# Blockchain Interoperability: Theory and Practice




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# Instructors

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**Early Stage Researcher** at INESC-ID

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**P.h.D in Information Systems and Computer Engineering** @ Técnico Lisboa, Portugal

**Senior Engineer** @ Blockdaemon

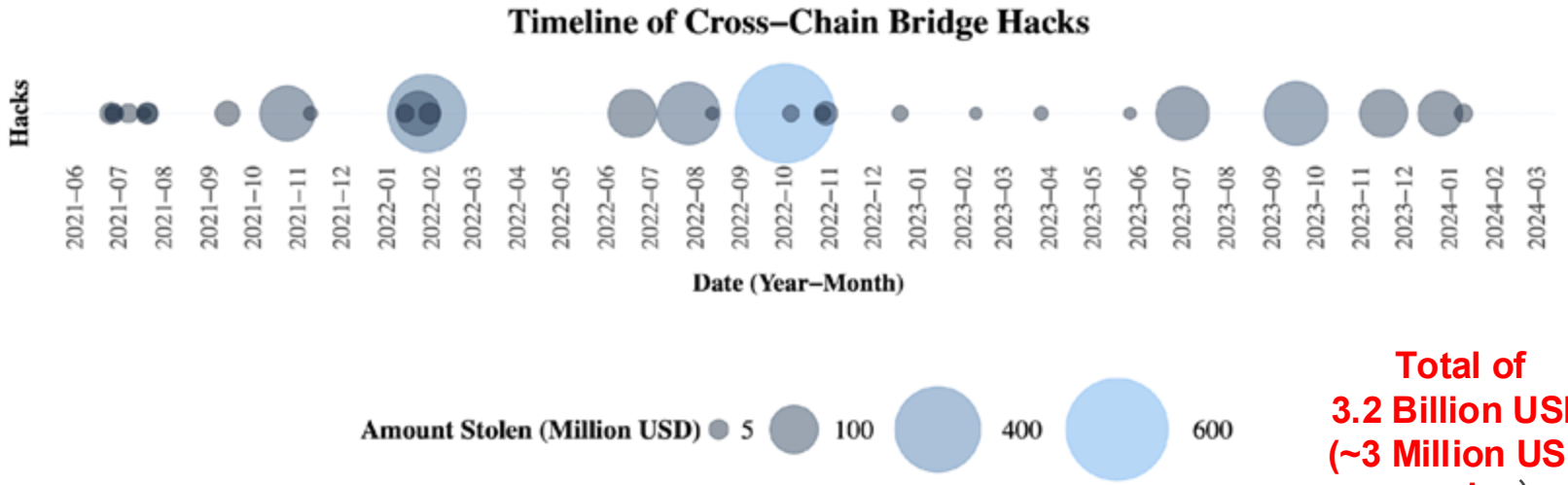
# Part 1: Theory

# **Why** should we **study Interoperability Mechanisms** in Blockchain?

# +3.2 BILLION USD

Stolen from cross-chain bridges since 2021

# A Recurrent Problem…

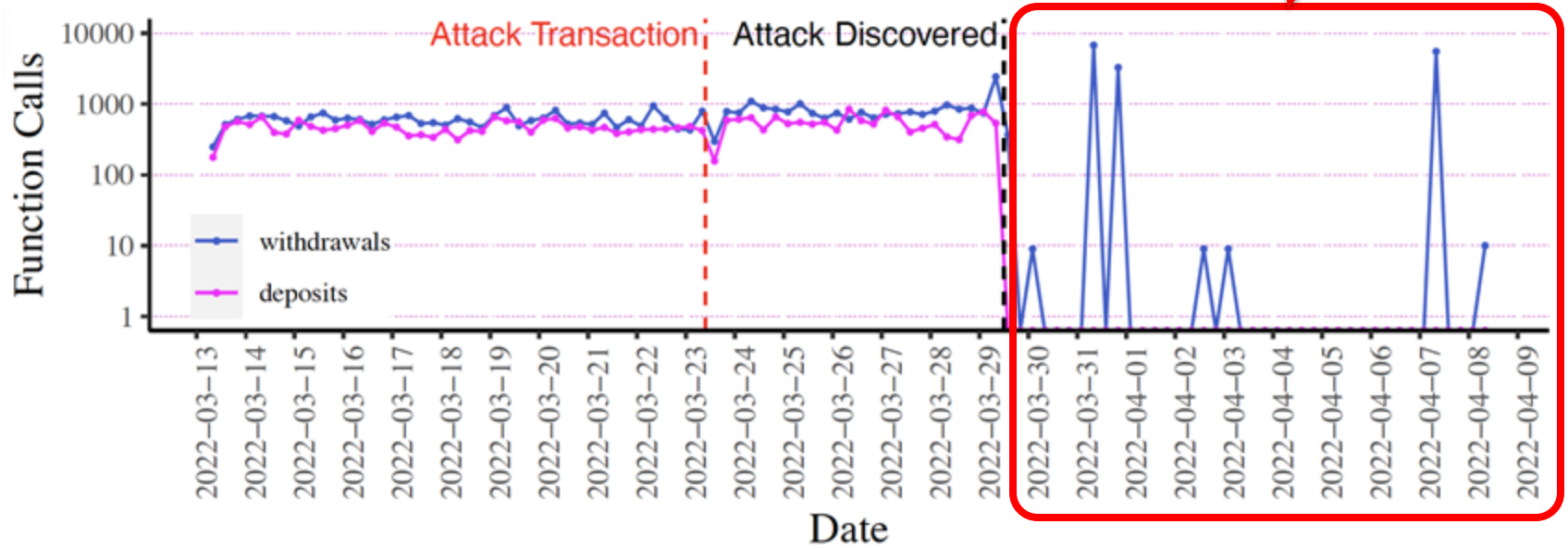



**Total of 3.2 Billion USD (~3 Million USD per day)**

*Augusto, R. Belchior, M. Correia, A. Vasconcelos, L. Zhang and T. Hardjono, "SoK: Security and Privacy of Blockchain Interoperability," 2024 IEEE Symposium on Security and Privacy (SP), San Francisco, CA, USA, 2024, pp. 3840-3865,*

# The Consequences

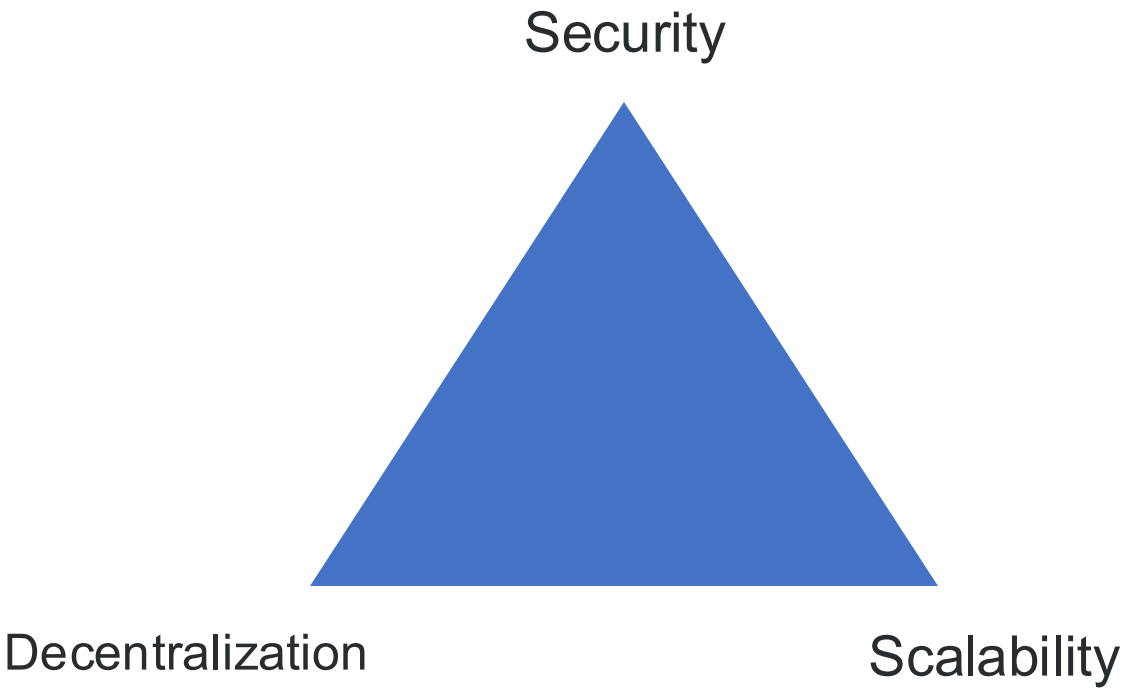
Decreases the flow of funds to other blockchains, and consequently to dApps deployed there




*Augusto, A., Belchior, R., Pfannschmidt, J., Vasconcelos, A., & Correia, M. (2024). XChainWatcher: Monitoring and IdentifyingAttacks in Cross-Chain Bridges. arXiv preprint arXiv:2410.02029.*

