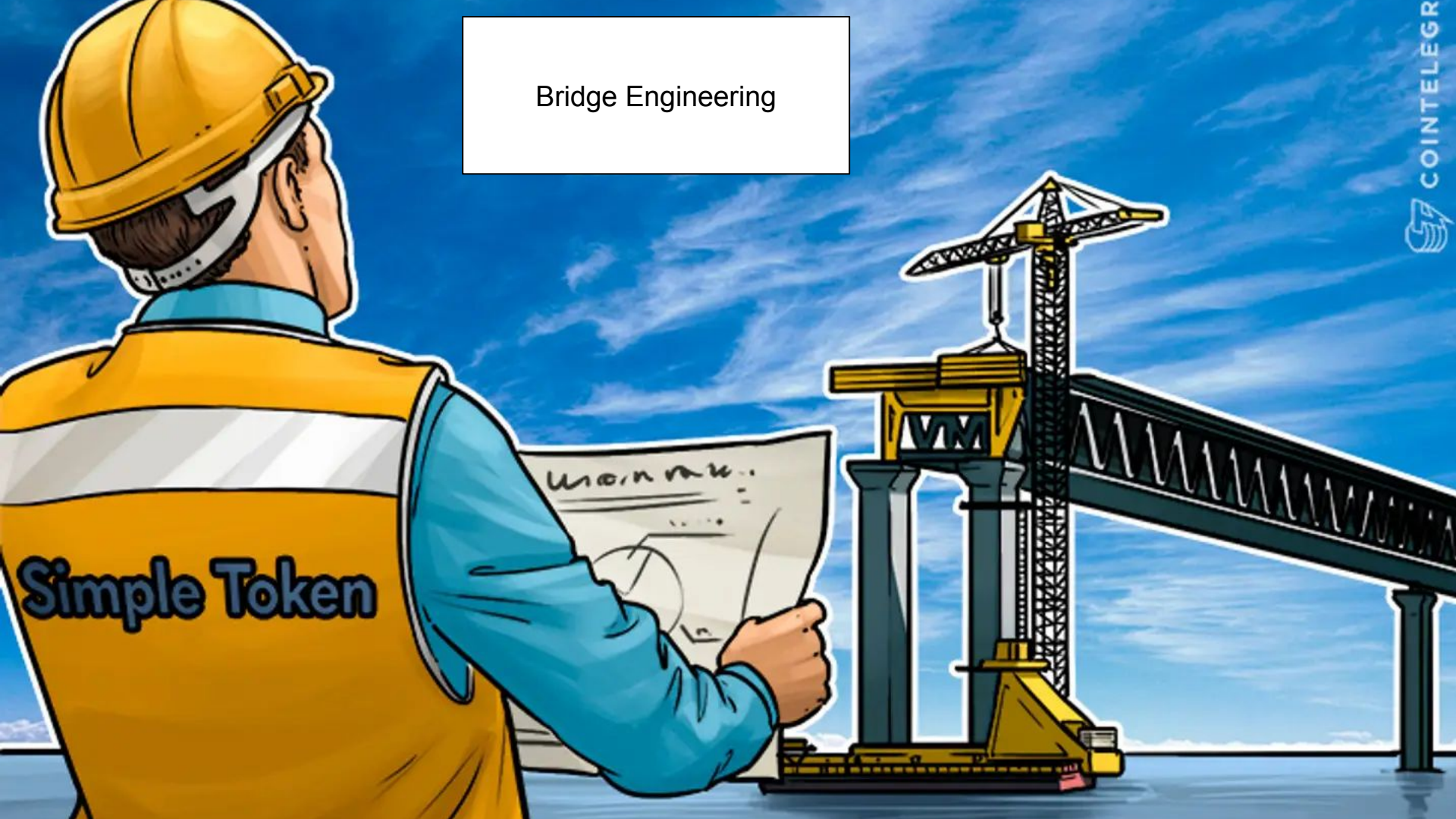
A Better Mental Model for Rollups, Plasma, and Validating Bridges

An Intro to Bridge Engineering

Patrick McCorry

Intern, Infura


Bridge Engineering
Simple Token
COINTELEGR

A bridge from Ethereum to Coinbase

coinbase

Ethereum & Users
Blockchain network

Bridge contract
Holds user funds

Single authority
One ring to rule them all

A bridge from Ethereum to Coinbase

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```
Deposit()

Withdraw()

Allowance(user, coins)
```

A bridge from Ethereum to Coinbase

Ethereum & Users
Blockchain network

Bridge contract
Holds user funds

`Deposit()`

`Withdraw()`

`Allowance(user, coins)`

coinbase

Single authority
One ring to rule them all

Alice can withdraw 1,000 ETH

A bridge from Ethereum to Coinbase

Ethereum & Users
Blockchain network

Bridge contract
Holds user funds

`Deposit()`

`Withdraw()`

`Allowance(user, coins)`

Coinbase has informed me that Alice can withdraw 1,000 ETH.

I trust Coinbase - the database must be OK

A bridge from Ethereum to Coinbase

Ethereum & Users
Blockchain network

Bridge contract
Holds user funds

coinbase

Single authority
One ring to rule them all

Alice

`Deposit()`

`Withdraw()`

`Allowance(user, coins)`

Alice withdraws 1,000 ETH

A bridge from Ethereum to Coinbase

Ethereum & Users
Blockchain network

Generically, what is happening?

coinbase

Single authority
One ring to rule them all

Alice

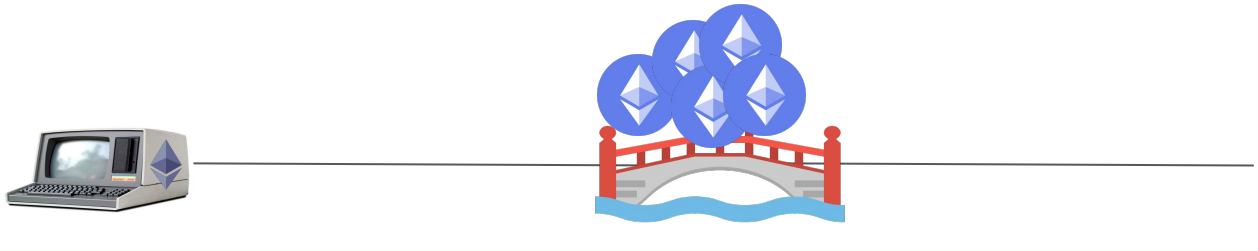
`Deposit()`

`Withdraw()`

`Allowance(user, coins)`

Alice withdraws 1,000 ETH

A bridge from Ethereum to an off-chain system



Ethereum & Users
Blockchain network

Bridge contract
Holds user funds

Off-chain database
(account balances, program state, etc).

Assets ========== Liabilities

Trust assumption

Before processing a withdrawal, I need to check the database is OK

Trust assumption for bridges have evolved over time

Thanks to Hasu for the terminology

Single authority

One ring to rule them all

coinbase Bitstamp

Thanks to Hasu for the terminology

Single authority

One ring to rule them all

coinbase Bitstamp

Multi-authority

K of N parties

RSK

Liquid by Blockstream

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K of N parties

RSK

Liquid by Blockstream

Crypto-economic bridge

Staked investment in its success

polygon

Previously Matic Network

Thanks to Hasu for the terminology

Polygon's proof of stake bridge:

Binance	506,183,677
Stakin	322,033,445
All nodes	206,676,574
Web3Nodes	123,762,284
Anonymous 94	100,622,650
Decentral Games	70,018,093
Total	**1,329,296,723**

Attack Target: 1,283,657,130 matic

9/12/2021

Single authority

One ring to rule them all

coinbase Bitstamp

Multi-authority

K of N parties

RSK Liquid by Blockstream

Crypto-economic bridge

Staked investment in its success

polygon

Previously Matic Network

Single authority

One ring to rule them all

coinbase Bitstamp

Trusting <10 parties to protect our funds

… sucks a bit right?

Multi-authority

K of N parties

RSK

Liquid by Blockstream

Crypto-economic bridge

Staked investment in its success

polygon

Previously Matic Network

Single authority hacks

Guarding custody of tokens is not trivial….

I ran out of space… this is only a small sample of hacks.

Taylor Monahan maintains a larger list

https://docs.google.com/spreadsheets/d/1ZEEAmXjpN8kL9BvITg9GKu-dbeUra6c14YLpLkCp5Zo/edit?usp=sharing

Name	Tokens	Comment
MtGox (2014)	850k BTC	6% of all bitcoin
Bitcoinica (2011)	61k BTC	Linode hosting provider hacked
Bitfloor (2012)	24k BTC	Wallets stored on server
Bitstamp (2015)	19k BTC	Hot wallet hacked
BTER (2015)	7k BTC	Inside job
Gatecoin (2015)	185k ETH	Hot wallet hacked
Bitfinex (2016)	119k BTC	Compromised server
Bithumb (2018)	2k BTC	Hot wallet hacked
Zaif (2018)	6k BTC	Hot wallet hacked
Coincheck (2018)	$534m NEM tokens	Hot wallet hacked
Coinbin (2019)	$26m in tokens	Inside job
CoinBene (2019)	$45m in tokens	Hot wallet hacked
Binance (2019)	7k BTC	Hot wallet hacked

Multi authority hacks

… trusting multiple folk to do the right thing … is also not good enough

5 out of 9 validators compromised

(4 compromised validators controlled by 1 company)

Old school motto

Can we transact on a off-chain system, while still allowing users to maintain self-custody of their funds?

Enabling Blockchain Innovations with Pegged Sidechains

Adam Back, Matt Corallo, Luke Dashjr,
Mark Friedenbach, Gregory Maxwell,
Andrew Miller, Andrew Poelstra,
Jorge Timón, and Pieter Wuille*†

2014-10-22 (commit 5620e43)

Abstract

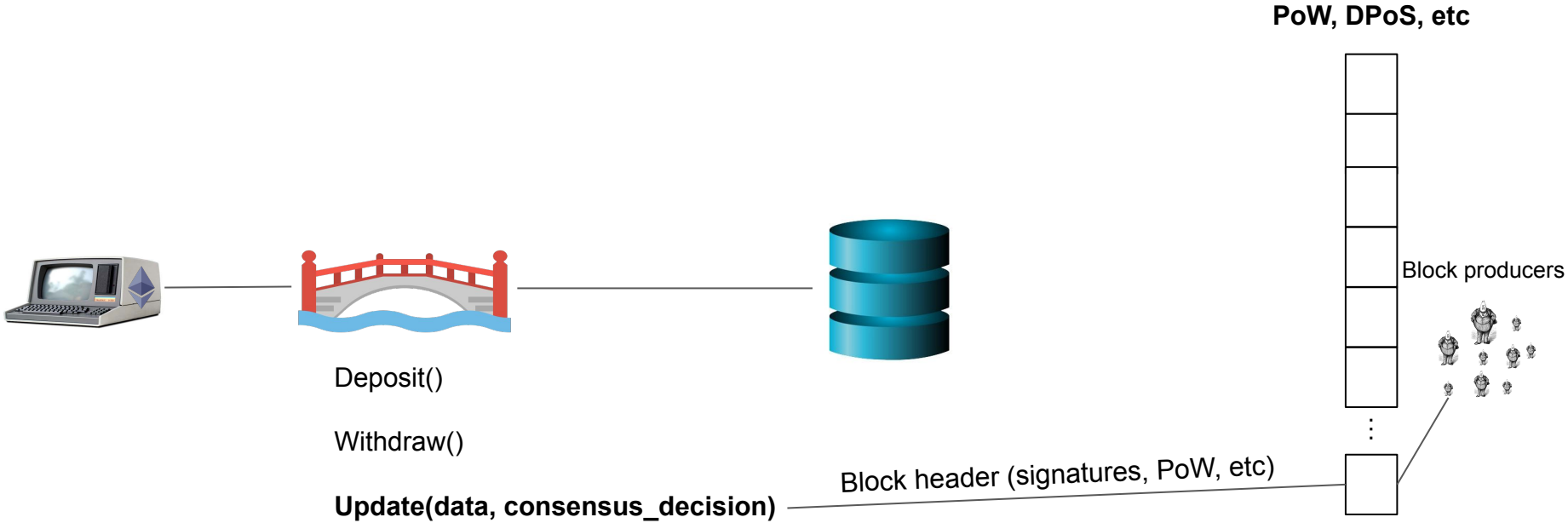
Since the introduction of Bitcoin[Nak09] in 2009, and the multiple computer science and electronic cash innovations it brought, there has been great interest in the potential of decentralised cryptocurrencies. At the same time, implementation changes to the consensus-critical parts of Bitcoin must necessarily be handled very conservatively. As a result, Bitcoin has greater difficulty than other Internet protocols in adapting to new demands and accommodating new innovation.

