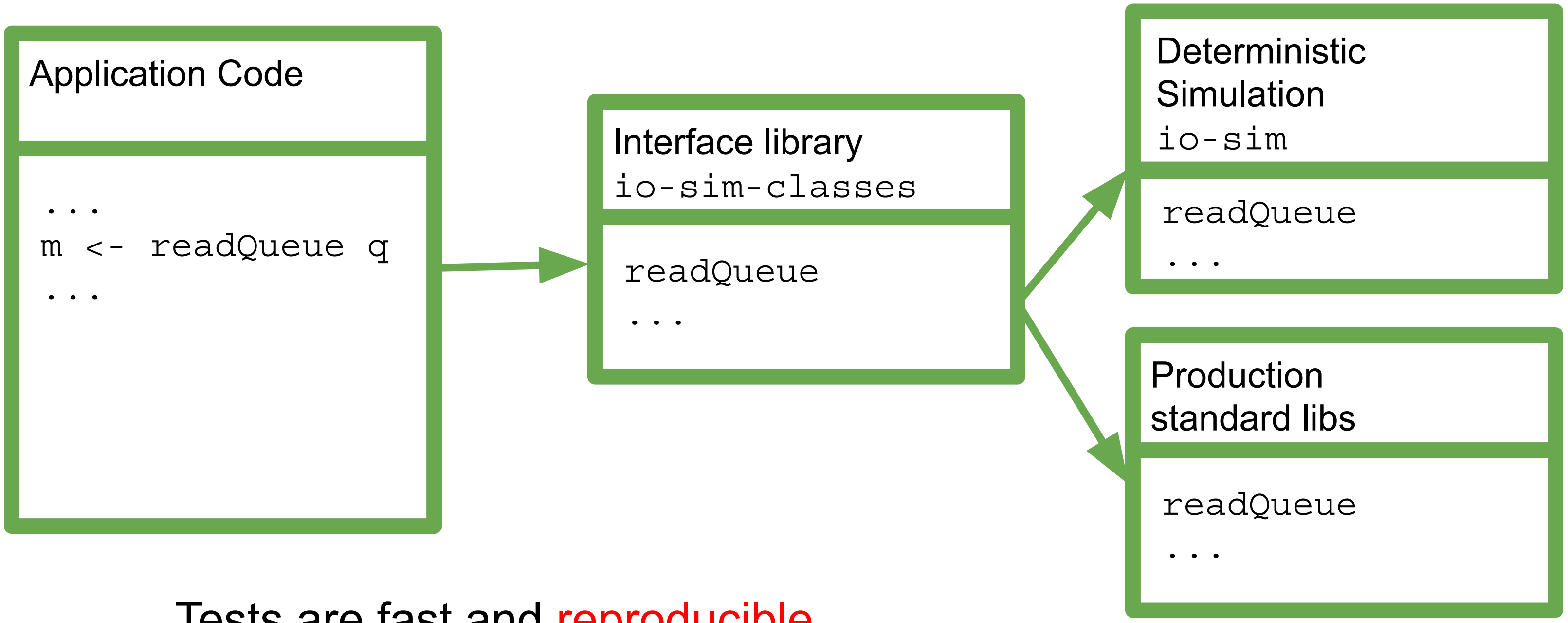
- Language of process calculi
- Not feasible to start from full formal specification within timeframe