# Why is Blockchain Interoperability needed?

# The Blockchain Trilemma

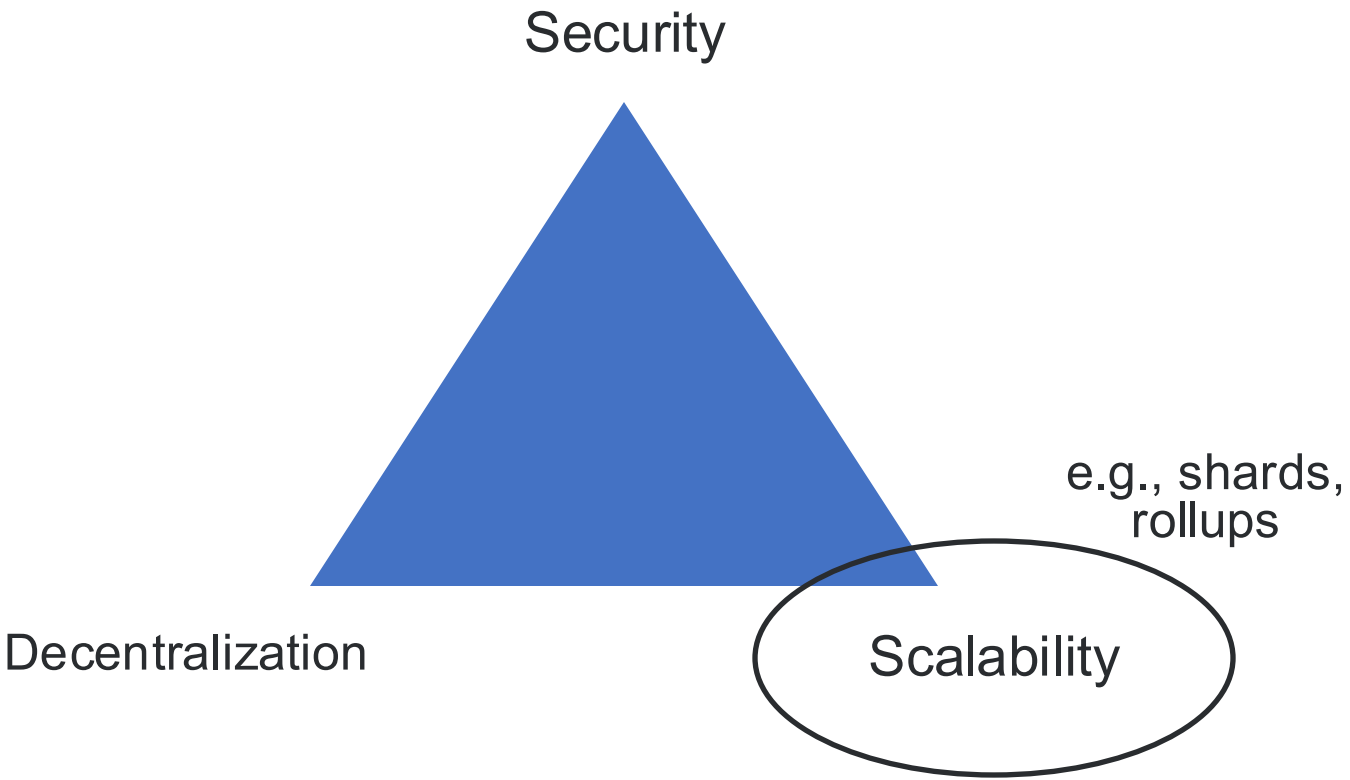


# Connect Different Ecosystems

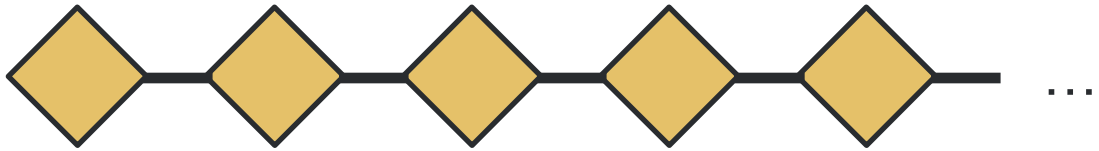
| # | Coin | | Price | 1h | 24h | 7d | 24h Volume | Market Cap |
|---|---|---|---|---|---|---|---|---|
| 1 | Bitcoin BTC | Buy | $68,389.59 | 0.3% | 1.0% | 3.3% | $13,663,947,240 | $1,347,551,070,887 |
| 2 | Ethereum ETH | Buy | $3,841.93 | 0.3% | 2.7% | 25.1% | $12,470,262,478 | $461,028,760,320 |
| 4 | BNB BNB | Buy | $598.73 | 0.0% | 0.4% | 4.4% | $429,266,868 | $92,207,772,331 |
| 5 | Solana SOL | Buy | $162.62 | 0.5% | 2.7% | 4.3% | $2,032,605,702 | $72,884,782,988 |
| 10 | Toncoin TON | Buy | $6.32 | 0.5% | 1.1% | 0.1% | $124,426,607 | $21,956,332,740 |
| 11 | Cardano ADA | Buy | $0.4578 | 0.2% | 0.4% | 2.1% | $200,474,590 | $16,169,141,159 |
| 12 | Avalanche AVAX | Buy | $36.77 | 0.1% | 3.2% | 2.5% | $232,265,046 | $14,427,629,064 |

| | | |
|---|---|---|
| 1 | Polygon MATIC | Monero XMR |
| 2 | Immutable X IMX | Arweave AR |
| 3 | Mantle MNT | Sui SUI |
| 4 | Stacks STX | Injective INJ |
| 5 | ARBITRUM ARB | Fantom FTM |
| 6 | Synthetix Network SNX | |
| 7 | StarkNet Token STRK | |
| 8 | Metis Token METIS | |

# The Blockchain Trilemma

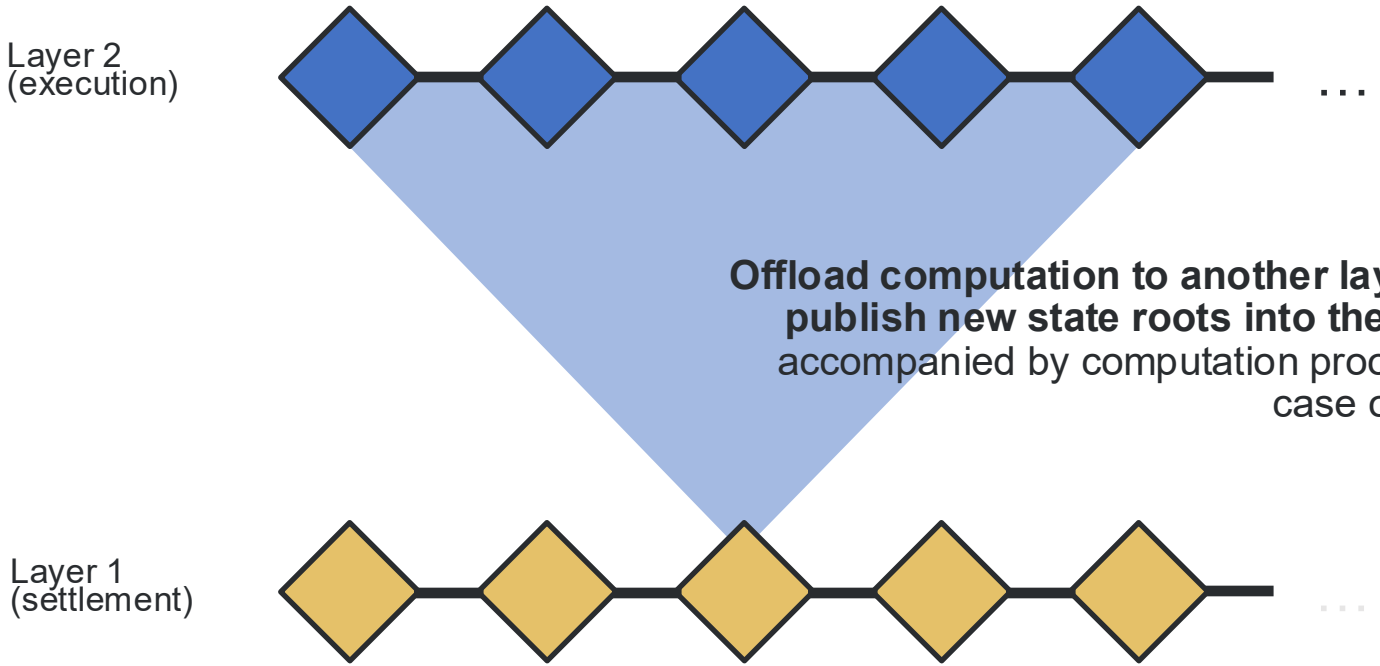


# The Scalability Problem of Blockchains



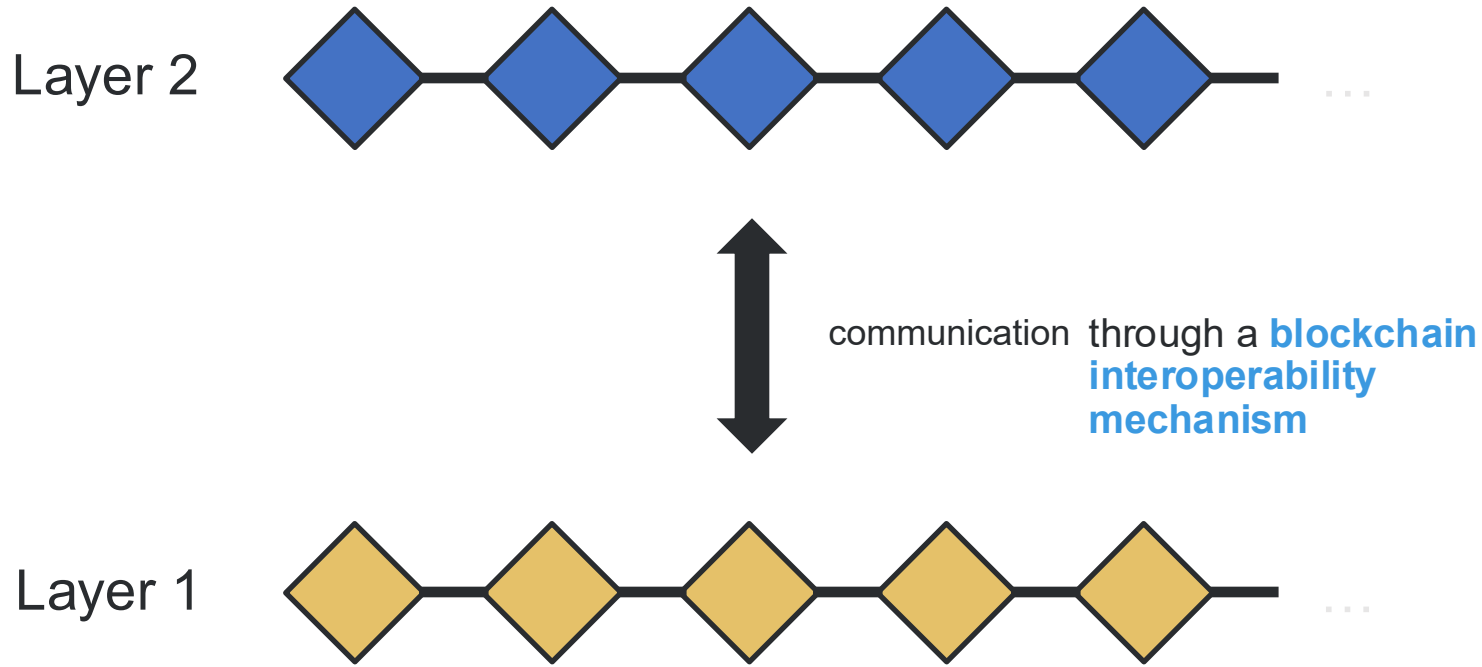
Limited number of transactions in each block
High transaction fees
…

# Scaling Blockchains

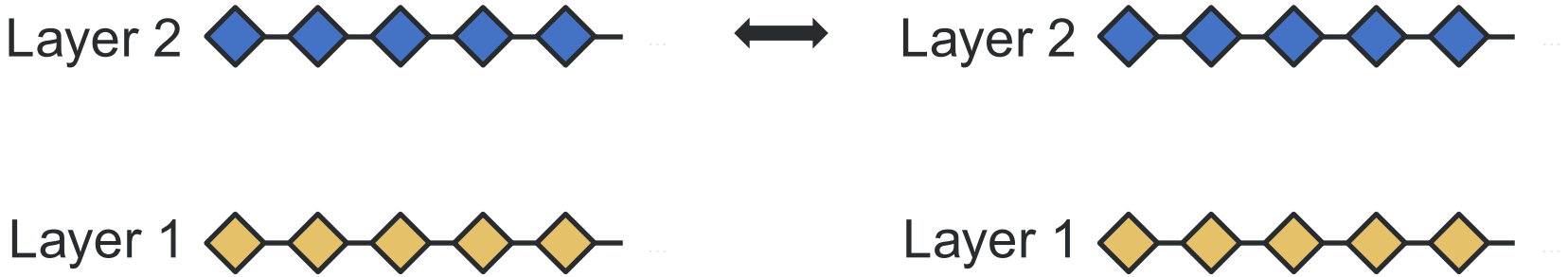



**Offload computation to another layer (L2) and publish new state roots into the L1**. May be accompanied by computation proofs (as in the case of zk-rollups)