We propose a new technology, *pegged sidechains*, which enables bitcoins and other ledger assets to be transferred between multiple blockchains. This gives users access to new and innovative cryptocurrency systems using the assets they already own. By reusing Bitcoin's currency, these systems can more easily interoperate with each other and with Bitcoin, avoiding the liquidity shortages and market fluctuations associated with new currencies. Since sidechains are separate systems, technical and economic innovation is not hindered. Despite bidirectional transferability between Bitcoin and pegged sidechains, they are isolated: in the case of a cryptographic break (or malicious design) in a sidechain, the damage is entirely confined to the sidechain itself.

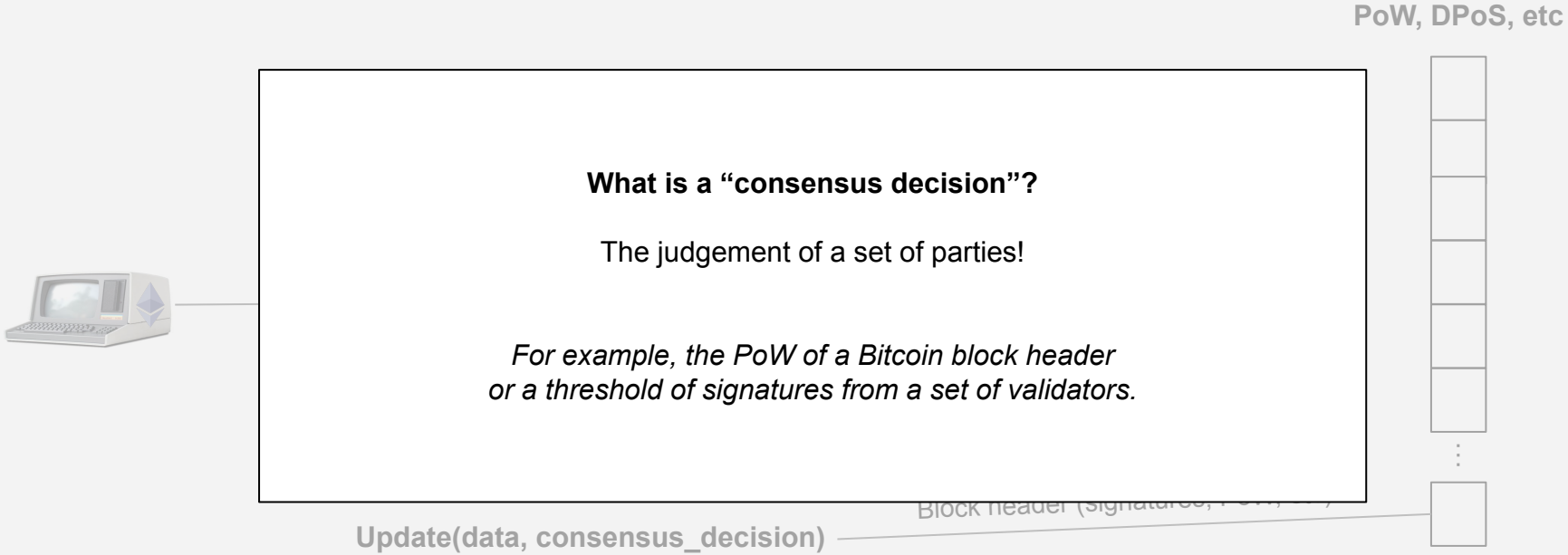
This paper lays out pegged sidechains, their implementation requirements, and the work needed to fully benefit from the future of interconnected blockchains.

At the heart of the original sidechain paper was a protocol to build ***a trustless bridge.***

The “Consensus” Bridge



The “Consensus” Bridge



The “Consensus” Bridge

What is trusted?

- **Consensus is online.** If the off-chain system goes offline, the funds are stuck forever.
- **Invalid transactions can be processed.** Ultimately, the bridge is trusting the “word” of the consensus protocol.

oW, DPoS, etc

Update(data, co

Can we really build a bridge that protects us from an all powerful authority?

Lightning strikes create plasma via a very strong jolt of electricity. Most of the Sun, and other stars, is in a plasma state. Certain regions of Earth's atmosphere contain some plasma created primarily by ultraviolet radiation from the Sun. Collectively, these regions are called the ionosphere.

https://scied.ucar.edu › learning-zone › sun-space-weather

Plasma - UCAR Center for Science Education

It all began with Plasma

Plasma: Scalable Autonomous Smart Contracts

Joseph Poon joseph@lightning.network
Vitalik Buterin vitalik@ethereum.org

August 11, 2017
WORKING DRAFT
https://plasma.io/

Abstract

Plasma is a proposed framework for incentivized and enforced execution of smart contracts which is scalable to a significant amount of state updates per second (potentially billions) enabling the blockchain to be able to represent a significant amount of decentralized financial applications worldwide. These smart contracts are incentivized to continue operation autonomously via network transaction fees, which is ultimately reliant upon the underlying blockchain (e.g. Ethereum) to enforce transactional state transitions.

We propose a method for decentralized autonomous applications to scale to process not only financial activity, but also construct economic incentives for globally persistent data services, which may produce an alternative to centralized server farms.

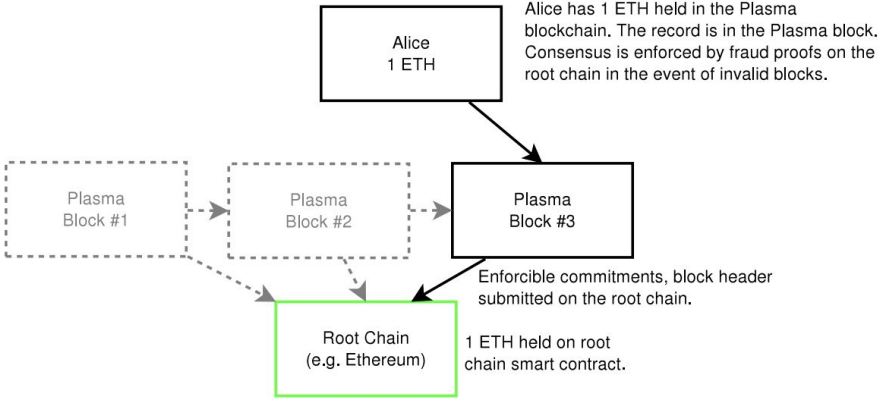
Plasma is composed of two key parts of the design: Reframing all blockchain computation into a set of MapReduce functions, and an optional method to do Proof-of-Stake token bonding on top of existing blockchains with the understanding that the Nakamoto Consensus incentives discourage block withholding.

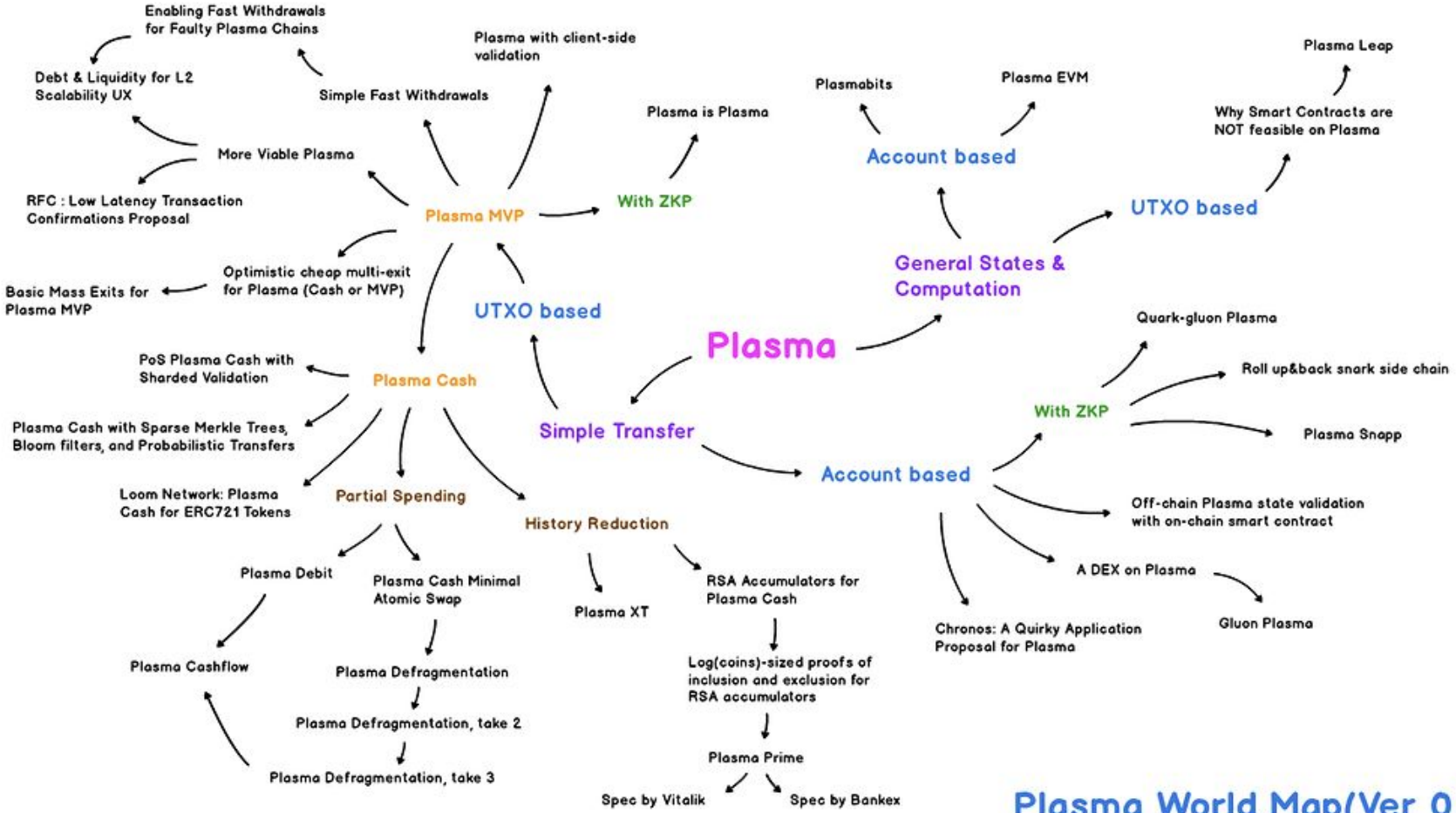
This construction is achieved by composing smart contracts on the main blockchain using fraud proofs whereby state transitions can be enforced on a parent blockchain. We compose blockchains into a tree hierarchy, and treat each as an individual branch blockchain with enforced blockchain history and MapReducible computation committed into merkle proofs. By framing one's ledger entry into a child blockchain which is enforced by the parent chain, one can enable incredible scale with minimized trust (presuming root blockchain availability and correctness).

The greatest complexity around global enforcement of non-global data revolves around data availability and block withholding attacks, Plasma has mitigations for this issue by allowing for exiting faulty chains while also creating mechanisms to incentivize and enforce continued correct execution of data.

As only merkleized commitments are broadcast periodically to the root blockchain (i.e. Ethereum) during non-faulty states, this can allow for incredibly scalable, low cost transactions and computation. Plasma enables persistently operating decentralized applications at high scale.