Strategy

- Write testable code → deterministic simulation
  property-based testing

- Use type system for guaranteeing invariants
- “Catch Up” on the formal side

Testing Concurrent Code in Simulation



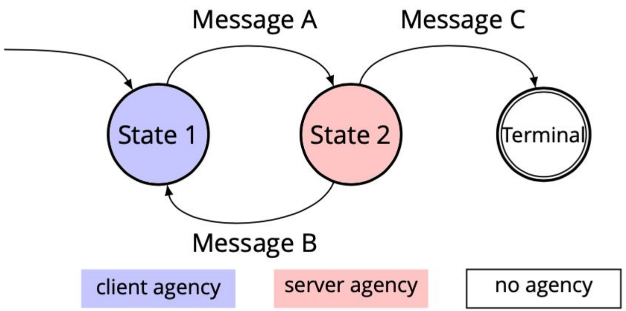
Tests are fast and reproducible

Shrink to minimal counterexample

Network Protocols: Session Types

Race Condition Too many are talking

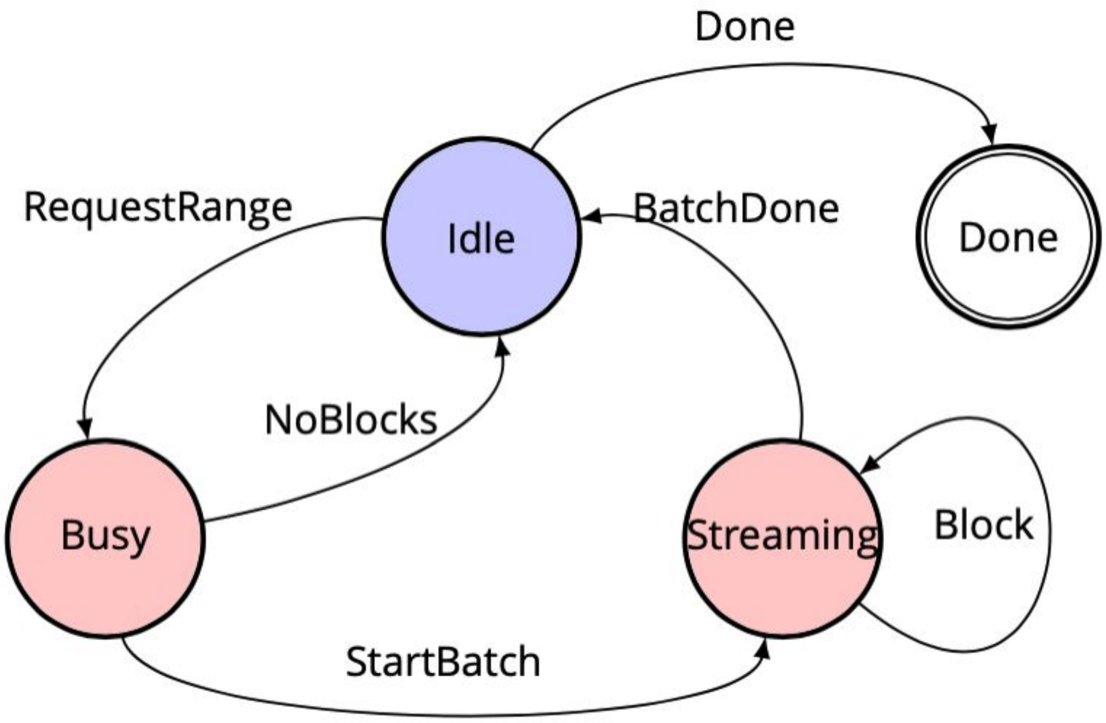
Deadlock Everyone is waiting



Typed Protocols

- Always one sender, one receiver
- Enforced by Haskell type system
  `Protocol` type class
- Violations prevented at compile time

Example: Fetching Blocks



Formal Treatment

Goal is to prove equivalence of high and low-level designs

- High level: described exactly as in the papers
- Low level:
  - a practical design;
  - matching how networks work; and
  - operate in bounded resources.
- Modular design: high and low-level related by a series of refinements
- Modular proof: prove equivalence of each refinement and compose
- Machine checked proofs

Formal Treatment

Results so far

- Formalised an asynchronous process calculus
  - Inspired by the π-calculus
  - Using Isabelle theorem prover
  - Proved all the usual properties of a process calculus
  - Framework for proving bisimilarity results
- Formalised high-level paper versions of Ouroboros BFT and Praos
- Proved equivalence of message broadcast vs relay over a network
- Proved equivalence of bulk vs incremental Ouroboros chain selection