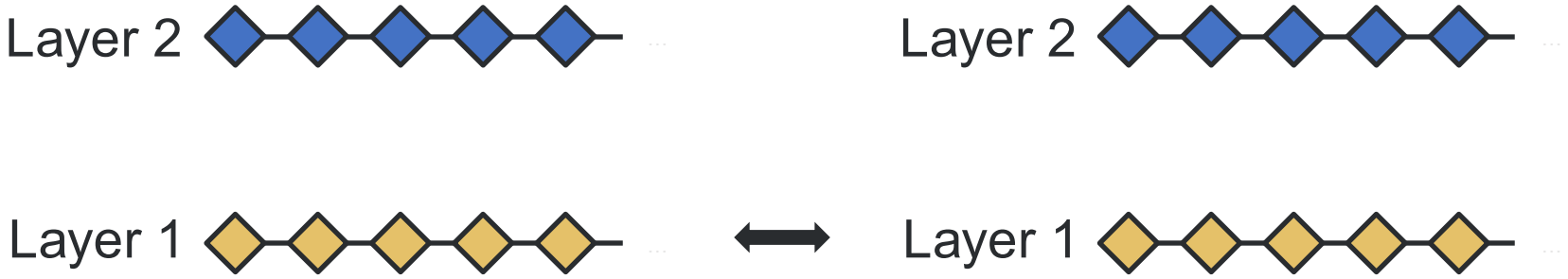
# Scaling Blockchains



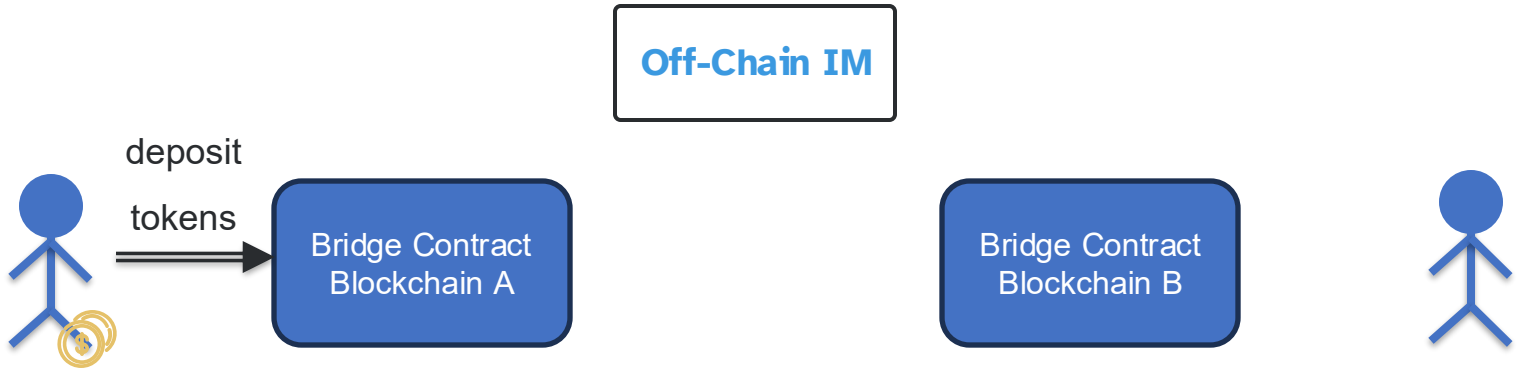
# What about connecting L2s?



# What about connecting L1s?



# Example: how does a token bridge work?



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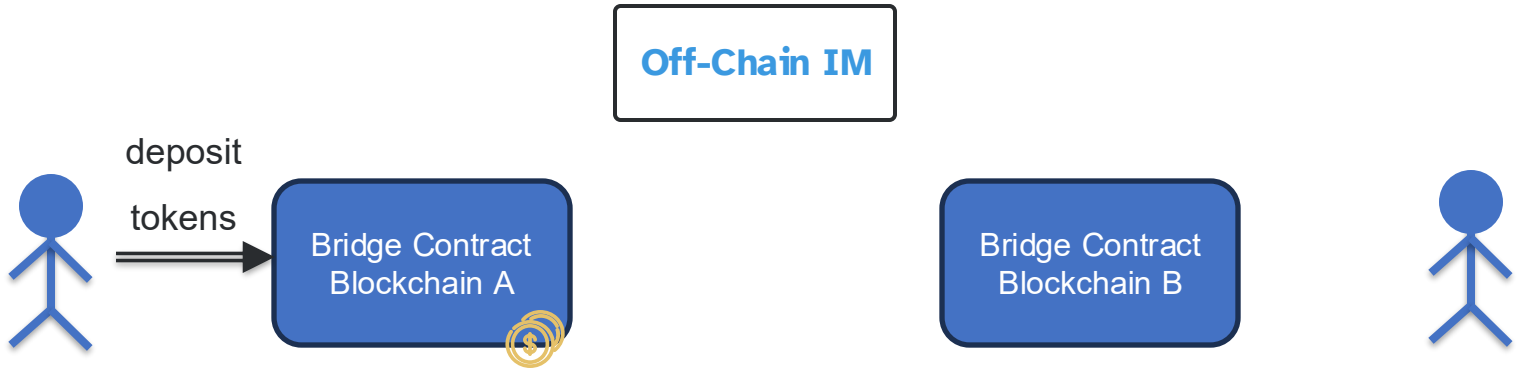

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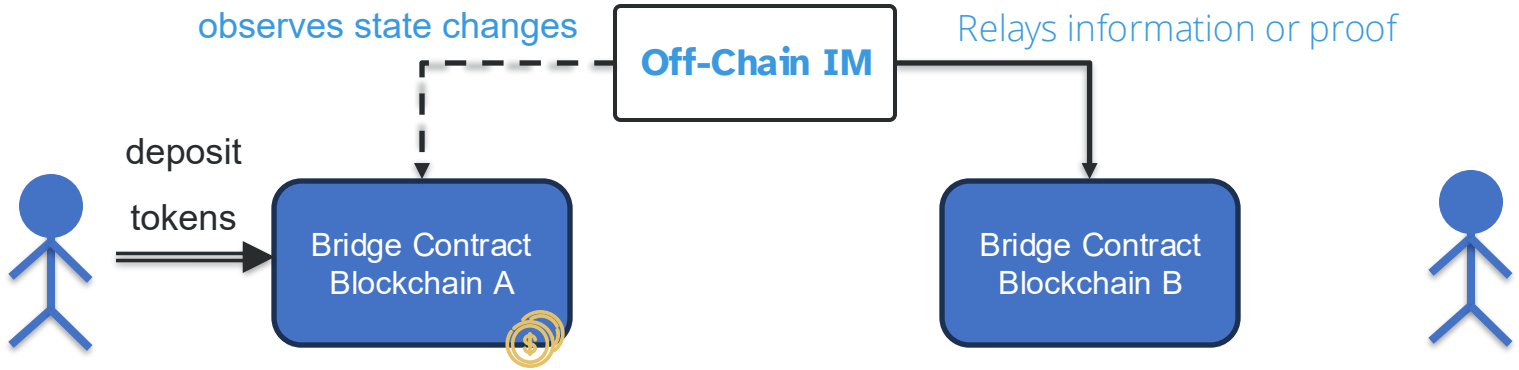

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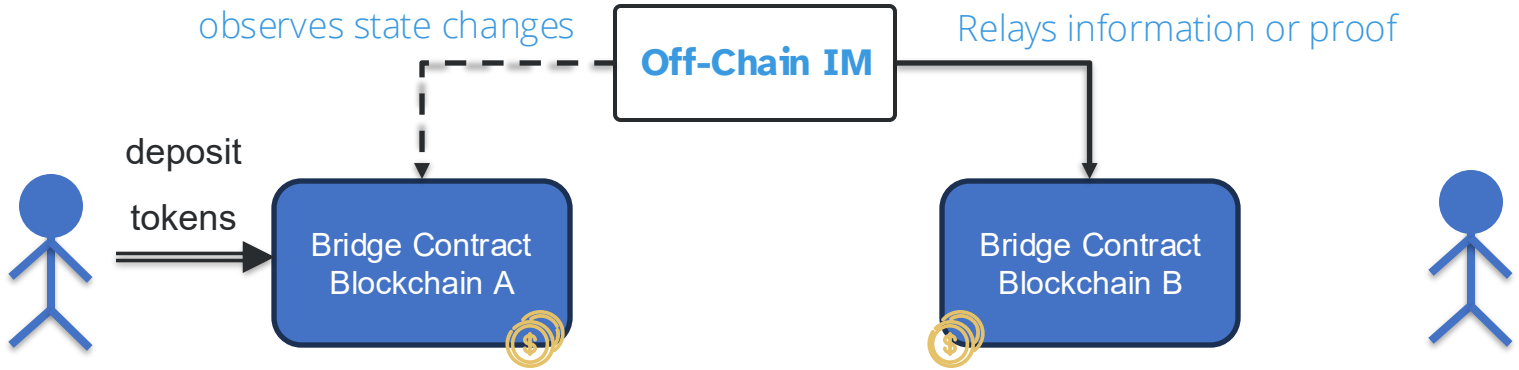

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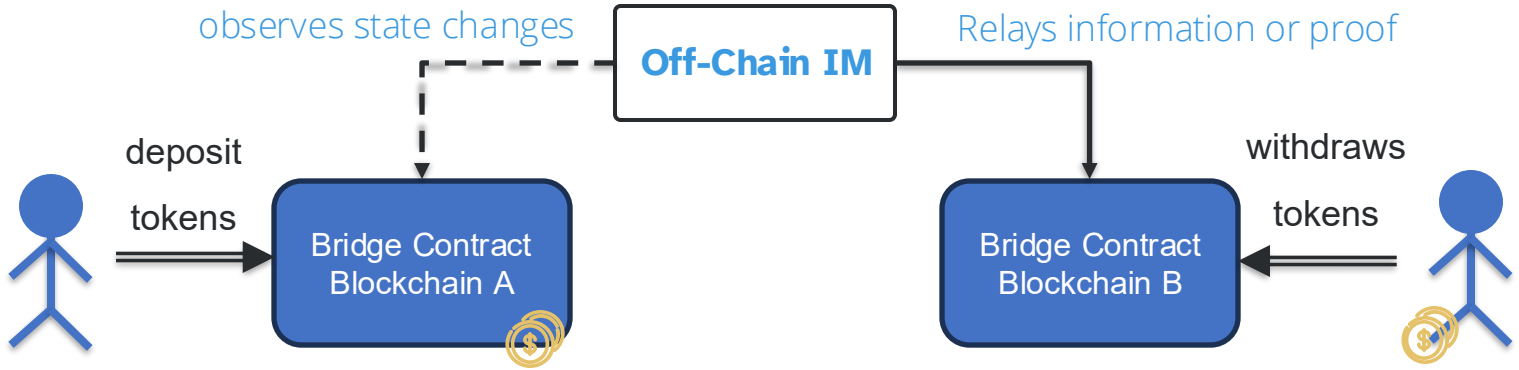


**There are multiple modes:**

- Lock-mint (in the diagram)
- Burn-mint
- Lock-unlock

# Blockchain Interoperability

*"**the ability of a source blockchain to change the state of a target blockchain** (or vice-versa), enabled by cross-chain or cross-blockchain transactions, spanning across a composition of homogeneous and heterogeneous blockchain systems"*

*Rafael Belchior, André Vasconcelos, Sérgio Guerreiro, and Miguel Correia. 2021. A Survey on Blockchain Interoperability: Past, Present, and Future Trends. ACM Comput. Surv. 54, 8, Article 168 (November 2022), 41 pages. https://doi.org/10.1145/3471140*

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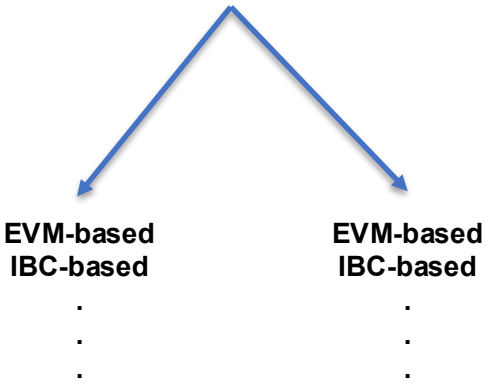


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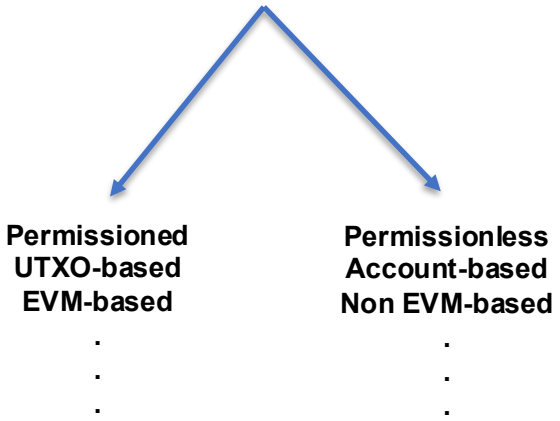


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# In a Nutshell… Interoperability Mechanisms:

Enable connectivity between **Homogeneous** or **Heterogeneous platforms**

**Reduce liquidity fragmentation** across DeFi protocols in multiple blockchains (L1s or L2s)

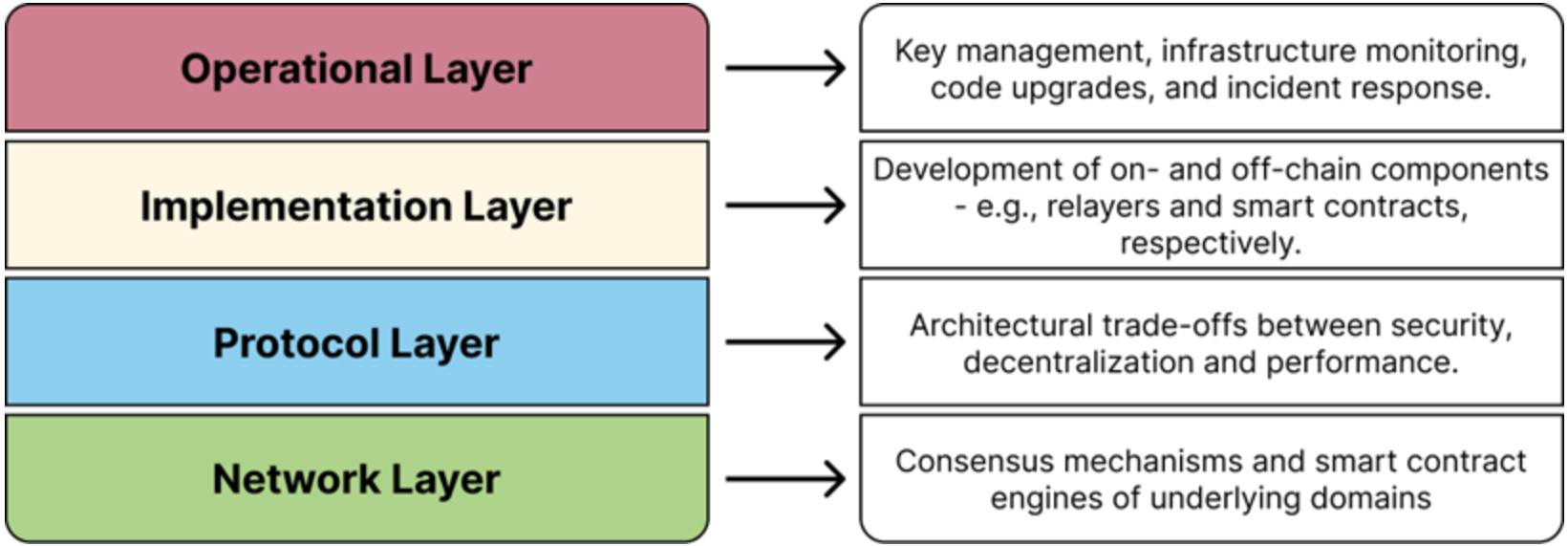
**The Core Idea:** Enable the **seamless flow of assets and data** across platforms

**The Core Idea:** Enable the **seamless flow of value** across platforms

# Outline

- ~~Motivation (Why?, How?, What?)~~
- Blockchain Interoperability and Interoperability Mechanisms
- Security and Privacy of Interoperability Mechanisms
- Securing interoperability solutions: Hephaestus and XChainWatcher
- Future Research Directions

# Building Blocks to Make It Work

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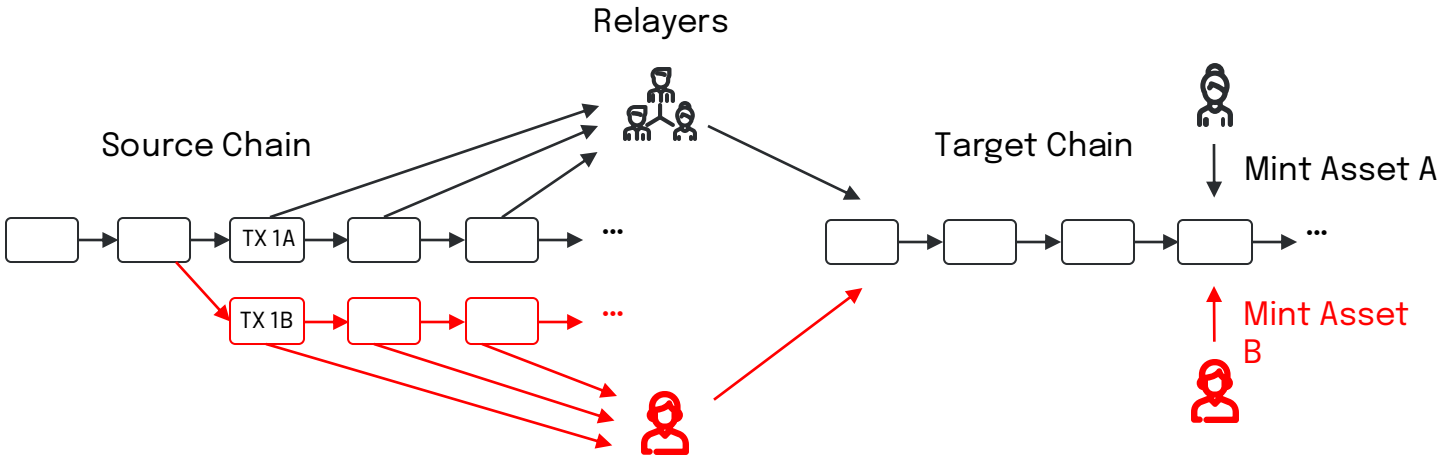
# Example: the importance of the network layer




wait for finality in the source chain

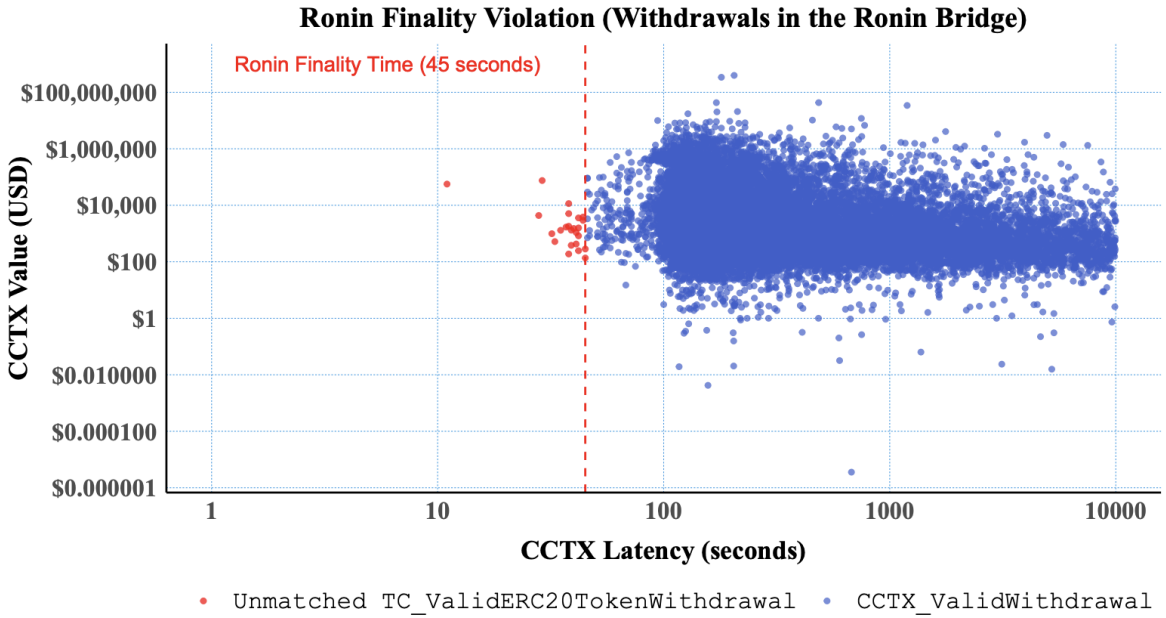
We must take into account the security of the underlying chains, and develop mechanisms to cope with possible vulnerabilities

TX 1A – Lock Asset A  TX 1B – Lock Asset B

# Show of Hands

**How many of you** would say protocols **accept transactions** in the destination chain **before the finality of the corresponding transaction** on the source chain?

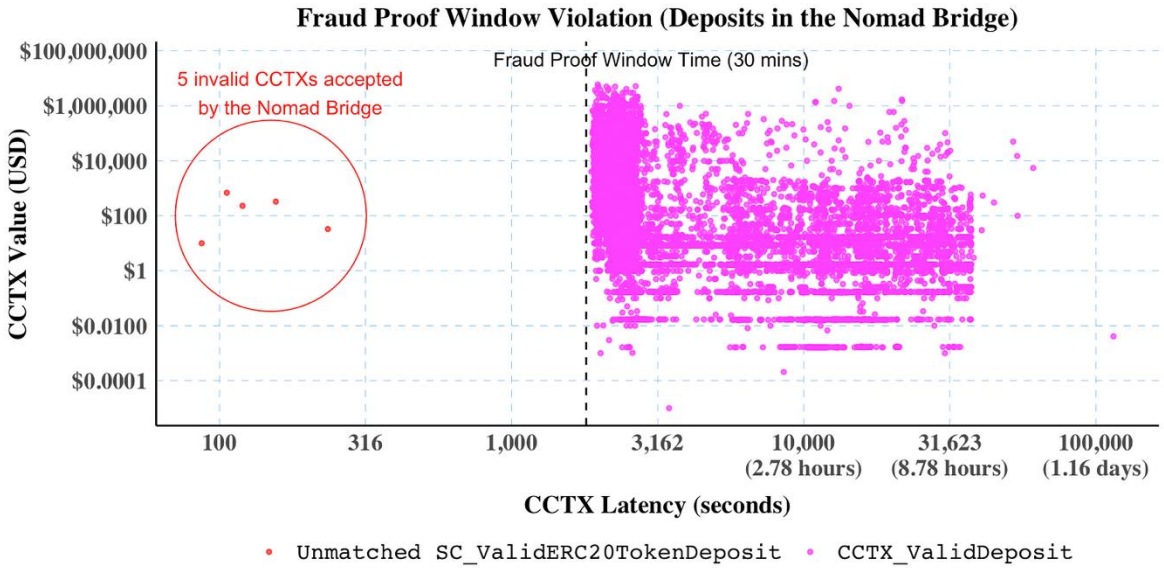
# Example: source chain finality




Paper

Augusto, A., Belchior, R., Pfannschmidt, J., Vasconcelos, A., & Correia, M. (2024). XChainWatcher: Monitoring and Identifying Attacks in Cross-Chain Bridges. arXiv preprint arXiv:2410.02029.