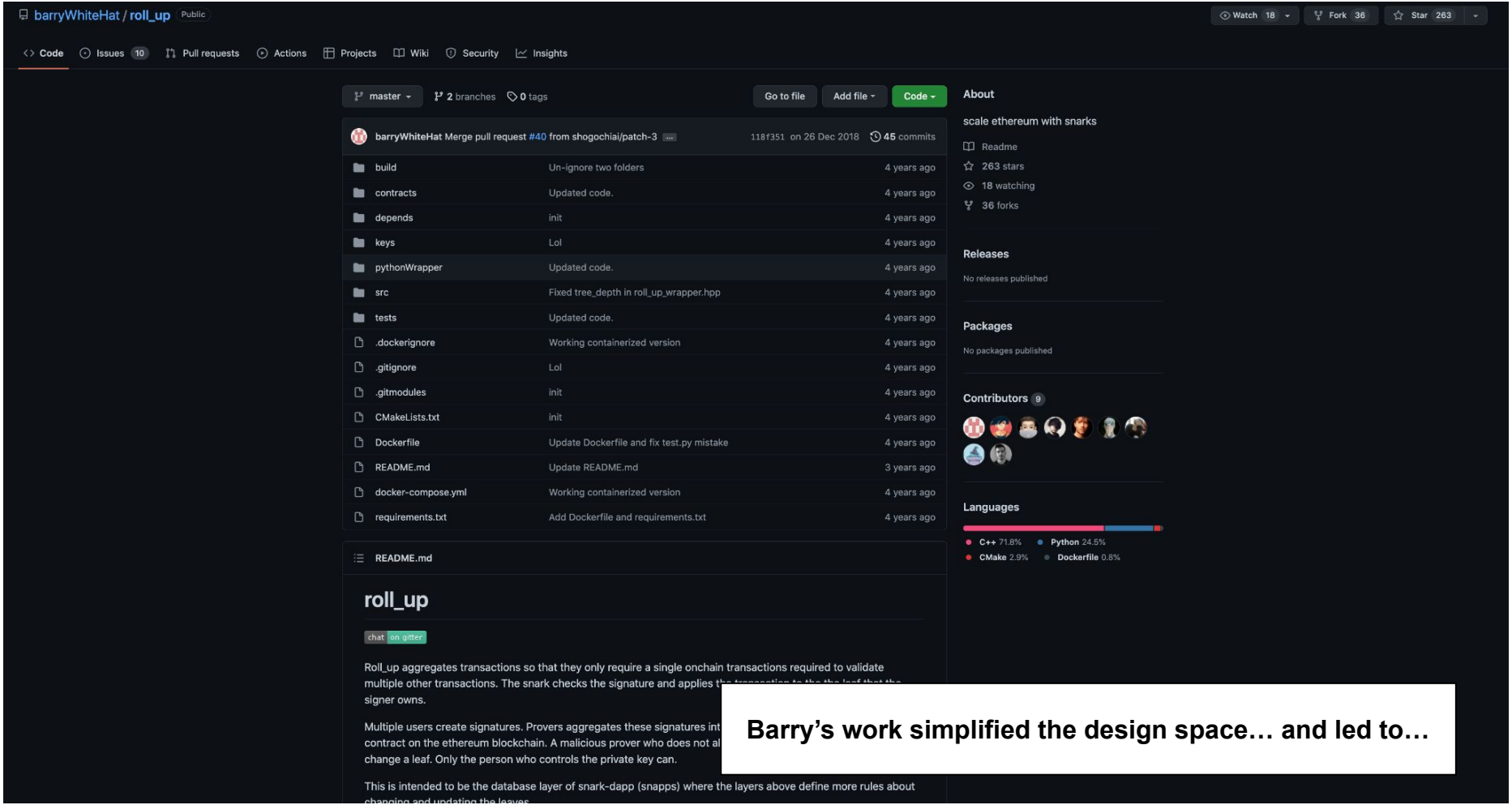
Again, an impossible paper to read





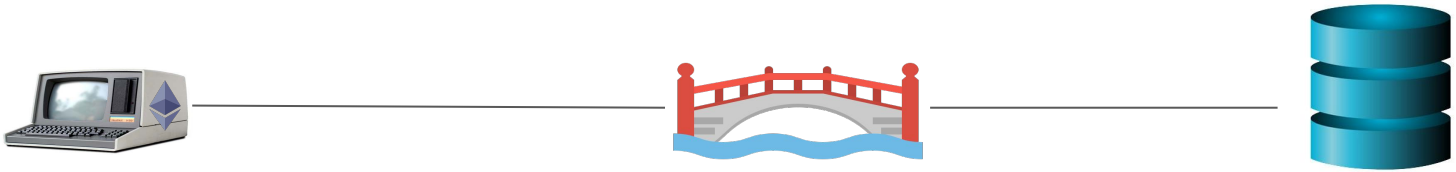
Plasma World Map(Ver 0.1)

Created by Aiden (aiden.p@ontther.io)



Barry's work simplified the design space… and led to…

The Validating Bridge (rollups)



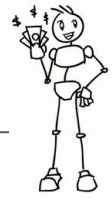
Deposit()

Withdraw()

Update(<.....>, <.....>)

The Validating Bridge (rollups)

update db



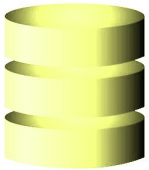
Executor

Deposit()

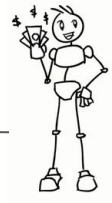
Withdraw()

Update(<.....>, <.....>)

The Validating Bridge (rollups)



update db



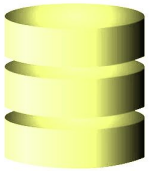
Executor

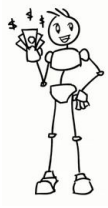
Deposit()

Withdraw()

Update(<.....>, <.....>)

The Validating Bridge (rollups)





Executor

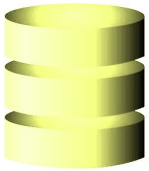
Deposit()

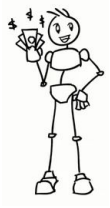
Withdraw()

Update(<.....>, <.....>)

Proposed update to db

The Validating Bridge (rollups)





Executor

Deposit()

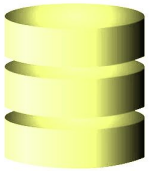
With

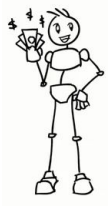
Upd

~~OK i'll accept this update~~

You must CONVINCE me why this update to the database it is correct.

The Validating Bridge (rollups)





Deposit()

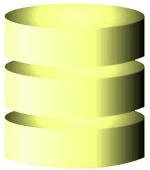
Withdraw()

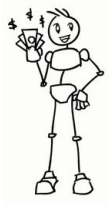
Update(proposed_update, evidence)

Convincing evidence

Executor

The Validating Bridge (rollups)





Executor

Deposit()

With

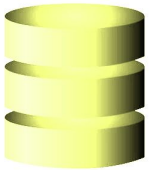
Upd

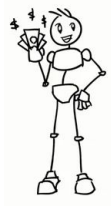
Database is safe and alive?

validates

I'll accept it.

The Validating Bridge (rollups)





Executor

Deposit()

Withdraw()

Update(proposed_update, evidence)

LOOPRING

Optimistic Ethereum

ARBITRUM

zkSync

STARKWARE

Continuously check the integrity of all proposed updates

The Validating Bridge (rollups)

Ultimately, the layer-1 blockchain, Ethereum, is protecting you.

Executor

LOOPR

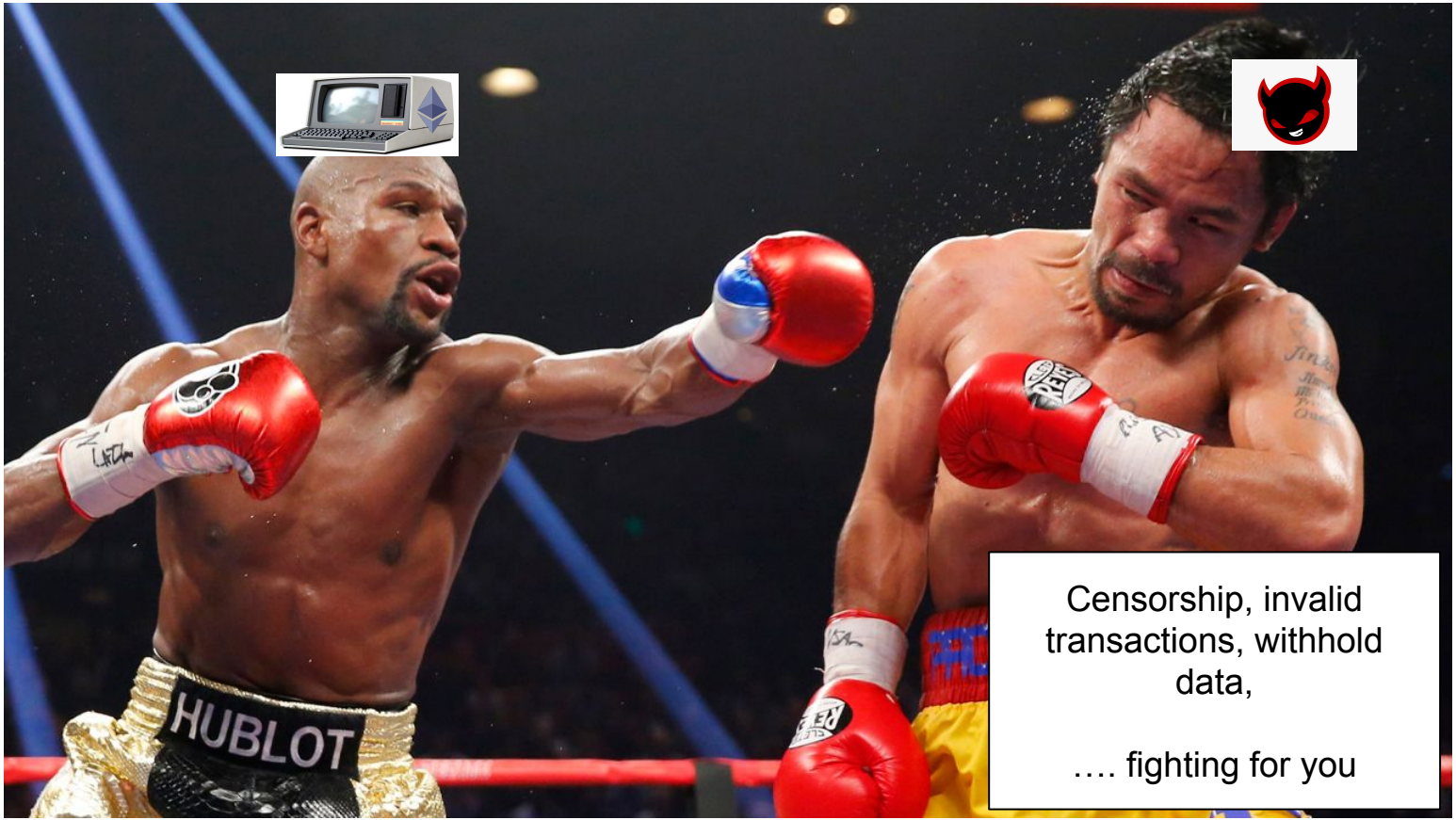
OP Optimistic Ether

ARBITRUM

zkSync

STARKWARE

Continuously check the integrity of all proposed updates


HUBLOT
Censorship, invalid transactions, withhold data,
…. fighting for you

Sounds so cool….

… but how do validating bridges work?

Let’s try to define the environment

- Agents
  - Who are the players?
- Overview of a validating bridge
  - How does it work at a high level?
- Threat Model and Security properties
  - Who is our adversary? And what special powers do they have?
  - What are we trying to secure?