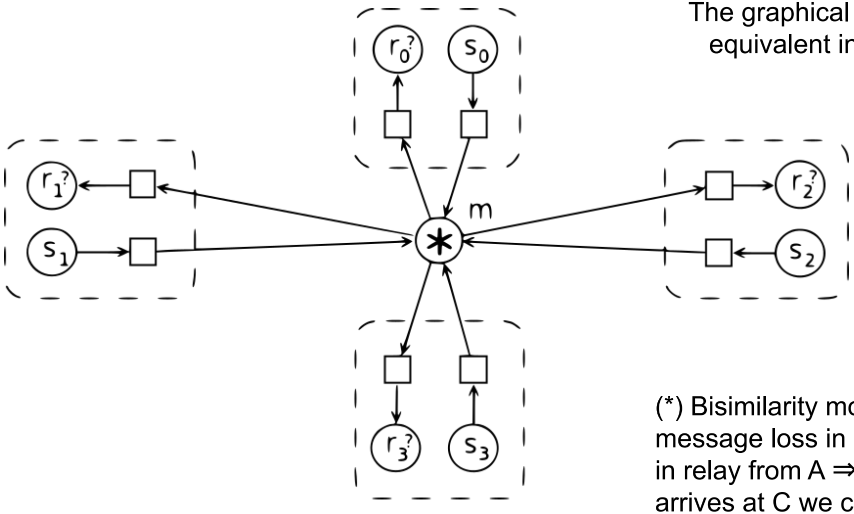
Formal Treatment

Message broadcast
(async, with loss and duplication)

Bisimilarity(*) proved within the process calculus.

Relay over a directed graph
(async, with loss and duplication)

The graphical notation has a syntactic equivalent in the process calculus.