# Another one: fraud-proof window violation

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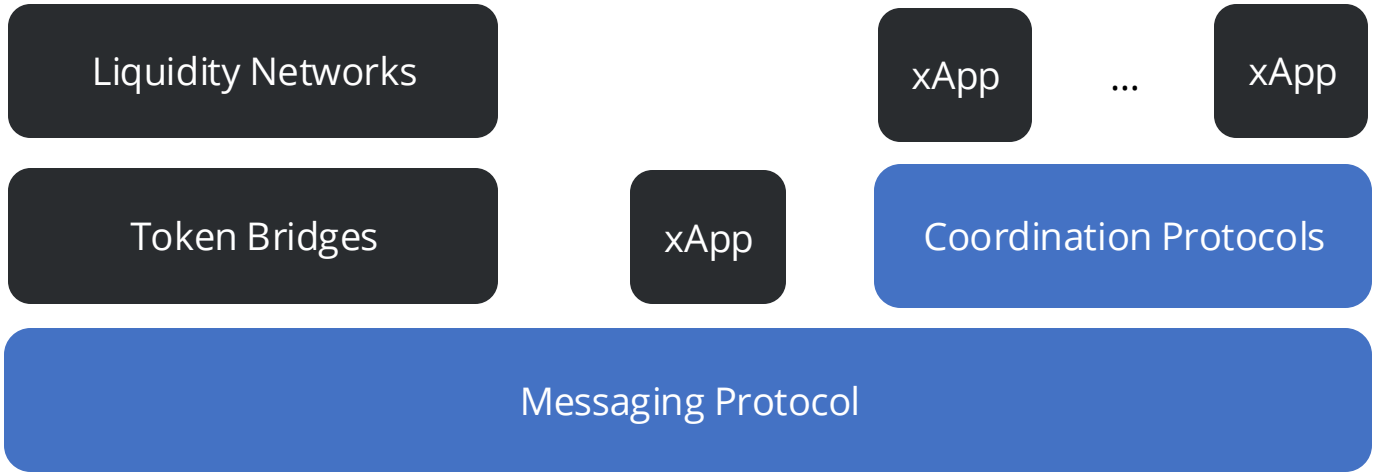
# The Protocol Layer




Abebe, E., Robinson, P., Chand, A., Murdock, M., & Hyland-Wood, D. Crosschain Risk Framework. https://crosschainriskframework.github.io/

# Blockchain Interoperability

# Architectures

## Centralization

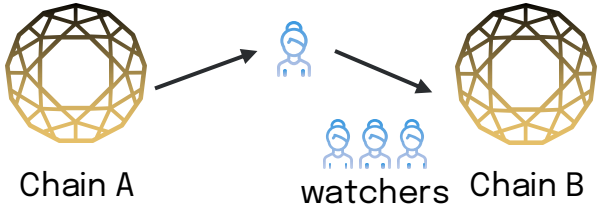

## Trusted Computation


## Permissionless Network

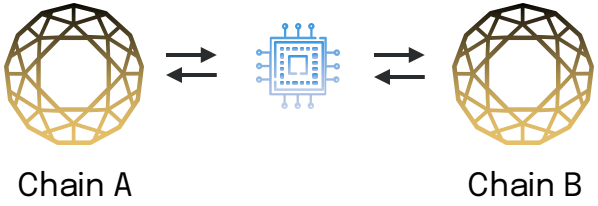

## Permissioned Network

# Architectures

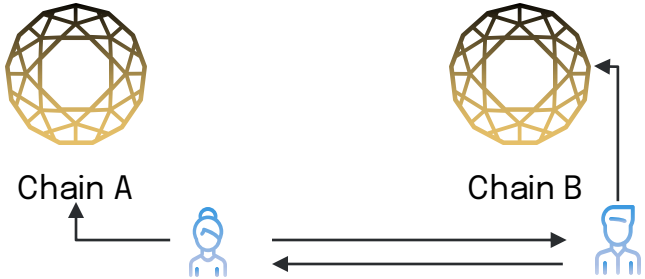
Fraud Proofs




Validity Proofs (e.g., SNARKs)




Hash and Time Locks




and more...

# Outline

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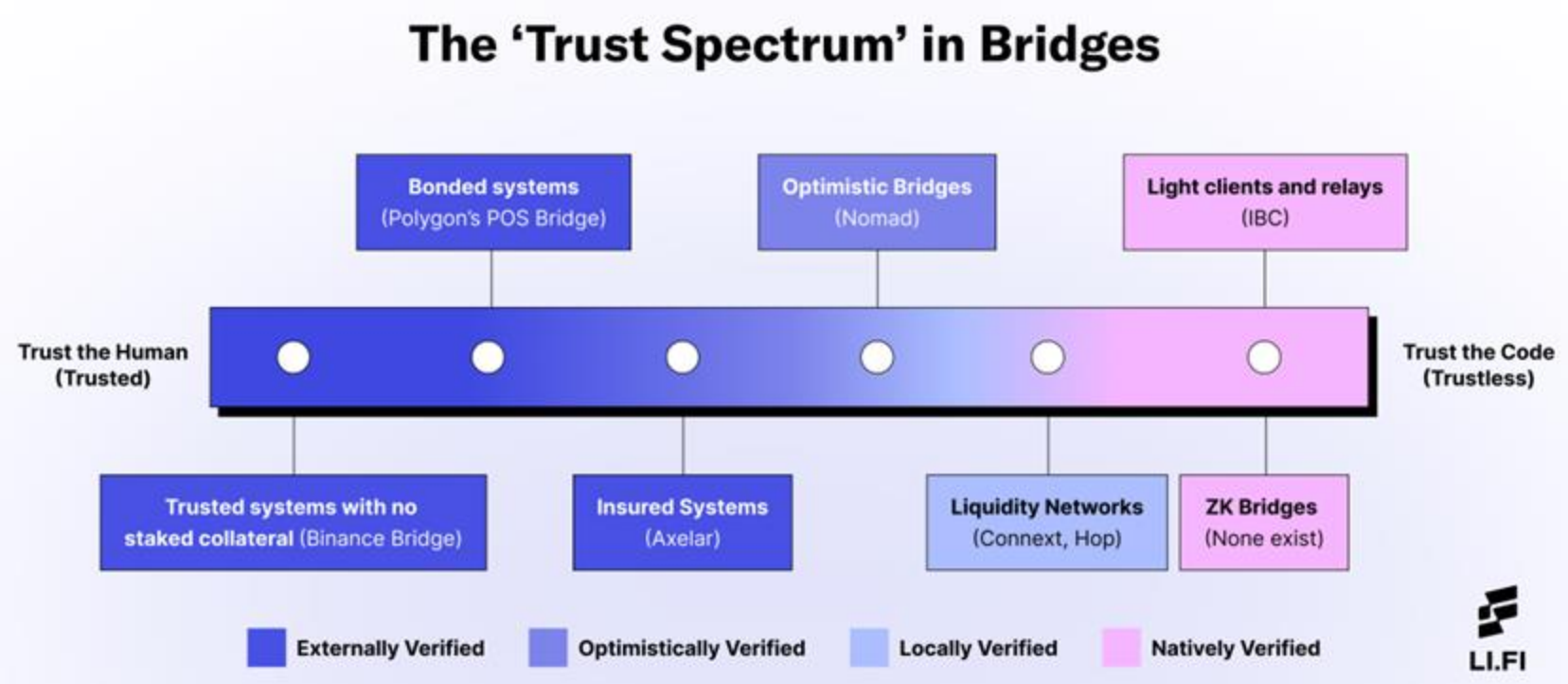
# How to classify IMs based on security guarantees?

*"There exists no asynchronous **cross-chain communication protocol** tolerant against misbehaving nodes without a **trusted** third **party**."*

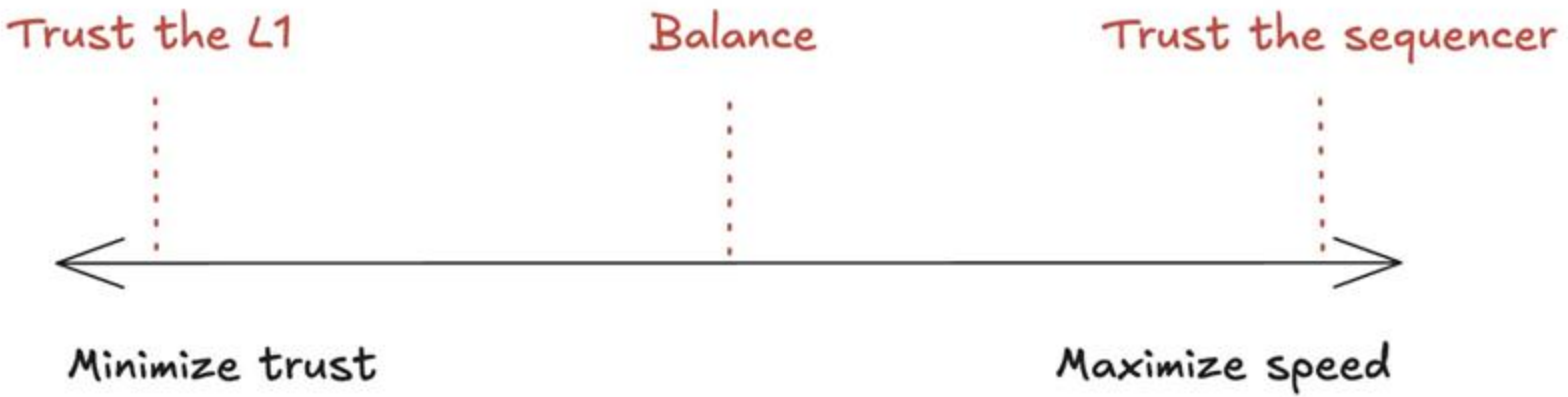
Zamyatin, A., Al-Bassam, M., Zindros, D., Kokoris-Kogias, E., Moreno-Sanchez, P., Kiayias, A., & Knottenbelt, W. J. (2021). Sok: Communication across distributed ledgers. In Financial Cryptography and Data Security: 25th International Conference, FC 2021, Virtual Event, March 1–5, 2021, Revised Selected Papers, Part II 25 (pp. 3-36). Springer Berlin Heidelberg.

# Trust spectrum




Source: https://blog.li.fi/li-fi-with-bridges-trust-is-a-spectrum-354cd5a1a6d8

# Trust spectrum (Rollups)




Source: https://x.com/brobobo_bo_bobo/status/1860004523101814956

# Is the *Trust Spectrum* Enough? NO

So…what does a secure interoperability solution look like?

# A set of properties

Inspired by the classic CIA triad for secure systems, to define a set of properties that characterize security in blockchain interoperability

**Integrity** — of the system, data, and assets

**Accountability** — of participants for integrity breach attempts

**Availability** — of system to process cross-chain transactions

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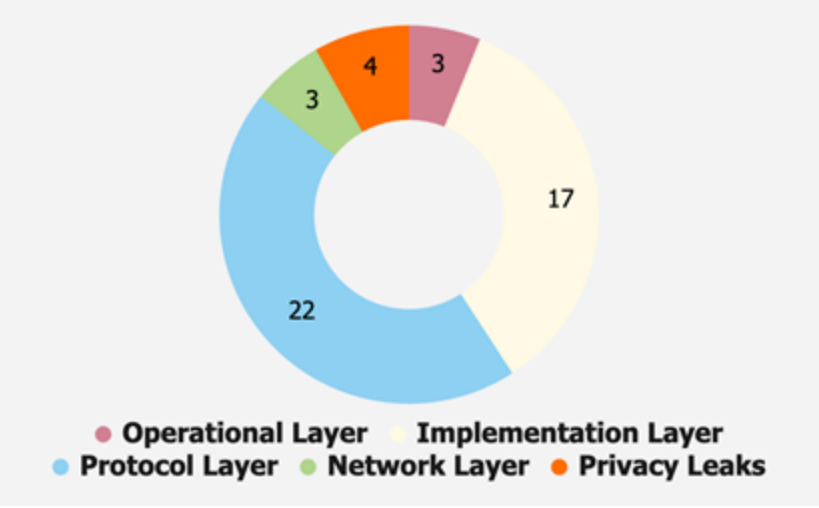
# Vulnerabilities in Interoperability




CROSS-CHAIN SYSTEMS. THE COLORED CIRCLE DENOTES THE LAYER WHERE IT CAN BE FOUND (CF. SECTION 3.1).