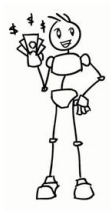
Agents

Honest user

Likes mooncats

Sequencer

Orders transactions off-chain



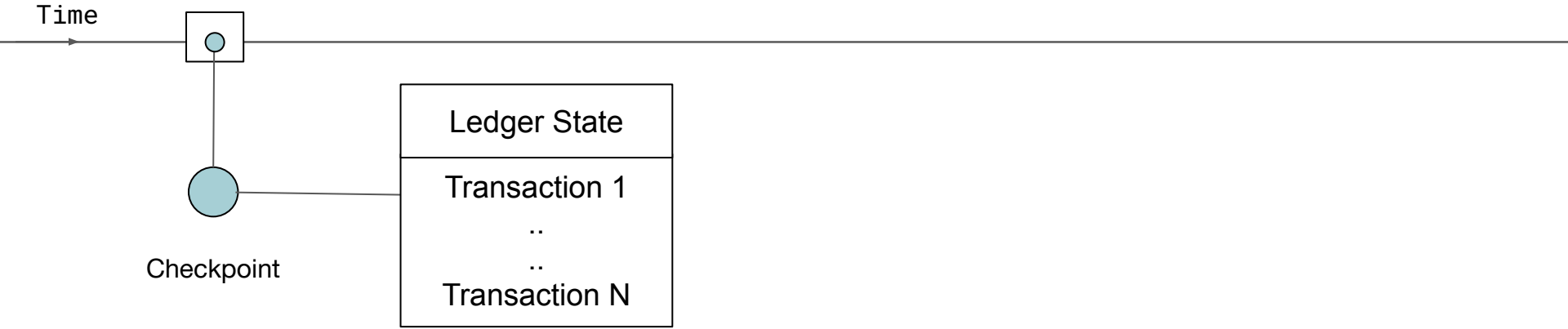
Executor

Forces bridge contract to execute transactions

Collect transactions for ordering

Sequencer

Optimistic transaction
ordering service



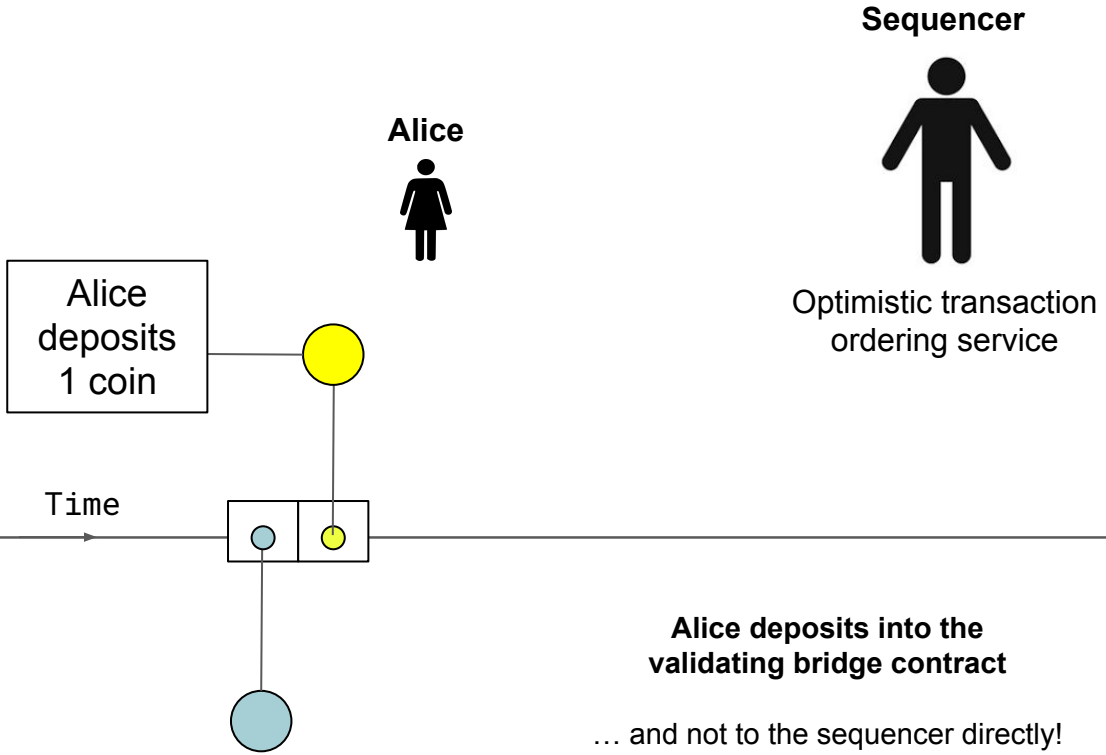
Collect transactions for ordering

Alice

Sequencer

Optimistic transaction ordering service

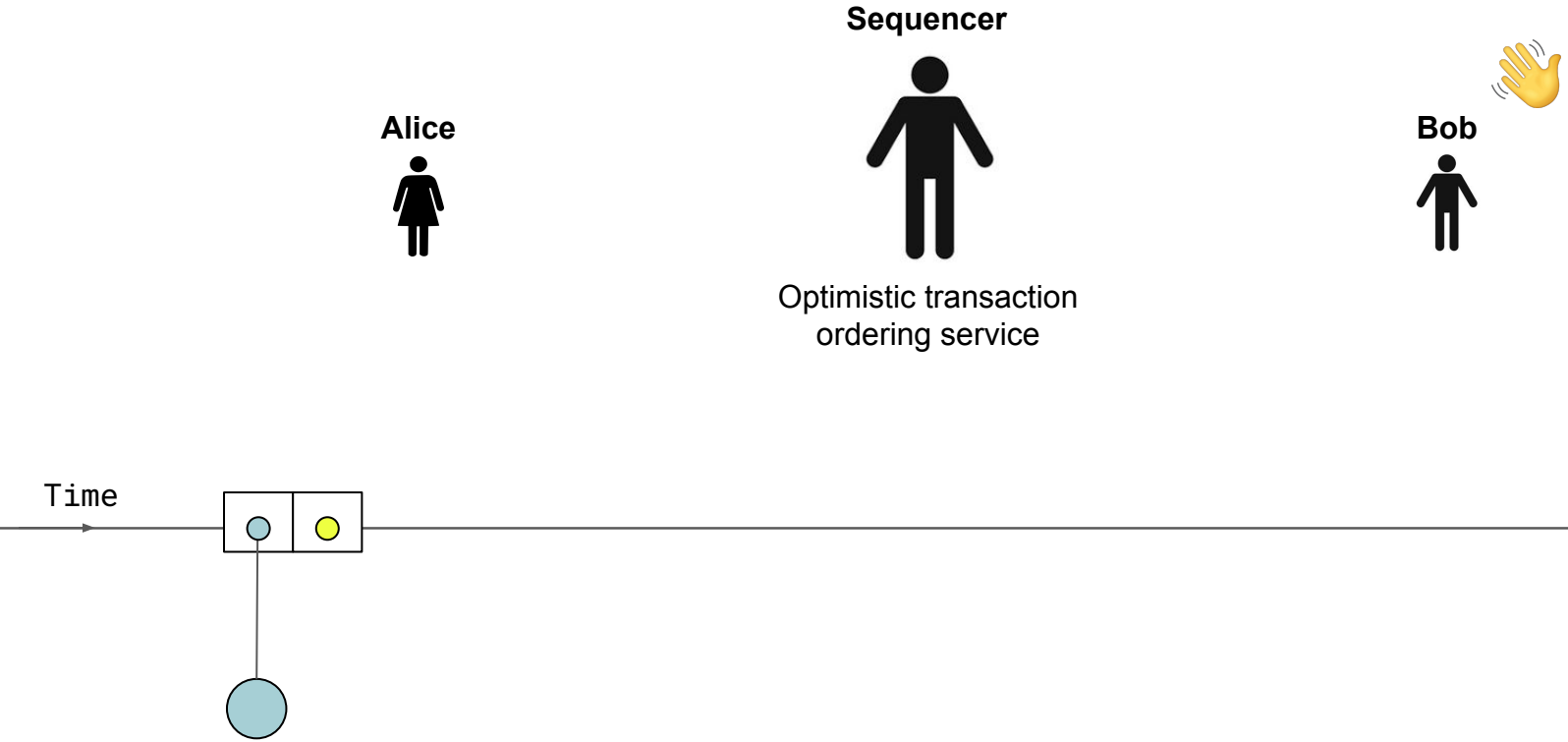
Collect transactions for ordering



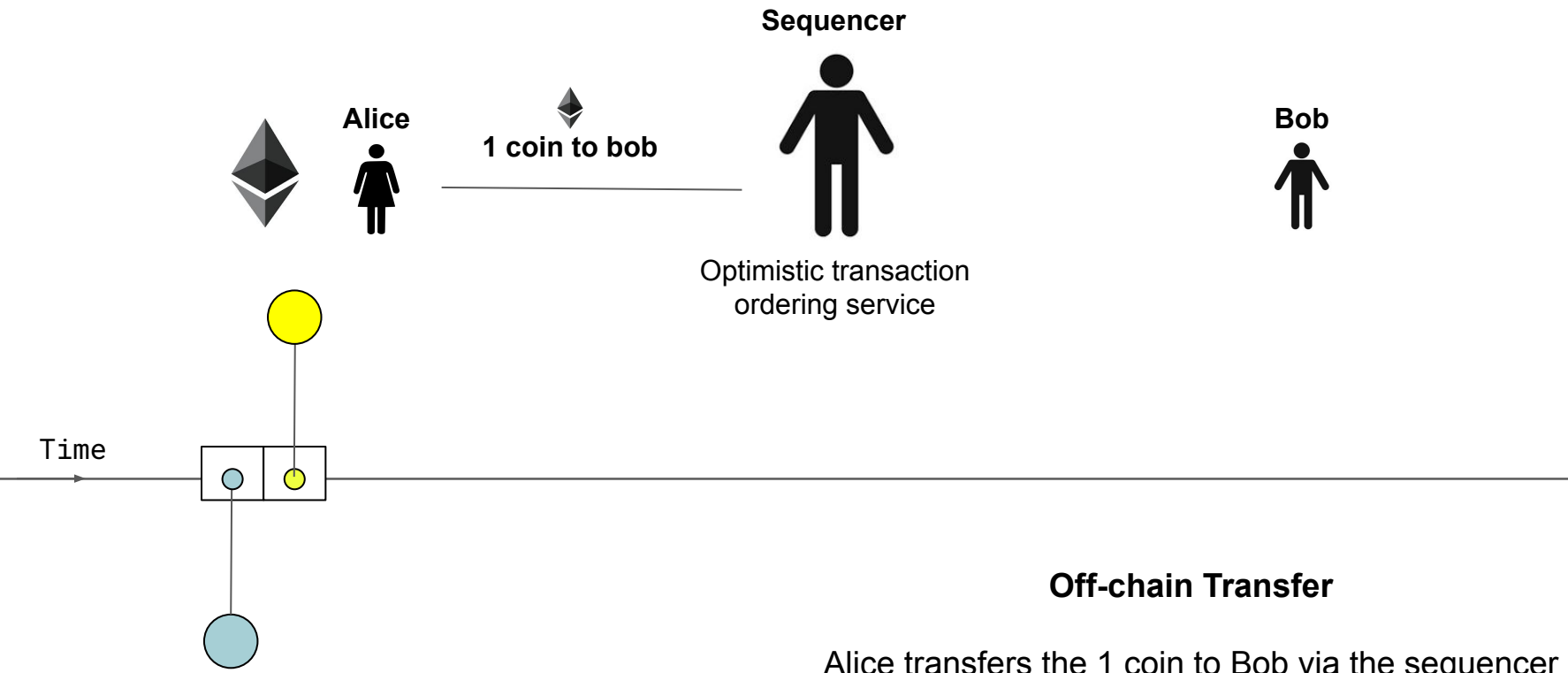
Alice deposits into the validating bridge contract

… and not to the sequencer directly!

Collect transactions for ordering



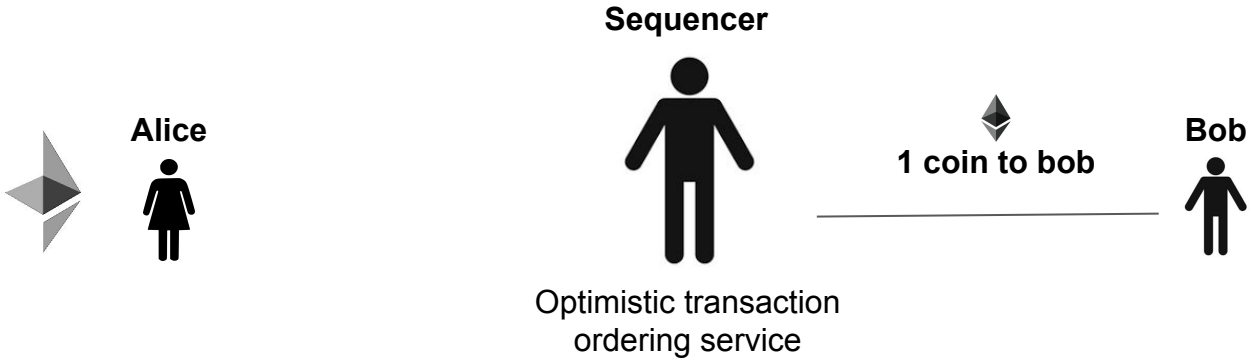
Collect transactions for ordering



Off-chain Transfer

Alice transfers the 1 coin to Bob via the sequencer

Collect transactions for ordering



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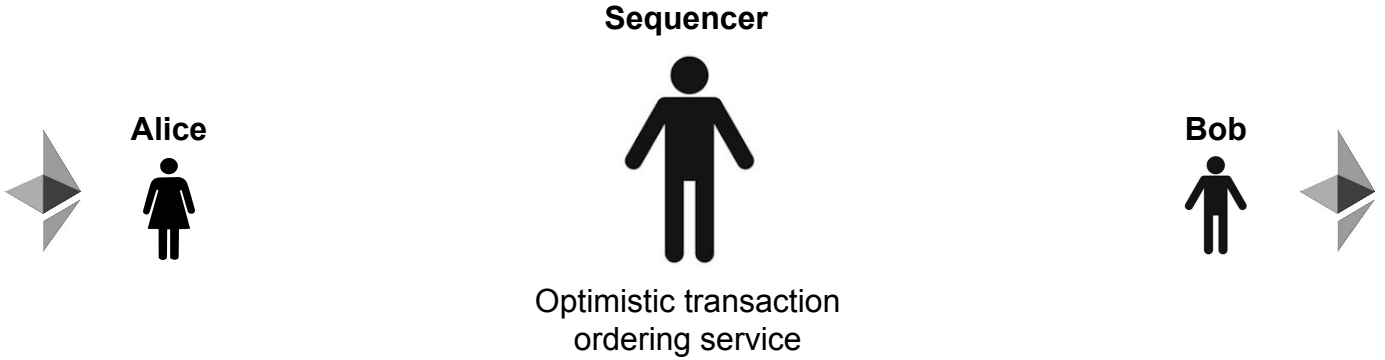


Sequencer waits around….