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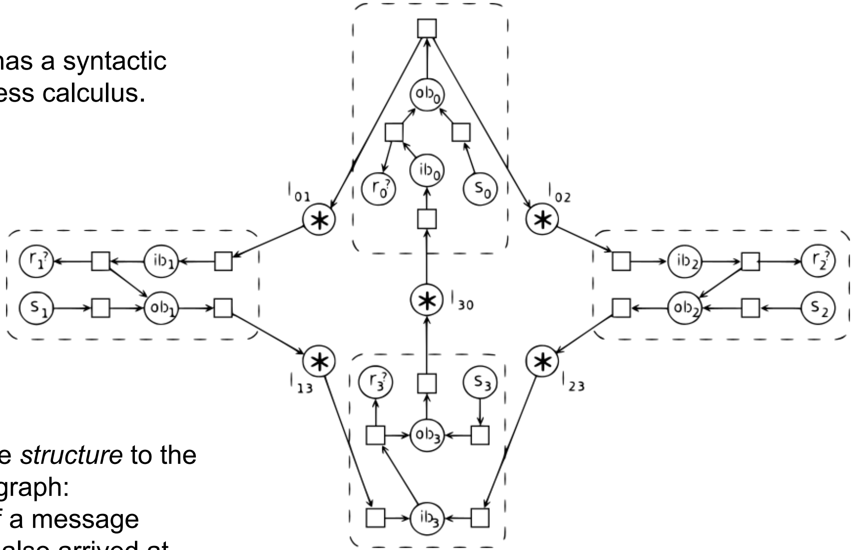
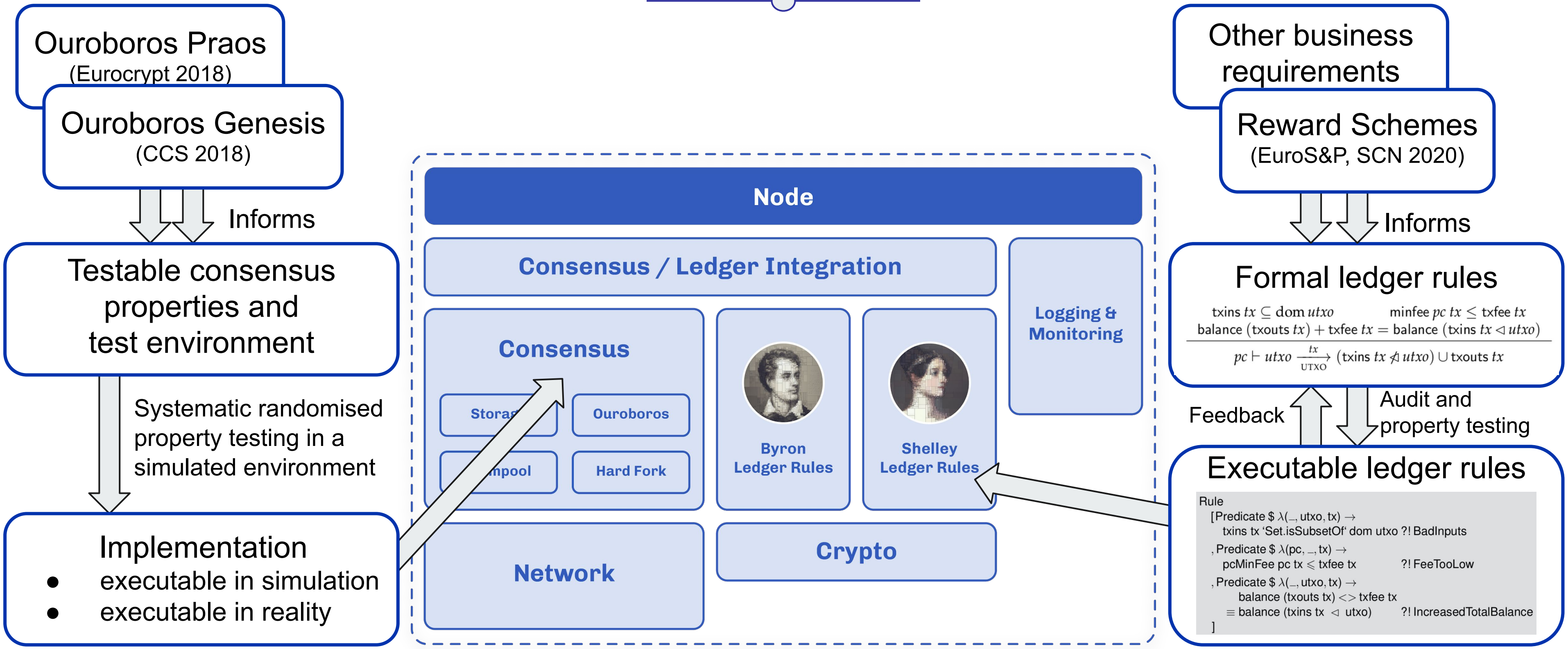


(*) Bisimilarity modulo more *structure* to the message loss in the relay graph:
in relay from A ⇒ B ⇒ C, if a message arrives at C we can infer it also arrived at B, which is not true for broadcast.

Connecting theory with implementation



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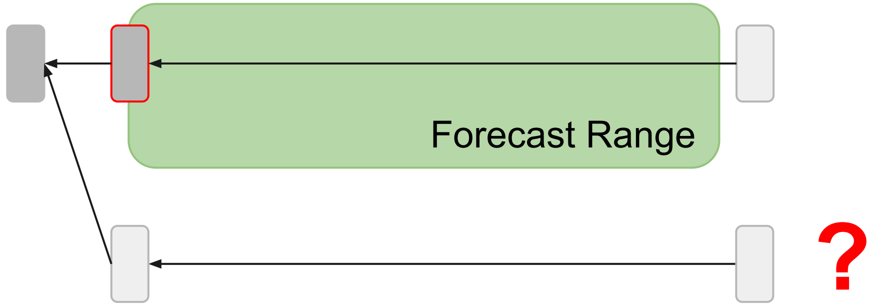
Block-Fetch, Forecasting, Denial of Service