| Vulnerability/Leak | Mitigations |
|---|---|
| $\mathcal{V}_1$ Honest mining assumption [45] | $\mathcal{M}_1$-$\mathcal{M}_5$ |
| $\mathcal{V}_2$ Absence of identity verification [45], [71], [72] | $\mathcal{M}_8$-$\mathcal{M}_{11}$ |
| $\mathcal{V}_3$ Network isolation [38], [45], [62], [77] | $\mathcal{M}_6$,$\mathcal{M}_7$ |
| $\mathcal{V}_4$ Outdated light client state [45], [53], [150] | $\mathcal{M}_{16}$ |
| $\mathcal{V}_5$ Wrong main chain identification [6], [45], [77] | $\mathcal{M}_{18}$ |
| $\mathcal{V}_6$ Incorrect event verification [151]–[154] | $\mathcal{M}_{12}$-$\mathcal{M}_{14}$ |
| $\mathcal{V}_7$ Acceptance of invalid consensus proofs [155] | $\mathcal{M}_{15}$ |
| $\mathcal{V}_8$ Absence of chain identification [156] | $\mathcal{M}_4$ |
| $\mathcal{V}_9$ Submission of repeated inclusion proofs [21], [45], [77], [157] | $\mathcal{M}_{17}$ |
| $\mathcal{V}_{10}$ Counterfeiting assets [45], [77], [158] | $\mathcal{M}_{19}$-$\mathcal{M}_{23}$ |
| $\mathcal{V}_{11}$ Involuntary timelock expiry [63], [85] | $\mathcal{M}_{29}$-$\mathcal{M}_{30}$ |
| $\mathcal{V}_{12}$ Unset withdrawal limits [156], [159] | $\mathcal{M}_{69}$ |
| $\mathcal{V}_{13}$ Action withhold [58], [61], [80], [86], [86], [94], [160] | $\mathcal{M}_8$,$\mathcal{M}_{27}$,$\mathcal{M}_{28}$ |
| $\mathcal{V}_{14}$ Unspecified gas limit [161] | $\mathcal{M}_{65}$ |
| $\mathcal{V}_{15}$ Resource exhaustion [45], [55], [57], [60], [65], [69] | $\mathcal{M}_{48}$-$\mathcal{M}_{50}$ |
| $\mathcal{V}_{16}$ Single point of failure [156], [162] | $\mathcal{M}_7$,$\mathcal{M}_{32}$,$\mathcal{M}_{47}$ |
| $\mathcal{V}_{17}$ Publicly identifiable operators [74] | $\mathcal{M}_{44}$-$\mathcal{M}_{46}$ |
| $\mathcal{V}_{18}$ Misaligned incentive mechanisms [38], [60], [65], [122] | $\mathcal{M}_{23}$,$\mathcal{M}_{31}$-$\mathcal{M}_{34}$ |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# Attacks in Cross-Chain Bridges

| Project Information | | General Attack | | Mapping to Theoretical Vulnerabilities | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Name & Ref | SA | Date | Amount | $\mathcal{V}_{44}$ | $\mathcal{V}_{43}$ | $\mathcal{V}_{28}$ | $\mathcal{V}_{27}$ | $\mathcal{V}_{24}$ | $\mathcal{V}_{6}$ |
| [218] Ronin | $\mathcal{SA}_{22}$ | Mar 2022 | 624M | ✓ | ✓ | ✗ | ✗ | ✗ | ✗ |
| [219] PolyBridge #1 | $\mathcal{SA}_{22}$ | Aug 2021 | 611M | ✗ | ✓ | ✓ | ✗ | ✗ | ✗ |
| [220] BNB | $\mathcal{SA}_{11}$ | Oct 2022 | 566M | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| [123] Wormhole | $\mathcal{SA}_{22}$ | Feb 2022 | 326M | ✗ | ✗ | ✓ | ✗ | ✓ | ✗ |
| [221] Nomad | $\mathcal{SA}_{33}$ | Aug 2022 | 190M | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| [222] BXH | $\mathcal{SA}_{11}$ | Oct 2021 | 139M | ✓ | ✓ | ✗ | ✗ | ✗ | ✗ |
| [223] Multichain #2 | $\mathcal{SA}_{22}$ | Jul 2023 | 126M | ✓† | ✓† | ✗ | ✗ | ✗ | ✗ |
| [224] Harmony | $\mathcal{SA}_{22}$ | Jun 2022 | 100M | ✓ | ✓ | ✗ | ✗ | ✗ | ✗ |
| [225] Qubit | $\mathcal{SA}_{11}$ | Jan 2022 | 80M | ✗ | ✗ | ✗ | ✓ | ✓ | ✗ |
| [226] pNetwork | $\mathcal{SA}_{33}$ | Sep 2021 | 13M | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ |
| [227] Thorchain #3 | $\mathcal{SA}_{21}$ | Jul 2021 | 8M | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ |
| [223] Anyswap | $\mathcal{SA}_{22}$ | Jul 2021 | 8M | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ |
| [227] Thorchain #2 | $\mathcal{SA}_{21}$ | Jul 2021 | 5M | ✗ | ✗ | ✗ | ✗ | ✓ | ✓ |
| [219] PolyBridge #2 | $\mathcal{SA}_{22}$ | Jul 2023 | 4.4M | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ |
| [228] Meter | $\mathcal{SA}_{22}$ | Jul 2021 | 4.4M | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| [229] Chainswap | $\mathcal{SA}_{22}$ | Jul 2021 | 4.4M | ✗ | ✗ | ✓ | ✗ | ✓ | ✗ |
| [223] Multichain #1 | $\mathcal{SA}_{22}$ | Jan 2022 | 3M | ✗ | ✗ | ✗ | ✓ | ✓ | ✗ |
| [227] Thorchain #1 | $\mathcal{SA}_{21}$ | Jun 2021 | 140K | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ |
| **Summary** | | **07/21 - 07/23** | **2.9B** | **22%** | **39%** | **17%** | **11%** | **44%** | **22%** |

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# Vulnerabilities Behind

| Project Information | | General Attack Information | | | | | Incident Resp | | Where | | Mapping to Theoretical Vulnerabilities | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name & Ref | SA | Date | Amount | AT | Txs | Mix | DT | CT | VL | EL | $\mathcal{V}_{44}$ | $\mathcal{V}_{43}$ | $\mathcal{V}_{28}$ | $\mathcal{V}_{27}$ | $\mathcal{V}_{24}$ | $\mathcal{V}_{6}$ |

Physical Infrastructure Backdoors

Bad key Management

Dead code

Unsafe Third-party software

Lack of access control

Incorrect event verification

~66% used a *Permissioned Network* as Architecture

# What about Privacy?

# Privacy Brings Additional Challenges

- What do… by privacy?
- A…
- …actions across blockchains
- …s-chain transaction data

What if we… design a system that guarantees all these properties?

Well…


OFAC
OFFICE OF FOREIGN ASSETS CONTROL

# The Obvious Example


...and it “only” provides the unlinkability of transactions in one blockchain

# Interesting Connection with Bridge Attacks

| Name & Ref | Date | Amount | Mix |
|---|---|---|---|
| [193] Ronin | Mar 2022 | 624M | ◑ |
| [194] PolyBridge #1 | Aug 2021 | 611M | ○ |
| [195] BNB | Oct 2022 | 566M | ◐ |
| [108] Wormhole | Feb 2022 | 326M | ◐ |
| [196] Nomad | Aug 2022 | 190M | ◑ |
| [197] BXH | Oct 2021 | 139M | ◐ |
| [198] Multichain #2 | Jul 2023 | 126M | ○ |
| [199] Harmony | Jun 2022 | 100M | ◑ |
| [200] Qubit | Jan 2022 | 80M | ◑ |
| [201] pNetwork | Sep 2021 | 13M | ○ |
| [202] Thorchain #3 | Jul 2021 | 8M | ◑ |
| [198] Anyswap | Jul 2021 | 8M | ◑ |
| [202] Thorchain #2 | Jul 2021 | 5M | ◑ |
| [194] PolyBridge #2 | Jul 2023 | 4.4M | ○ |
| [203] Meter | Jul 2021 | 4.4M | ◑ |
| [204] Chainswap | Jul 2021 | 4.4M | ● |
| [198] Multichain #1 | Jan 2022 | 3M | ● |
| [202] Thorchain #1 | Jun 2021 | 140K | ◑ |

14 out of 18
used Transaction Mixers,
mainly Tornado Cash

**Usage of Mixers (Mix)**
- ○ Not used
- ◐ Before the attack
- ◑ After the attack
- ● Before and after the attack

**Would a cross-chain protocol** with the same level of privacy **be sanctioned**?


Explore the notion of ***Revokable Privacy***. Is it possible to **guarantee these properties** if and only **if there is no misbehavior**?

# Outline

- ~~Motivation (Why?, How?, What?)~~
- ~~Blockchain Interoperability and Interoperability Mechanisms~~
- ~~Security and Privacy of Interoperability Mechanisms~~
- Securing interoperability solutions: Hephaestus and XChainWatcher
- Future Research Directions

# A Prominent Problem

TABLE 5. CLASSIFICATION OF MOST PROFITABLE CROSS-CHAIN BRIDGE HACKS GROUPED BY USD. THE CELLS WITH THE VULNERABILITY NUMBER ARE FILLED WITH THE COLOR ACCORD WE ADD A "SUMMARY" ROW THAT AGGREGATES INFORMATION. SPECIFICALLY, WE USE CELL EACH VULNERABILITY WAS FOUND.

| Project Information | | General Attack Information | | | | | Incident Resp | |
|---|---|---|---|---|---|---|---|---|
| Name & Ref | SA | Date | Amount | AT | Txs | Mix | DT | CT |
| [218] Ronin | $SA_{22}$ | Mar 2022 | 624M | ■ | ○ | ◑ | 6d | ● |
| [219] PolyBridge #1 | $SA_{22}$ | Aug 2021 | 611M | □ | ◔ | ○ | – | ◔ |
| [220] BNB | $SA_{11}$ | Oct 2022 | 566M | ■ | ◔ | ◐ | – | ◑ |
| [123] Wormhole | $SA_{22}$ | Feb 2022 | 326M | ■ | ○ | ◐ | – | ○ |
| [221] Nomad | $SA_{33}$ | Aug 2022 | 190M | ◧ | ◕ | ◑ | – | ◔ |
| [222] BXH | $SA_{11}$ | Oct 2021 | 139M | ■ | ○ | ◐ | – | ◑ |
| [223] Multichain #2 | $SA_{22}$ | Jul 2023 | 126M | ■ | ○ | ○ | – | ◑ |
| [224] Harmony | $SA_{22}$ | Jun 2022 | 100M | ■ | ◔ | ◑ | – | ◕ |
| [225] Qubit | $SA_{11}$ | Jan 2022 | 80M | ■ | ◔ | ◑ | – | ◔ |
| [226] pNetwork | $SA_{33}$ | Sep 2021 | 13M | ■ | ◔ | ○ | 13m | ◔ |
| [227] Thorchain #3 | $SA_{21}$ | Jul 2021 | 8M | ■ | ○ | ◑ | – | – |
| [223] Anyswap | $SA_{22}$ | Jul 2021 | 8M | ■ | ○ | ◑ | – | ◕ |
| [227] Thorchain #2 | $SA_{21}$ | Jul 2021 | 5M | ■ | ◕ | ◑ | – | ◑ |
| [219] PolyBridge #2 | $SA_{22}$ | Jul 2023 | 4.4M | ■ | ◑ | ○ | 7h | ◕ |
| [228] Meter | $SA_{22}$ | Jul 2021 | 4.4M | ■ | ○ | ◑ | – | ◔ |
| [229] Chainswap | $SA_{22}$ | Jul 2021 | 4.4M | ■ | ● | ● | – | ◑ |
| [223] Multichain #1 | $SA_{22}$ | Jan 2022 | 3M | ◧ | – | ● | – | ◕ |
| [227] Thorchain #1 | $SA_{21}$ | Jun 2021 | 140K | ■ | – | ◑ | 5m | – |
| **Summary** | | **07/21 - 07/23** | **2.9B** | | | | | |