For more off-chain transfers…

Alice to Bob transfer is “pending” and not yet confirmed.

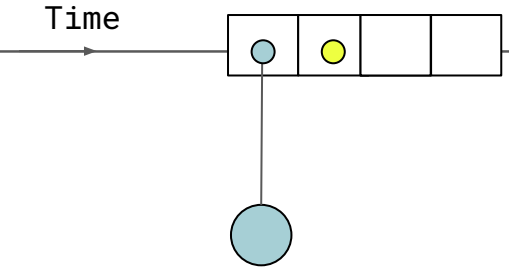
Collect transactions for ordering

Sequencer

Alice

Bob

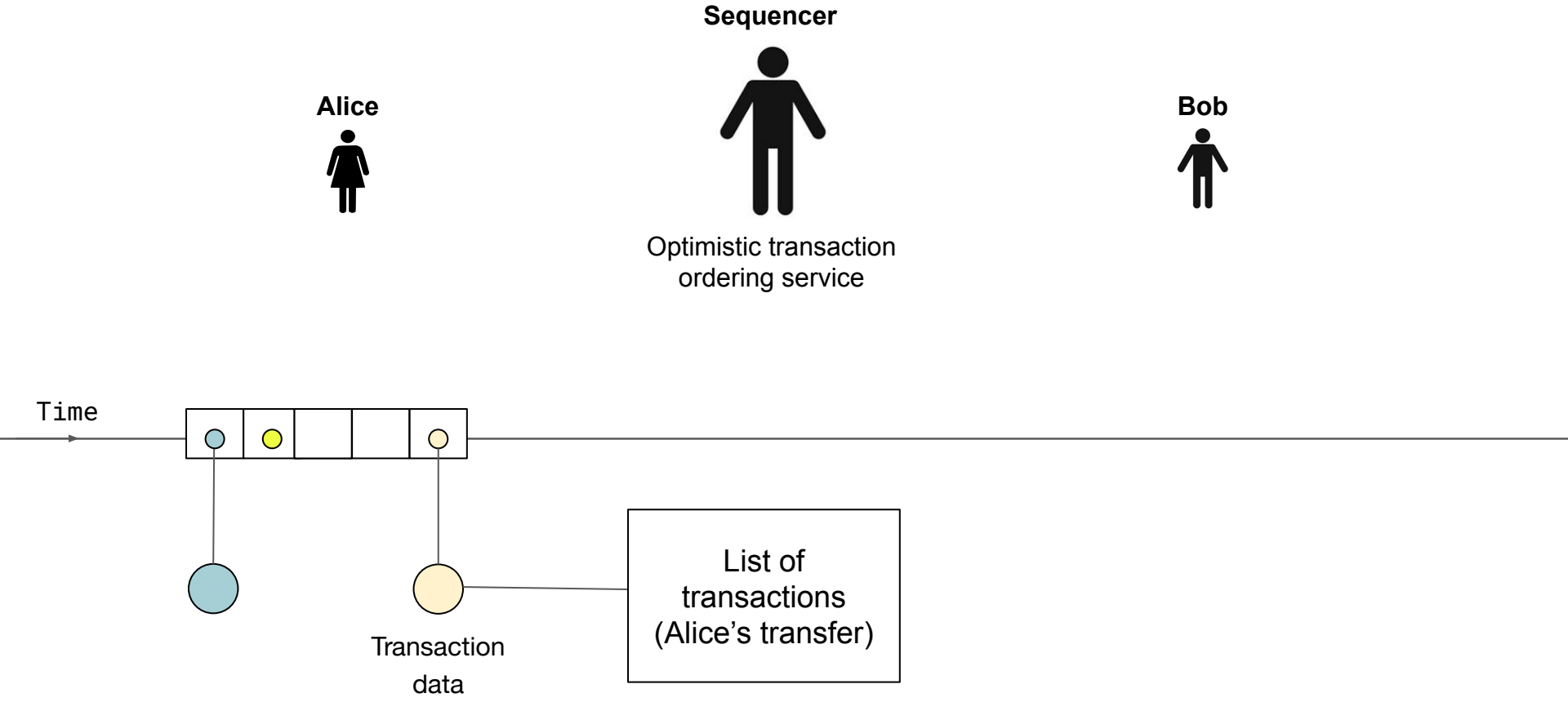
Optimistic transaction ordering service



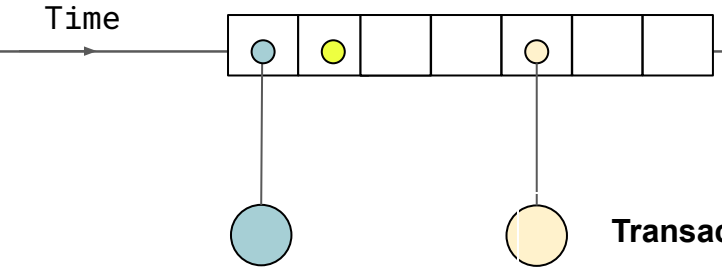
Sequencer waits around….
For more off-chain transfers…

Alice to Bob transfer is pending and not yet confirmed.

Bridge contract orders the pending transactions

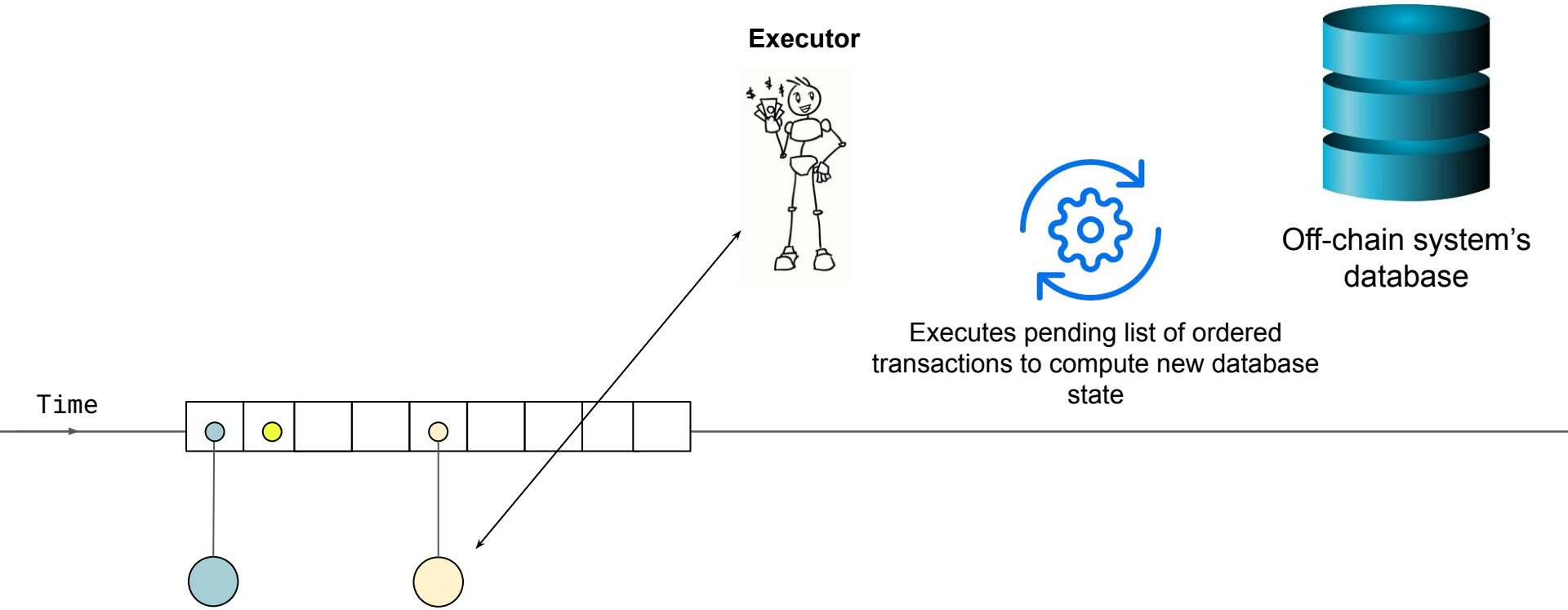


Bridge contract orders the pending transactions



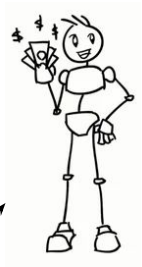
Transactions are “ordered”, but not executed.

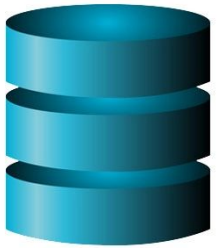
Convince a validating bridge of final execution



Convince a validating bridge of final execution

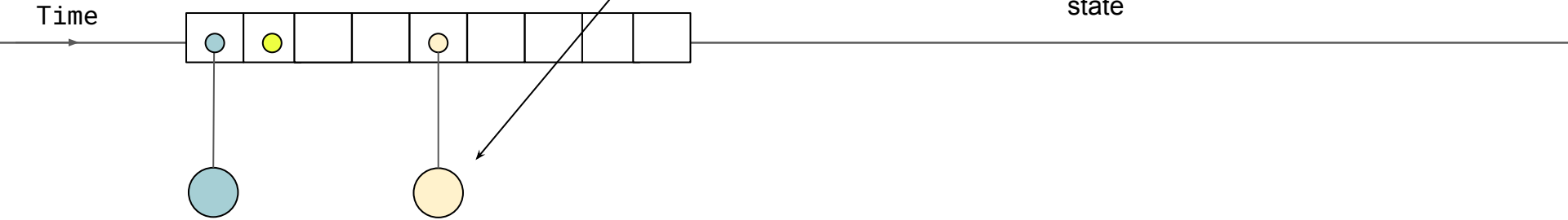
Executor



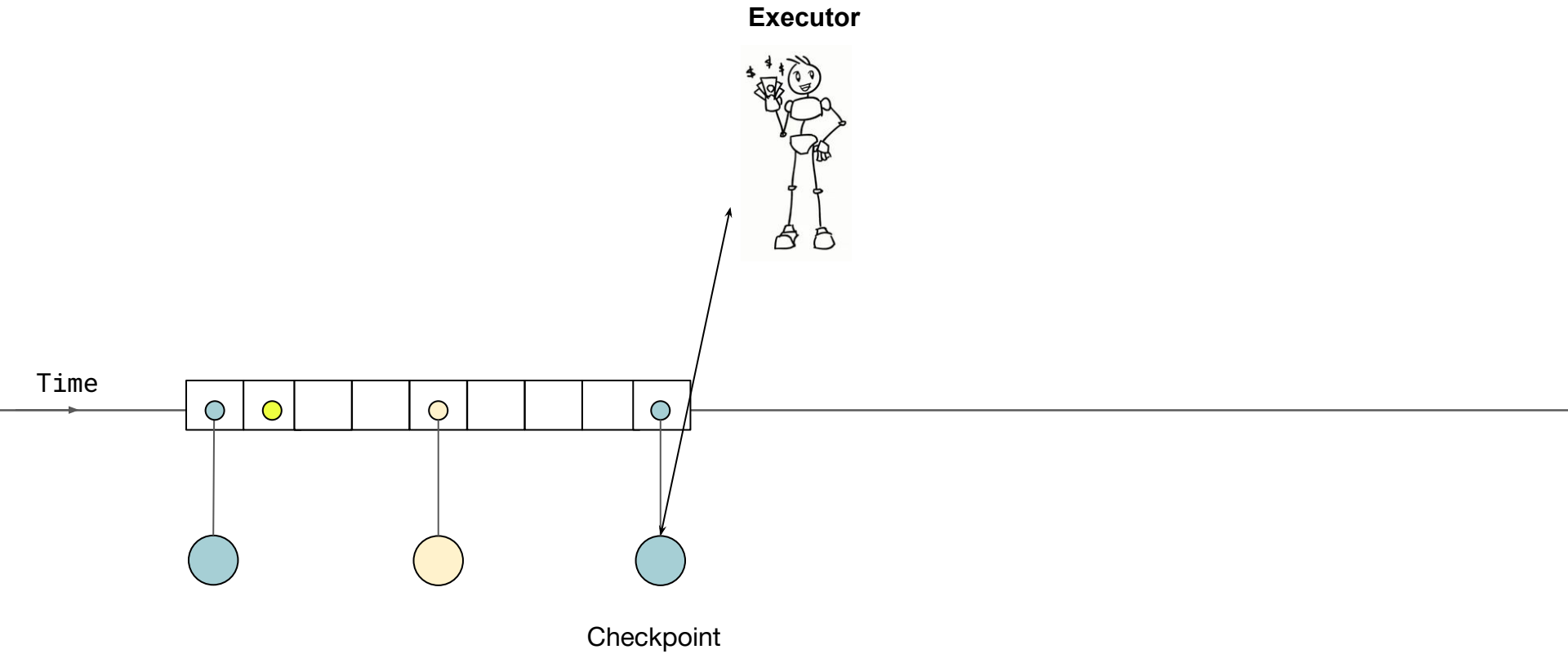


Off-chain system's database

Executes pending list of ordered transactions to compute new database state



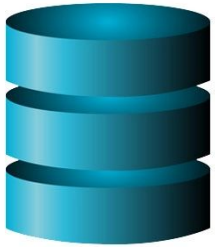
Convince a validating bridge of final execution



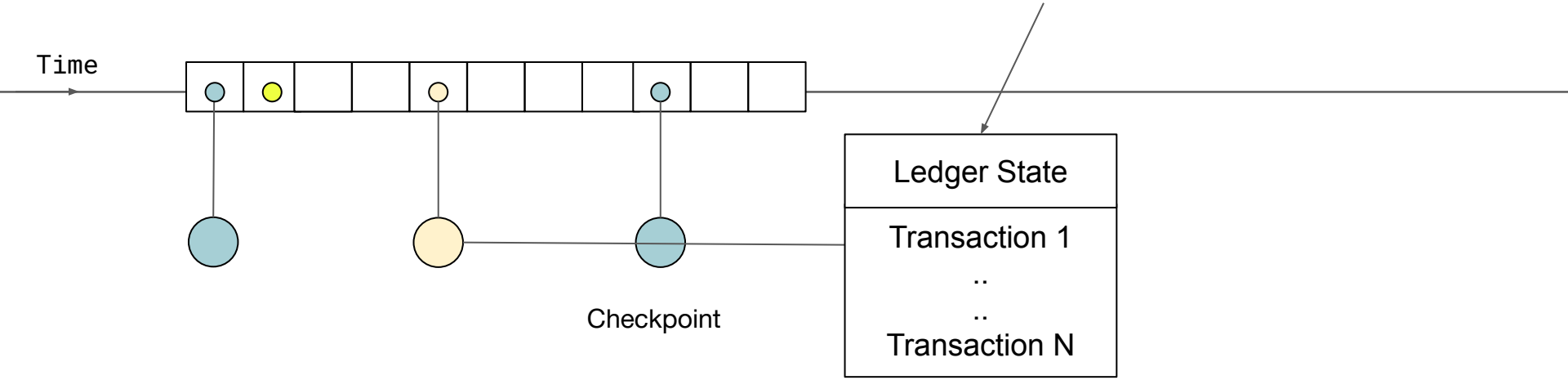
Continuously convince a validating bridge

It is a continuous process that never really ends

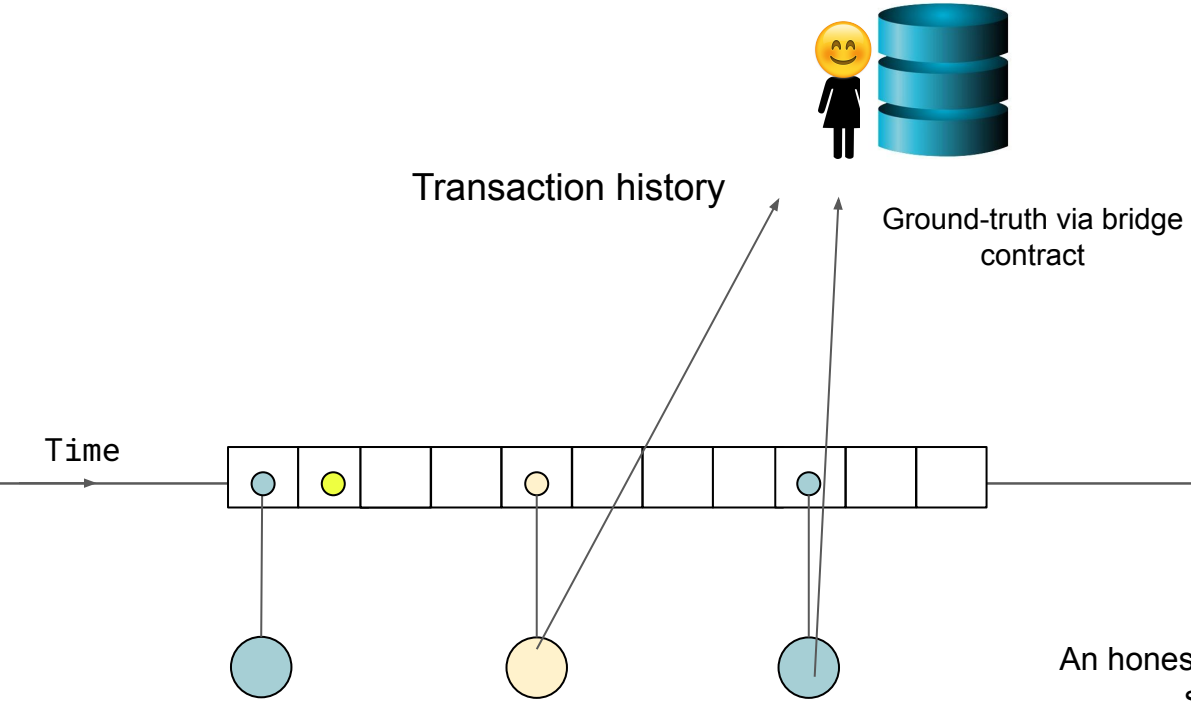
- **Checkpoint** asserts a new update to the database.
- **Execution** dictates the correctness of the update.