Tension: Open Participation, Limited Resources

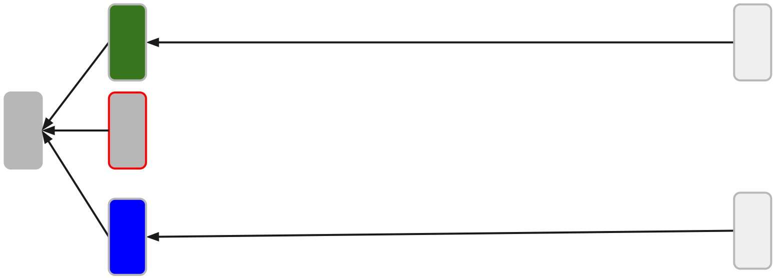
- Needs aggressive filtering
- Select chain based on headers before downloading blocks



Block-Fetch, Forecasting, Denial of Service

Edge Cases Require Block Download Before Choosing a Chain

- Proposal: only do that when there is no other way to follow any chain



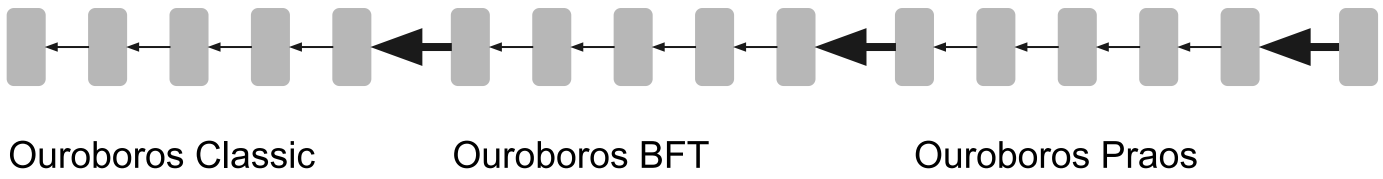
Implemented: tests show disagreement between nodes

Note: general, randomised test, not unit test

Hard-Fork Combinator

Research: One protocol, starting from scratch

Real-World System: Protocol evolves, but history is immutable



Challenges:

- One codebase needs to understand the whole chain
- Need agreement on when to transition

Hard-Fork Combinator:

- Define new protocol as sequential composition of protocols

De-Risking Decentralisation

Risks in Switching to Decentralised Protocol

- Operators need to gain experience → system not stable
- Little active stake → danger of 51% attack

Gradual Transition

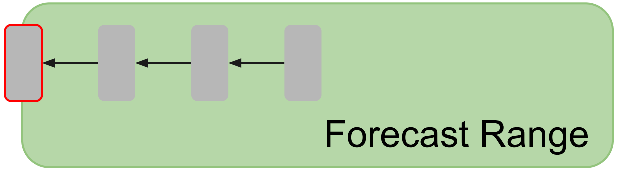
- Fraction `d` of blocks produced by fixed federation
- Gradually hand over control, from `d=1` to `d=0`

Real-World Concern: Finite Resources

Open Participation, Limited Resources: worry about DoS

- Proof of Work: producing a chain is much more difficult than validating it
  → obvious, significant advantage for honest nodes
- Proof of Stake: finer balance
  → problem: attacker can cheaply occupy honest resources
- Design needs to analyse worst-case behaviour
  excludes many off-the-shelf libraries

  e.g. aggressive filtering



Refine Carefully

Papers are Quite Abstract, Implementation Introduces Details

- Interactions of the adversary with the system also more detailed
- Avoid creating new interactions that are detrimental to the security, which are not describable at the high level
- Mind the resource balance between honest and adversarial nodes

Future Work

- Close remaining gaps between theory and implementation
- Formalised version of the security guarantees of Ouroboros
  Ph.D. thesis, using Isabelle theorem prover
- Implement newer versions of Ouroboros
- Adding additional ledger functionality
  smart contracts, decentralised software updates