**Communication Time (CT)**
- ○ ]0; 2] hours
- ◔ ]2; 4] hours
- ◑ ]4; 6] hours
- ◕ ]6; 24] hours
- ● >= 6 days

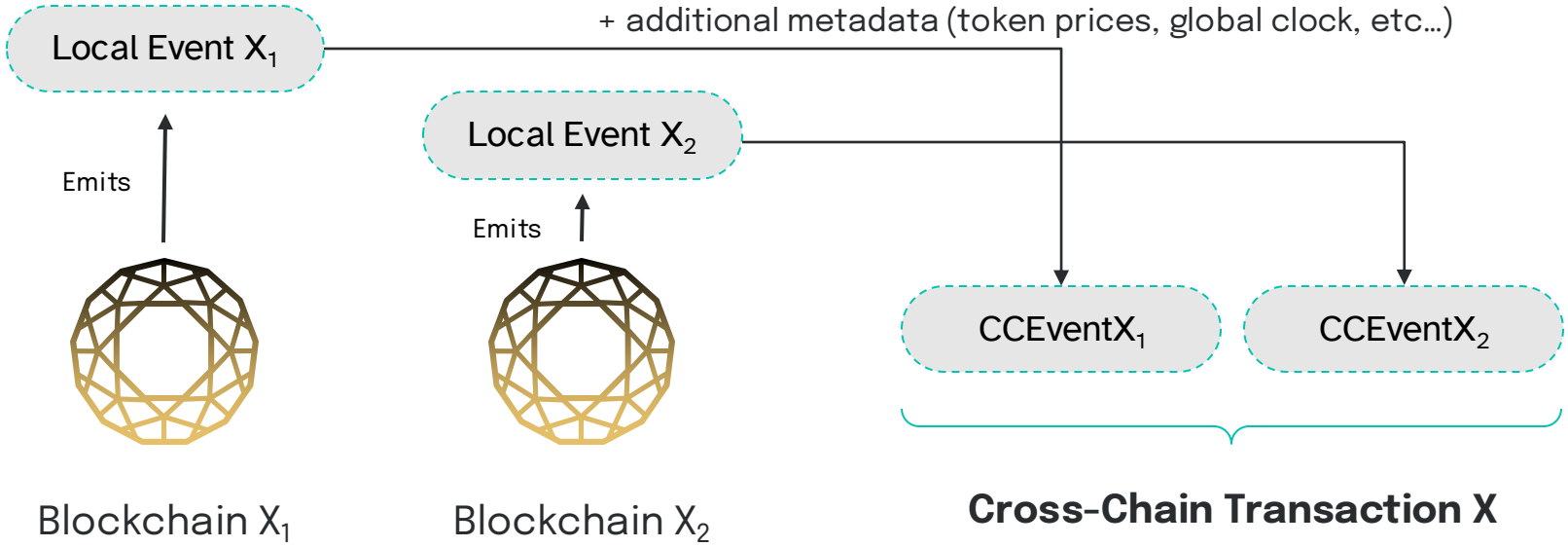
Attacks stole between 140K USD and ~620M USD

**Defi Protocol LI.FI Struck by $11M Exploit**

The exploit is reported to be related to the LI.FI bridge.

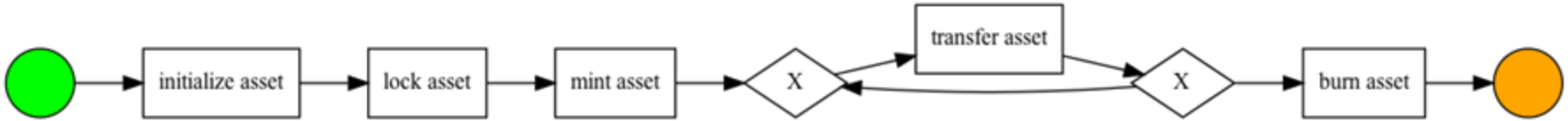
By Oliver Knight · Jul 16, 2024 at 2:30 p.m. · Updated Jul 16, 2024 at 8:45 p.m.

# The Solution: Cross-Chain Modelling

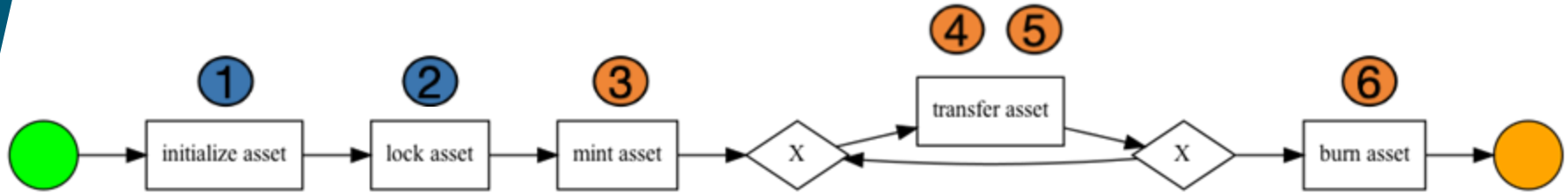



Belchior, R., Somogyvari, P., Pfannschmidt, J., Vasconcelos, A., & Correia, M. (2023). Hephaestus: Modeling, analysis, and performance evaluation of cross-chain transactions. *IEEE Transactions on Reliability*.

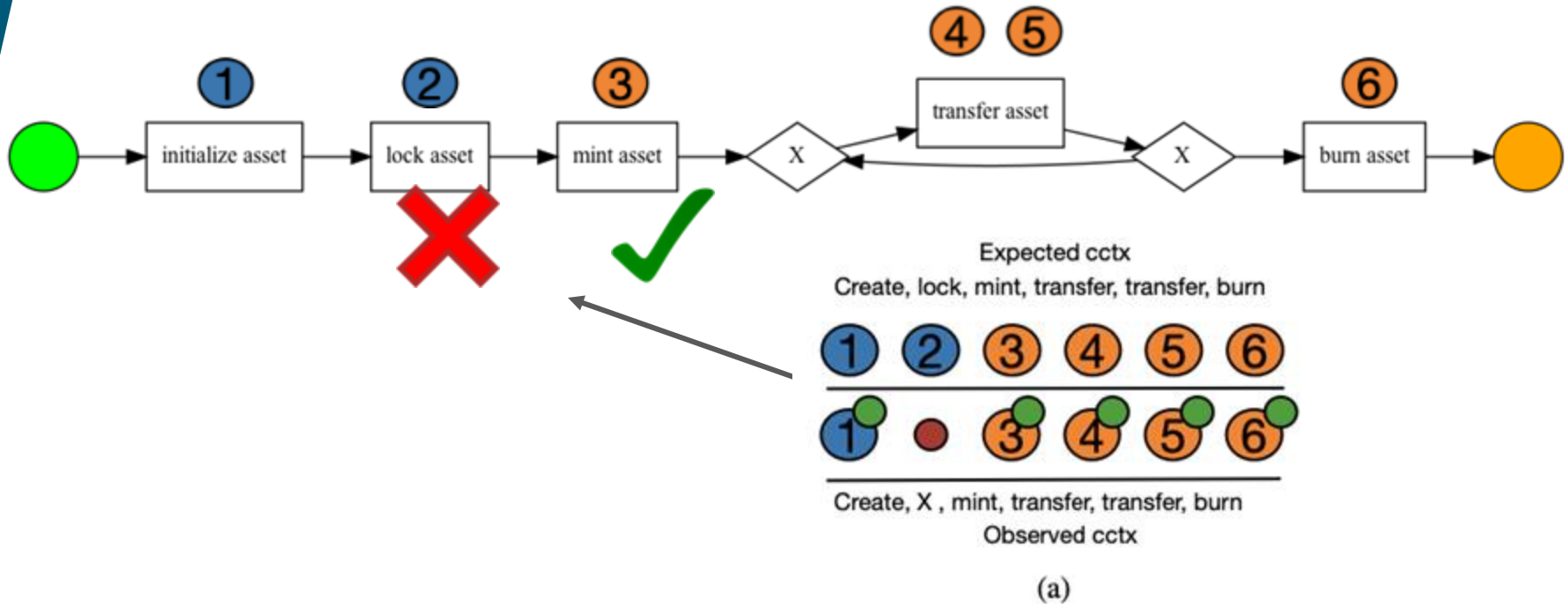
# Key Idea (burn-mint model)



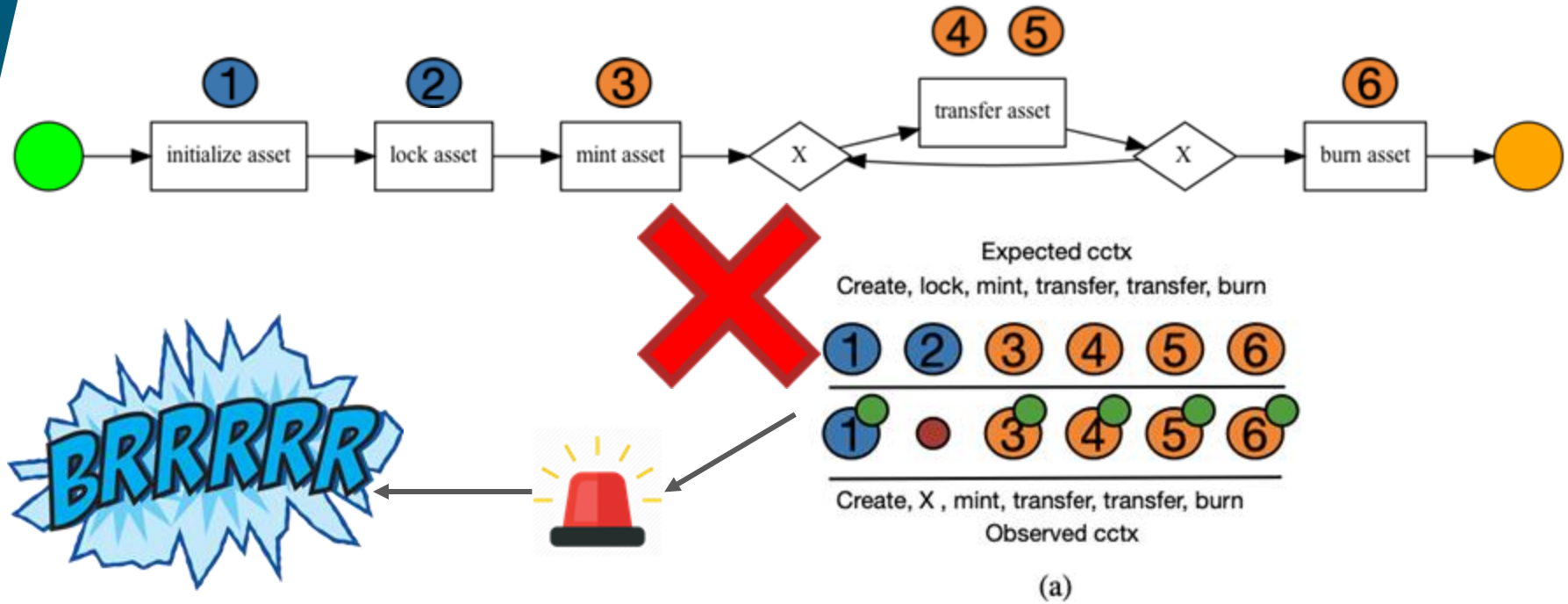
# Key Idea (burn-mint model)



# Key Idea (burn-mint model)



# Key Idea (burn-mint model)



**Algorithm 1:** Cross-Chain State Update.
Creation of a cross-chain state from a set of *ccevents*

**Input:** Set of events $\mathcal{E}$
**Input:** State update algorithm `createCCState`
**Input:** Cross-chain rules $\mathcal{R}$
**Input:** Cross-chain state $\mathcal{S}$
**Output:** Upon success returns cross-chain state $\mathcal{S}$, and a *SYNC MOVE* 🟢

**require** `verifySatisfability`$(e, \mathcal{R}, \mathcal{S})$ `// Returns tuple (event,MOVE ON LOG` 🔴`) if event do not conform to the rules, cross-chain state is invalid.`
**foreach** $e \in \mathcal{E}$ **do**
  `// For each event in retrieved event set`
  **if** $\nexists \mathcal{S}[e.caseID]$ **then**
    `// each cross-chain state key is indexed by case ID.`
    $cc =$ `populateCCTX`$(\mathcal{S}[e.caseID], e)$
  **end if**
  **else**
    $cc =$ `updateCCTx`$(\mathcal{S}[e.caseID], e)$
  **end if**
  $\mathcal{S} = \mathcal{S} \cup cc$
  $\mathcal{S}' =$ `createCCState`$(\mathcal{S}, e.caseID)$
  `// Calculates updated ccstate, algorithm is parametrizable`
**end foreach**
**return** ($\mathcal{S}'$, SYNC MOVE 🟢)