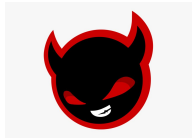
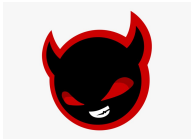
Off-chain system's database

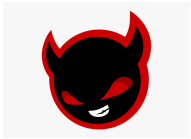
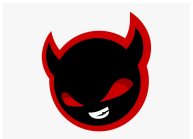
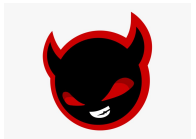
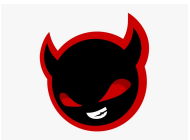


Proof of reserves and fully auditable by default



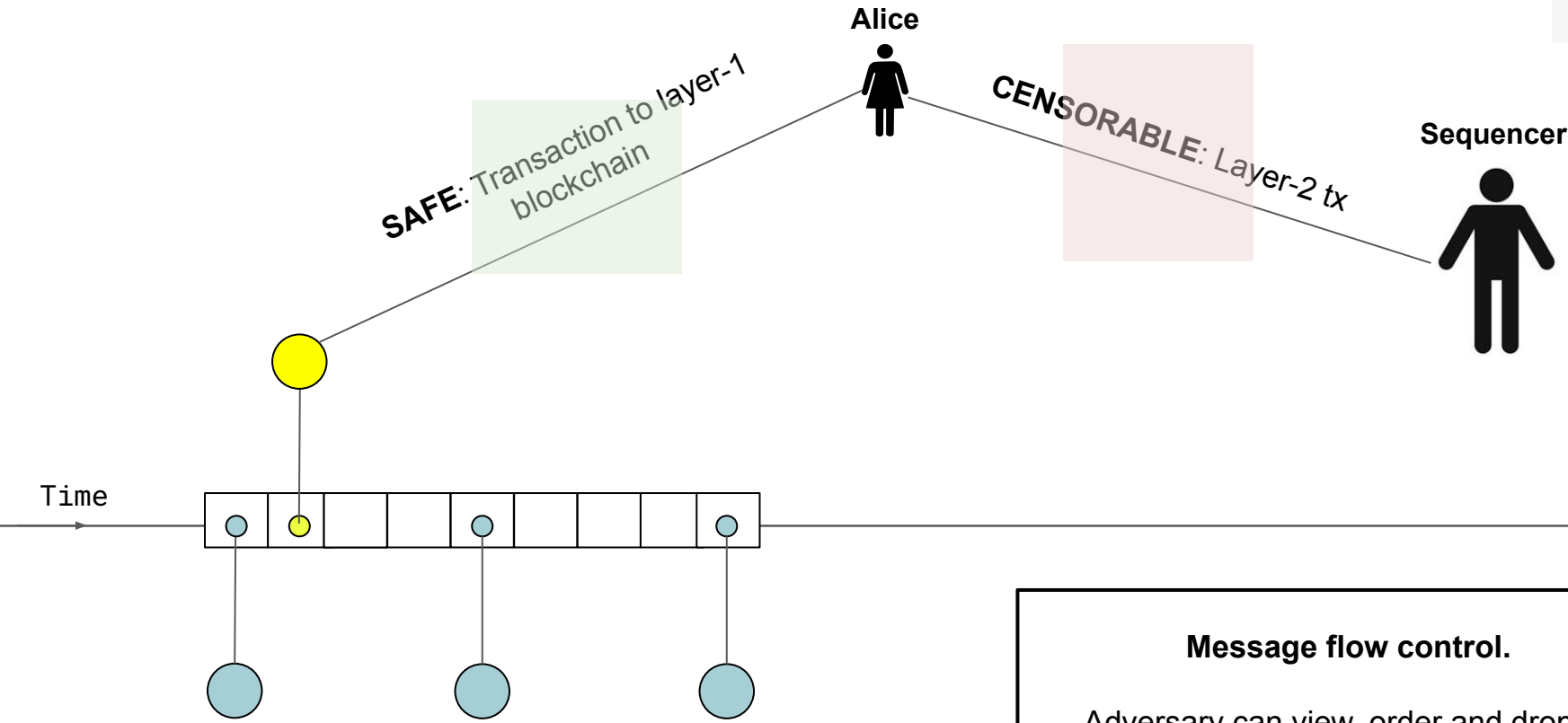
An honest party (Alice) can recompute the off-chain system's database independently.

Adversarial threat model

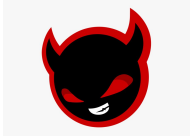
Adversarial Model

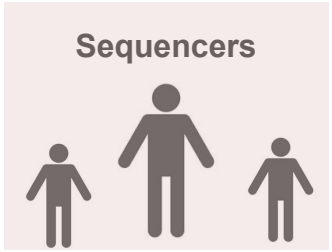


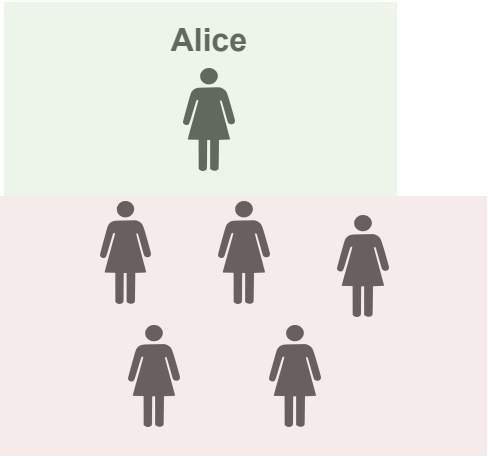
Message flow control.

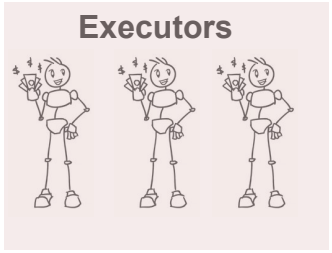
Adversary can view, order and drop all messages except for transactions sent to the layer-1 blockchain.

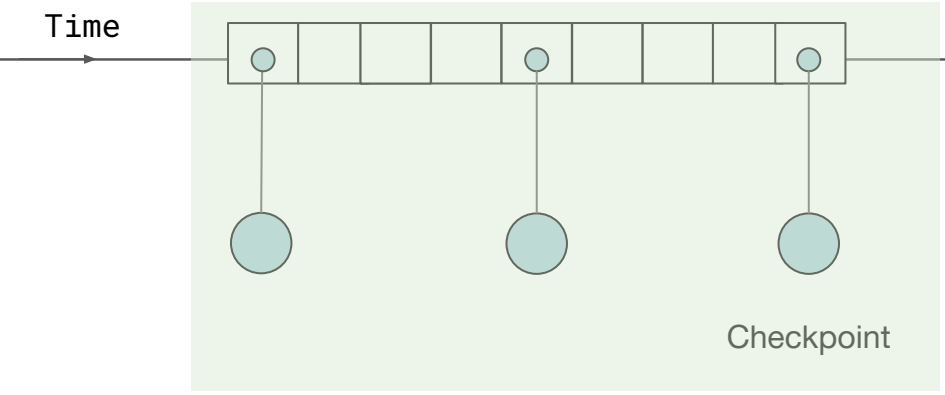
Adversarial Model











Corrupt nearly all parties

An honest user, optionally a challenger, and the blockchain (smart contract) vs everyone else.

Threat model (power of adversary)

- **Message flow control.** Control the order (and drop) all messages at will except for messages destined for the parent blockchain (eventual delivery protocol assumption).

- **Corrupt nearly all parties.** Adversary can corrupt all sequencers and N-1 users. They cannot corrupt one honest user and the parent blockchain.

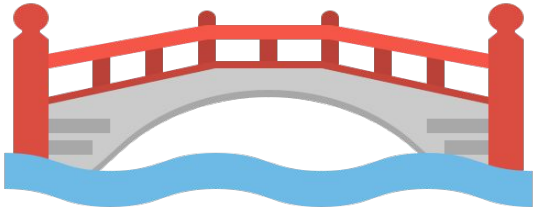
- **Financially motivated (optional):** Adversary may require to place a security bond in the parent blockchain that is slashed if fraudulent behaviour is detected.

- **Cannot break cryptography:** Weak against hashes, signatures, SNARKS

We have described the most POWERFUL adversary and **some rollups lack the tools to fully constrain or out-right defeat it.**

Security properties

Goal: Protecting the safety & liveness of the off-chain database.



What the validating bridge checks

Data availability

- Are all state updates to the database publicly available?

State transition integrity

- Are all state updates to the database valid and well-formed?

Censorship-resistance

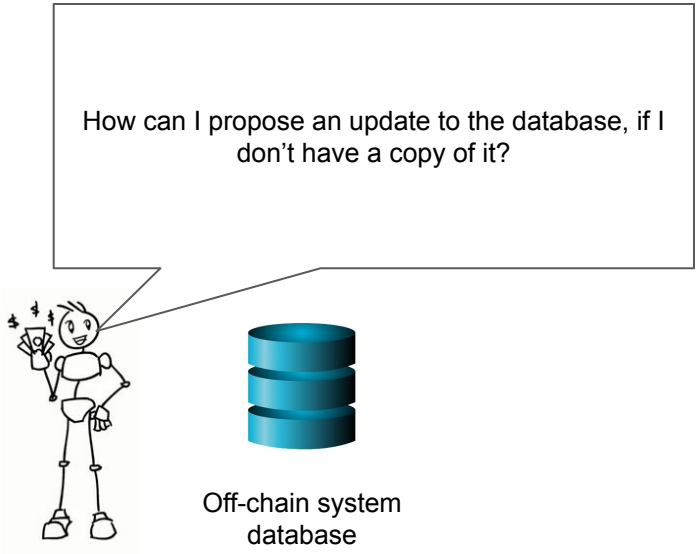
- Can the user self-enforce that a transaction will eventually execute?

The Data Availability Problem

Data Availability Problem

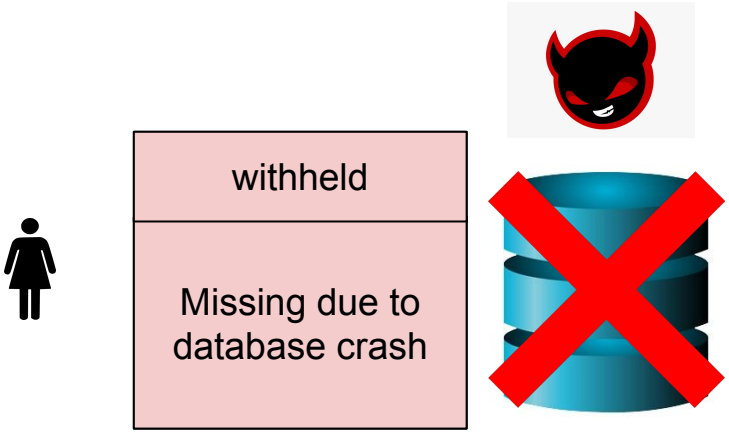
- Why does the data need to be publicly available?
- What data needs to be publicly available?
- How do we guarantee it is publicly available?

Why does the data need to be publicly available?



1 honest party (assistant) assumption

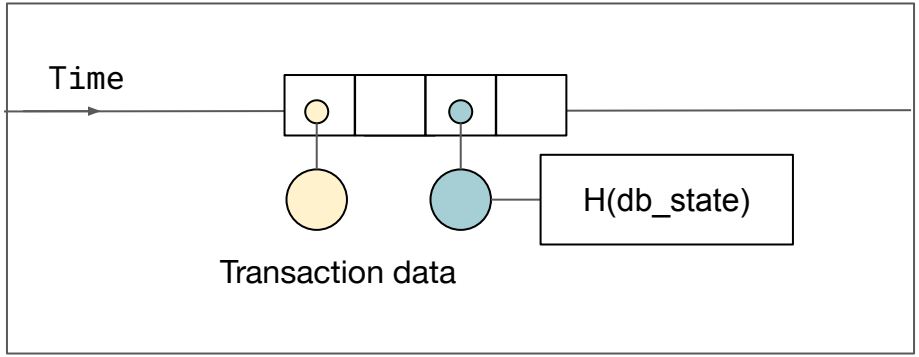
We need to assume there is one party, somewhere on the web, who will have a copy of the database and propose an update.

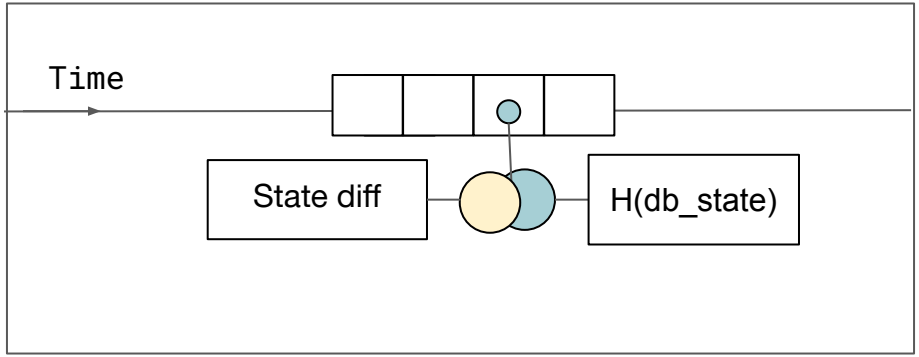


Adversary winning: Safety & Liveness issues

Adversary can freeze the system, potentially steal funds and lie about entries in the database.

What data needs to be publicly available?





Transaction history

Enforces the ordering of all transactions and its execution

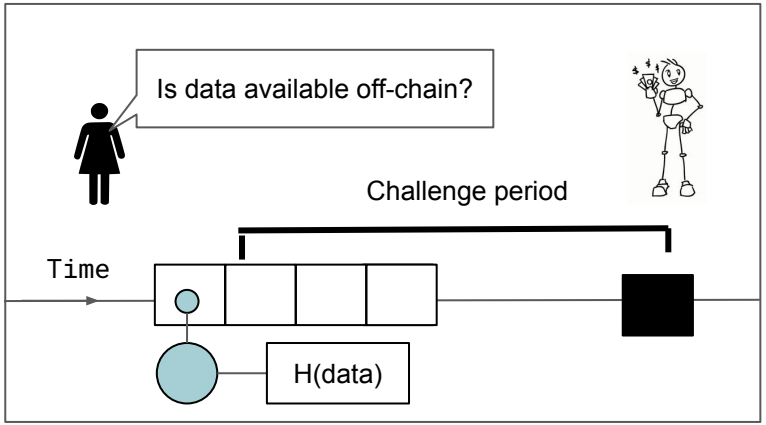
Honest party: Computes all transactions to get a copy of the database

State diffs

Bridge is not aware of individual transactions, just their aggregation

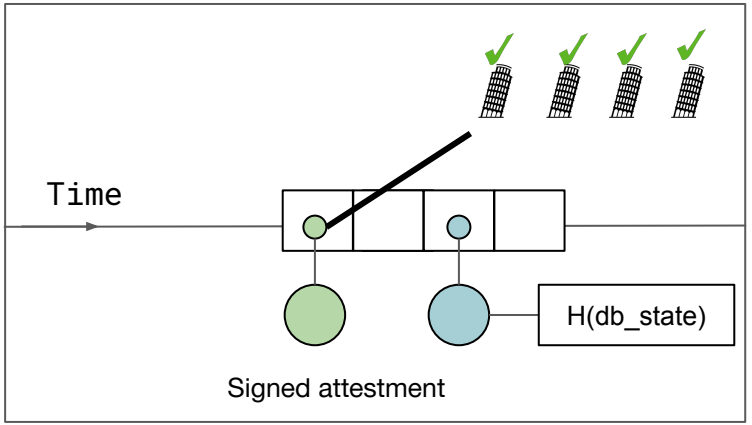
Honest party: Computes all state diffs to get a copy of the database (updates storage slots)

How do we guarantee the data is publicly available?



On-chain data availability challenge

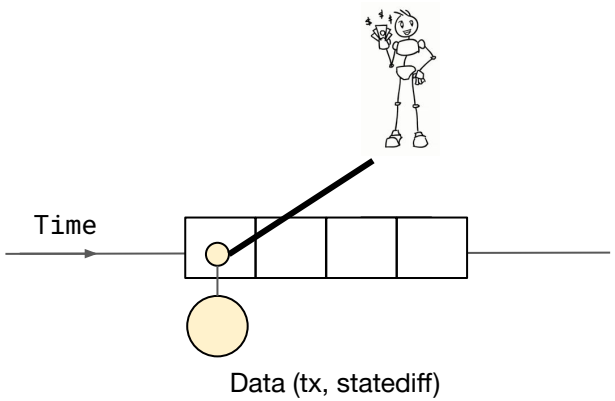
Force the operators to reveal the data via the bridge in a timely manner



Data availability committee

K of N data availability providers will sign off and attest to the fact the data is publicly available

How do we guarantee the data is publicly available?



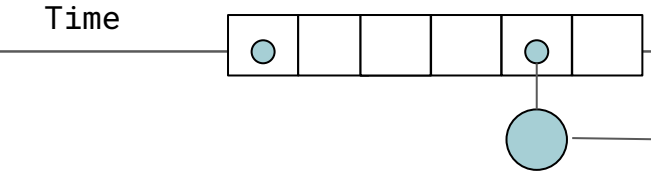
Rollup

Post all the data to the blockchain.

Bingo!

The State Transition Integrity Problem

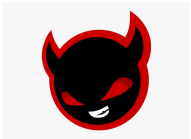
State transition integrity (protecting the layer-2 database)



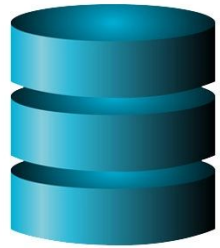
Checkpoint

Checkpoint = H(<send sequencer all coins>)

If the adversary can get **1 invalid transaction processed**, then they can **steal all funds** in the bridge



State
Transaction 1 .. Invalid Transaction .. Transaction N



Layer-2 database

State transition integrity (protecting the layer-2 database)

Time

Bingo!

Optimistic vs ZK
Fault Proofs vs Validity proofs

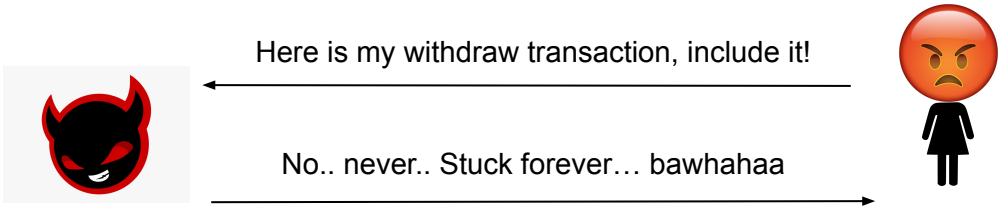
… but we can go deep into this another day :)

Layer-2 database

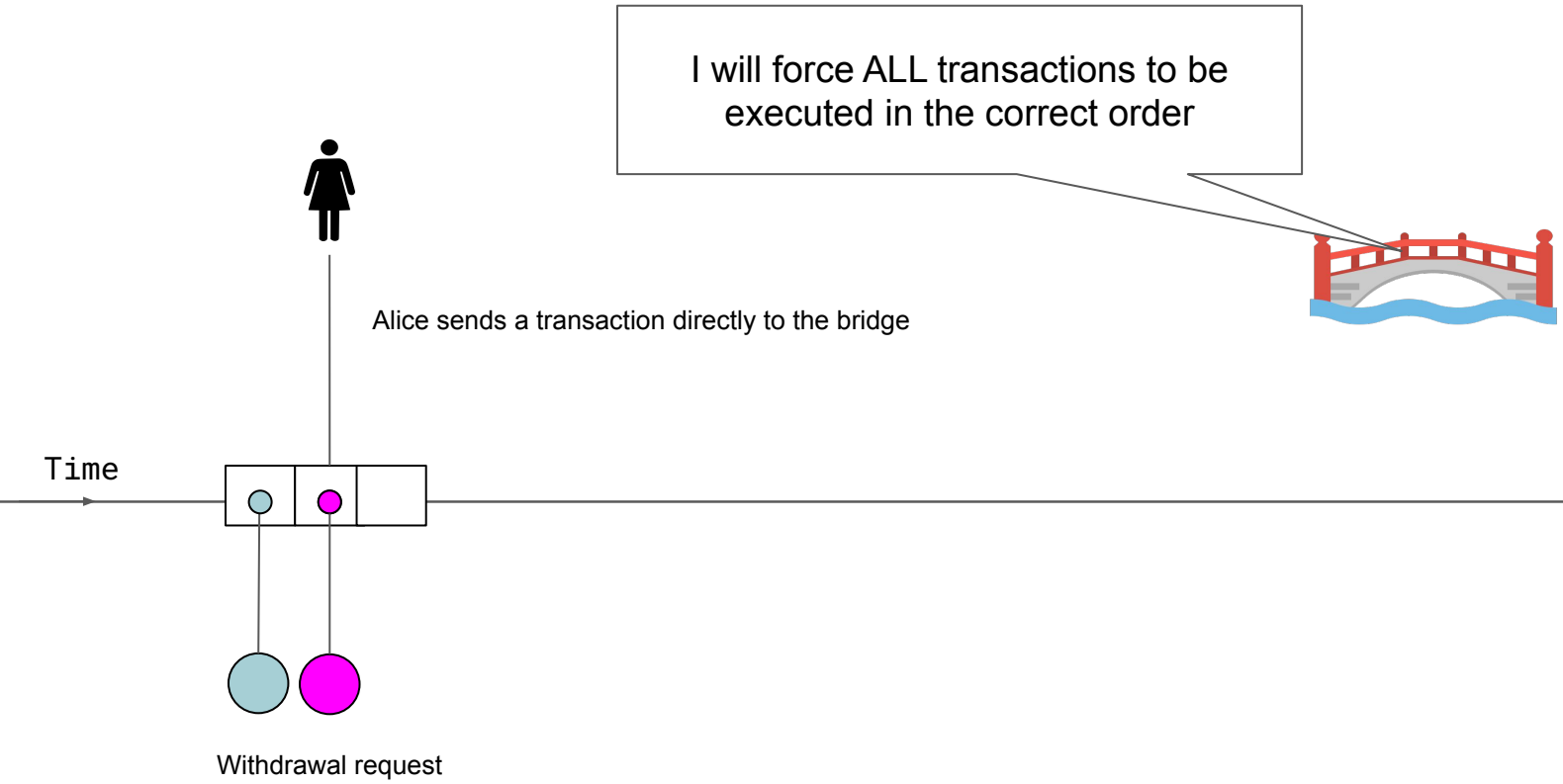
Enforcing censorship resistance

Censorship resistance

How can I withdraw my funds if the sequencer does not cooperate?



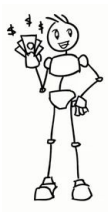
Forced inclusion: Bridge forces ordering of execution



Execution liveness (and the fast path)

Sequencer

Offers the “fast-path” and should have nothing to do with censorship-resistance

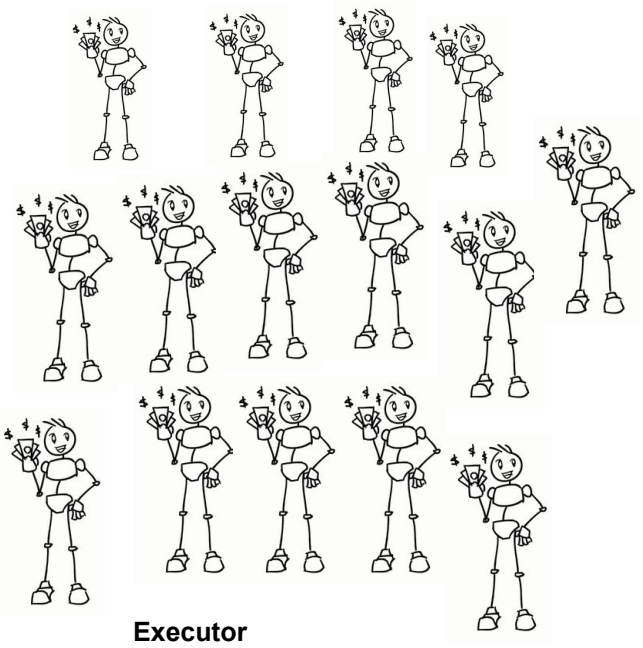


Executor

Trusted with liveness of execution (i.e., a transaction is eventually executed

Execution liveness (and the fast path)

Sequencer can be fully centralized and the off-chain system remains censorship resistant



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Execution liveness (and the fast path)

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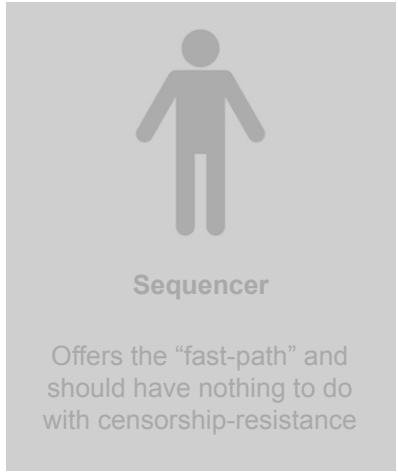
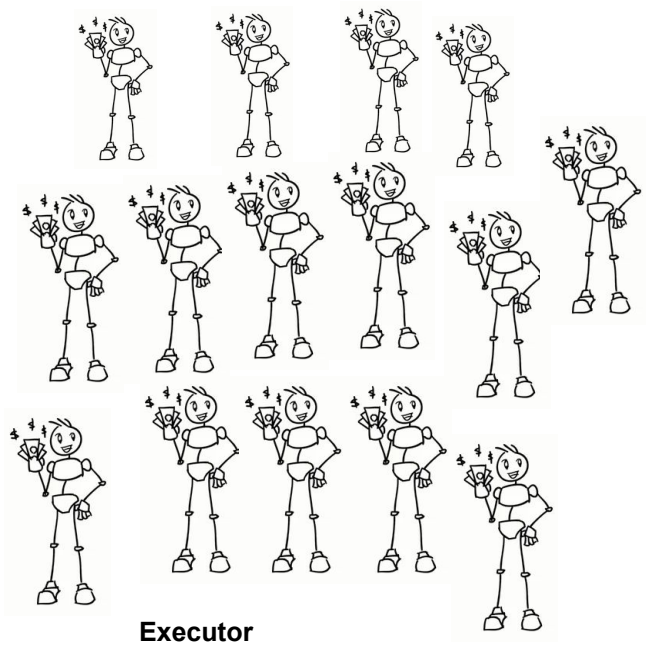




Trusted with liveness of execution

One honest party

Security properties (summarised)

- **Data availability.** How does an honest user access the transaction history and recompute the same layer-2 ledger as everyone else?

- **State transition integrity.** How can we convince the layer-1 blockchain that all transactions in the layer-2 blockchain are valid?

- **Censorship resistance.** How can an honest user withdraw their funds from the layer-2 blockchain without the sequencer cooperation?

If we can satisfy the above properties….


Then, hopefully we slay the beast and deploy a secure layer-2 system…

Other problems emerge

Fragmentation of Assets & Interoperability

- Bypass bridge on L1 and send funds across rollups
- Gracefully handle failures while routing with smart contract execution
- Minimise trust for passive liquidity providers

Return of the data availability challenge?

- Posting data on-chain is still expensive
- EIP-4844 will help, but can optimistically avoid sending data on-chain?
- Only obstacle is the “Fisherman problem”

Experimental virtual machines on L2

- EVM-equivalence, compatibility or native?
- ZK-friendly virtual machines like Cairo?
- Compile to a simple virtual machine or build for every “opcode” of the machine?

Censorship-resistance is non-trivial

- Delay attacks by the executors to “hold out” execution of a tx
- Adversary may abuse race-condition to minimise computation
- Proving invalidity of a transaction for zkrollups (circuit overhead)

Sequencer’s privilege and MEV

- Only sequencer has access to the “ordered mempool”
- Amble time to order transactions for maximum extraction
- Can we defeat MEV? Smooth MEV? Or Constrain MEV?

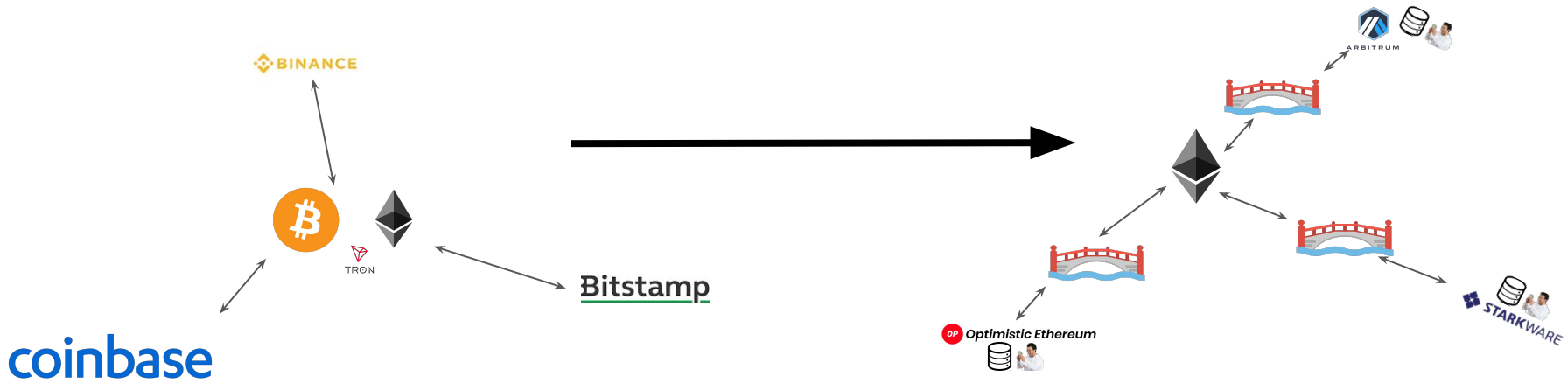
A formal model and evaluation of the “ideal bridge”

- Can we combine tx history and state diffs for data availability?
- How can we rate-limit who is an executor while upholding the 1 honest party assumption?
- Should a bridge enforce the transaction fees? Minimum quantity of execution?

Is it still worth it?

Welcome to Web3

Rise of public databases to
replace custodial services (and exchanges)

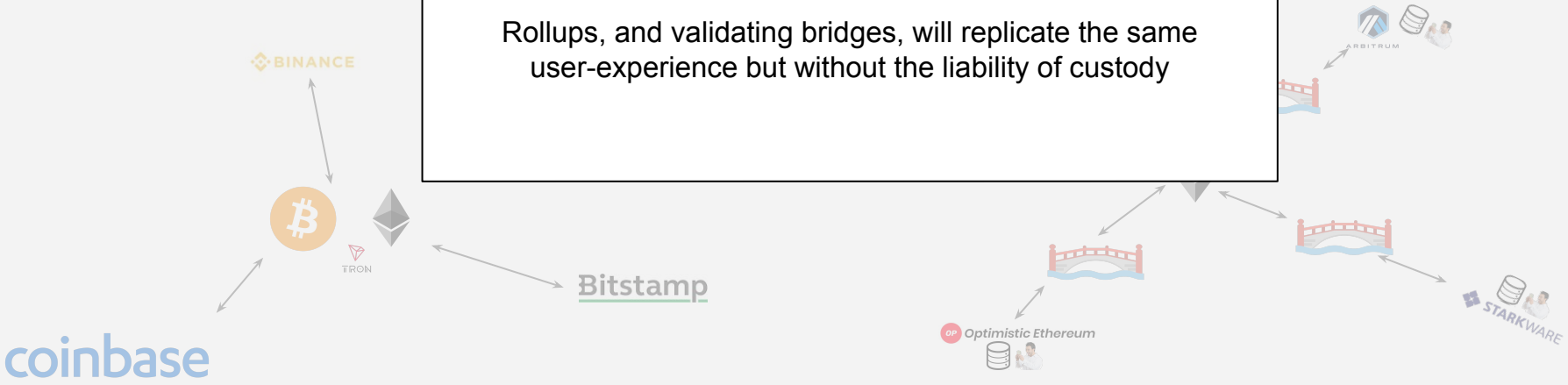


Welcome to Web3

Rise of public databases to

Custody is a liability for most off-chain systems

Rollups, and validating bridges, will replicate the same user-experience but without the liability of custody



It is VERY difficult to replicate human processes to secure billions of dollars

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We just need ONE rollup team to get it right and it can be re-instantiated for all service providers

It is VERY difficult to replicate human processes to secure billions of dollars

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We just need ONE rollup team to get it right and it can be re-instantiated for all service providers

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Users do not care about the custody issues.

Operators do and they'll drive its adoption.

Custody is an unnecessary liability.