Our state is at position X. Each time a tx happens, we update the state

**Algorithm 1:** Cross-Chain State Update.
Creation of a cross-chain state from a set of *ccevents*

**Input:** Set of events $\mathcal{E}$
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7 **end if**
8 **else**
9 $cc =$ `updateCCTx`$(\mathcal{S}[e.caseID], e)$
10 **end if**
11 $\mathcal{S} = \mathcal{S} \cup cc$
12 $\mathcal{S}' =$ `createCCState`$(\mathcal{S}, e.caseID)$
`// Calculates updated ccstate, algorithm is parametrizable`
13 **end foreach**
14 **return** ($\mathcal{S}'$, SYNC MOVE 🟢)


Our state is at position X. Each time a tx happens, we update the state

Check for non-modelled behavior

**Algorithm 1:** Cross-Chain State Update.
Creation of a cross-chain state from a set of *ccevents*

**Input:** Set of events $\mathcal{E}$
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**Input:** Cross-chain rules $\mathcal{R}$
**Input:** Cross-chain state $\mathcal{S}$
**Output:** Upon success returns cross-chain state $\mathcal{S}$, and a *SYNC MOVE*

**require** `verifySatisfability`$(e, \mathcal{R}, \mathcal{S})$ // Returns tuple (event, *MOVE ON LOG*) if event do not conform to the rules, cross-chain state is invalid.
**foreach** $e \in \mathcal{E}$ **do**
  // For each event in retrieved event set
  **if** $\nexists \mathcal{S}[e.caseID]$ **then**
    // each cross-chain state key is indexed by case ID.
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  **end if**
  **else**
    $cc =$ `updateCCTx`$(\mathcal{S}[e.caseID], e)$
  **end if**
  $\mathcal{S} = \mathcal{S} \cup cc$
  $\mathcal{S}' =$ `createCCState`$(\mathcal{S}, e.caseID)$
  // Calculates updated ccstate, algorithm is parametrizable
**end foreach**
**return** ($\mathcal{S}'$, SYNC MOVE)


Our state is at position X. Each time a tx happens, we update the state

Check for non-modelled behavior

Update the state of the cross-chain model

**Algorithm 1:** Cross-Chain State Update.
Creation of a cross-chain state from a set of *ccevents*

**Input:** Set of events $\mathcal{E}$
**Input:** State update algorithm `createCCState`
**Input:** Cross-chain rules $\mathcal{R}$
**Input:** Cross-chain state $\mathcal{S}$
**Output:** Upon success returns cross-chain state $\mathcal{S}$, and a *SYNC MOVE*

```
require verifySatisfability(e, R, S) // Returns tuple (event, MOVE ON LOG) if event do not conform to the rules, cross-chain state is invalid.
foreach e ∈ E do
    // For each event in retrieved event set
    if ∄S[e.caseID] then
        // each cross-chain state key is indexed by case ID.
        cc = populateCCTX(S[e.caseID], e)
    end if
    else
        cc = updateCCTx(S[e.caseID], e)
    end if
    S = S ∪ cc
    S' = createCCState(S, e.caseID)
     // Calculates updated ccstate, algorithm is parametrizable
end foreach
return (S', SYNC MOVE)
```


Our state is at position X. Each time a tx happens, we update the state

Check for non-modelled behavior

Update the state of the cross-chain model

Valid move = cross-chain rules are being respected

# Capabilities of a Cross-Chain Model

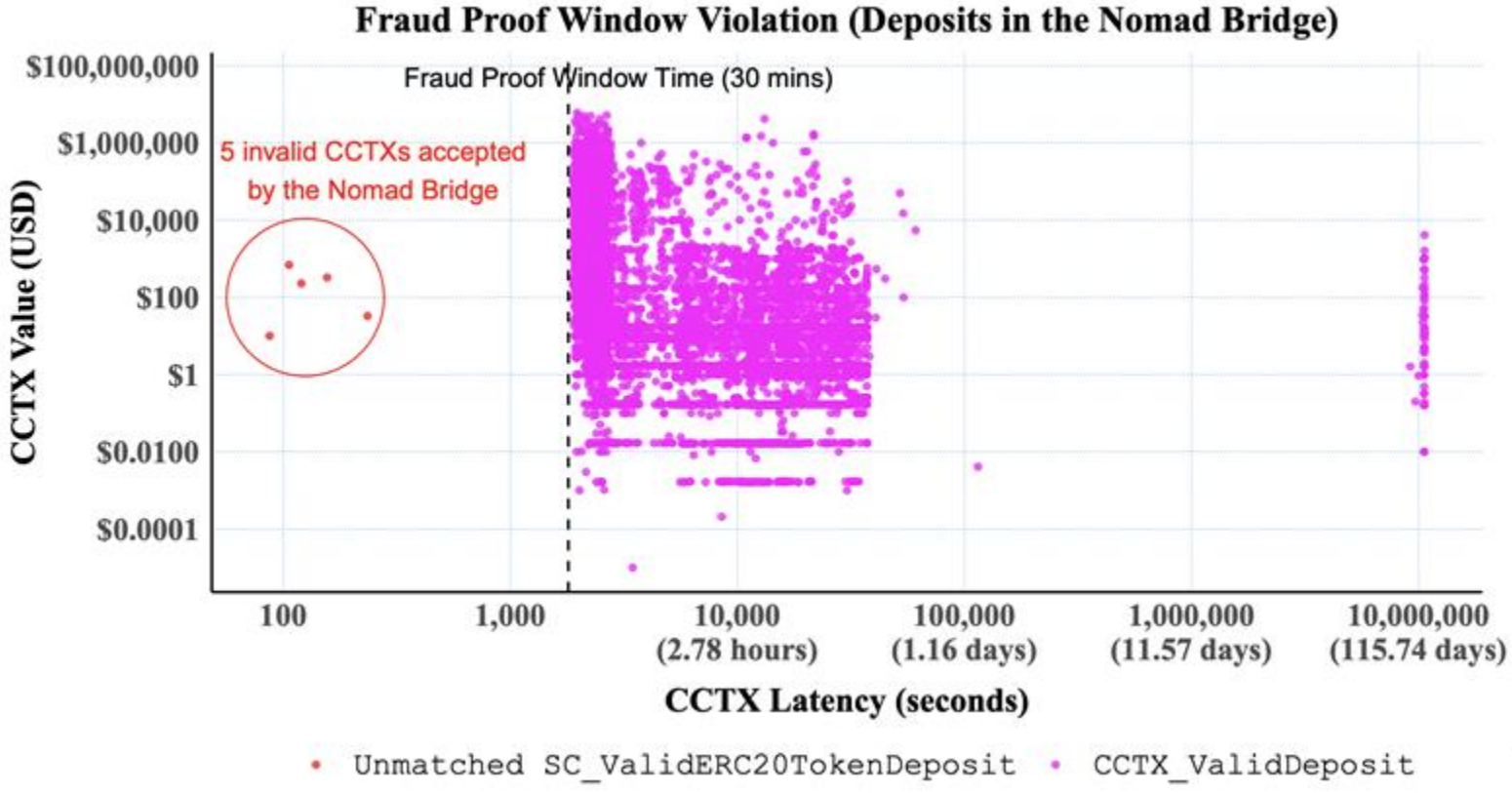
Finding anomalies in cross-chain protocols through **cross-chain rules**.

Example: defining what a valid deposit of tokens should look like

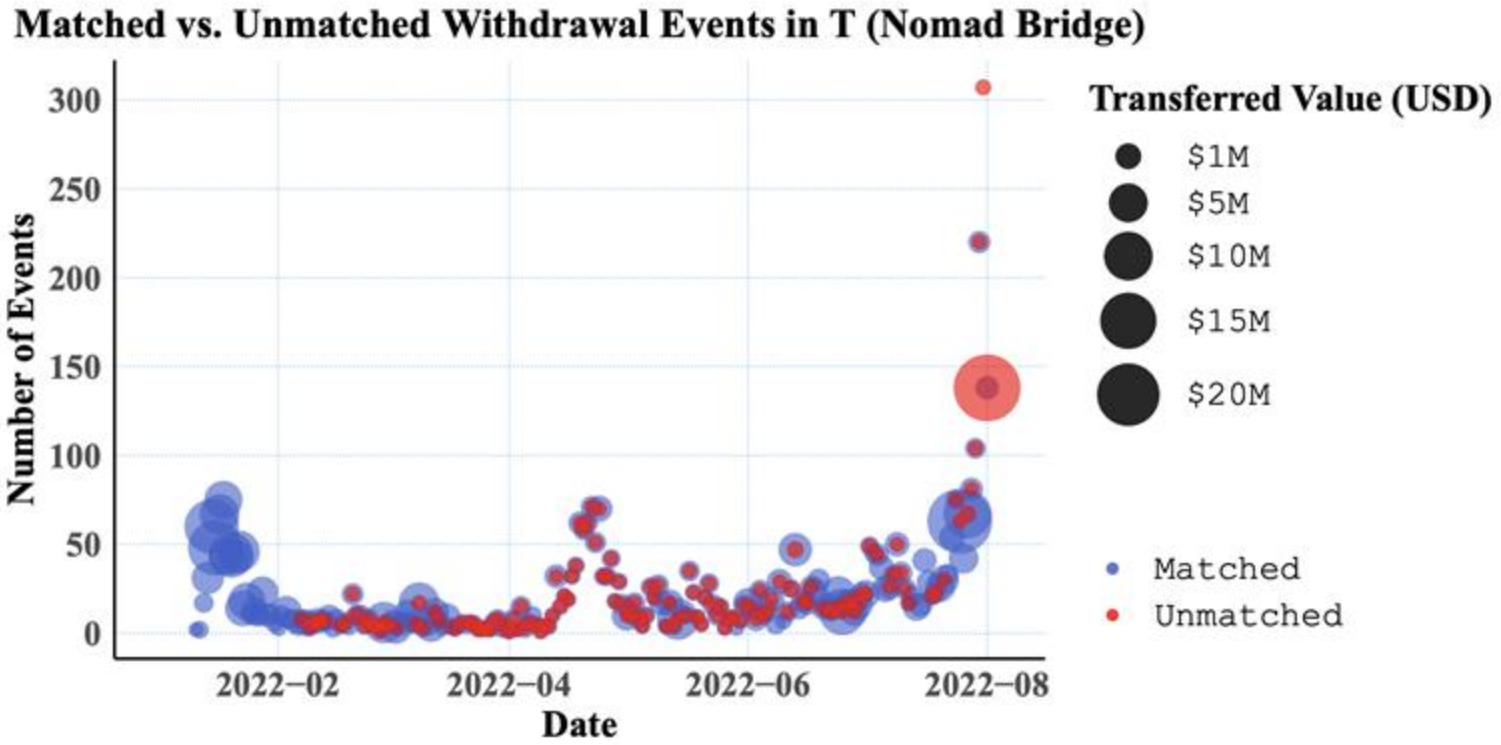
```
// Rule 4 (D)
CCTX_ValidDeposit(orig_chain_id, orig_timestamp, orig_tx_hash, dst_chain_id, dst_tim
     orig_token, dst_token, sender, benef, amount) :-
   TC_ValidERC20TokenDeposit(dst_timestamp, dst_tx_hash, deposit_id, benef, dst_toke
   (
     SC_ValidERC20TokenDeposit(orig_timestamp, orig_tx_hash, deposit_id, sender, _,
     orig_chain_id, dst_chain_id, _, amount) ;
     SC_ValidNativeTokenDeposit(orig_timestamp, orig_tx_hash, deposit_id, sender, _,
     orig_chain_id, dst_chain_id, _, amount)
   ),
   cctx_finality(orig_chain_id, orig_chain_finality),
   orig_timestamp + orig_chain_finality < dst_timestamp.
```

*Augusto, A., Belchior, R., Pfannschmidt, J., Vasconcelos, A., & Correia, M. (2024). XChainWatcher: Monitoring and IdentifyingAttacks in Cross-Chain Bridges. arXiv preprint arXiv:2410.02029.*

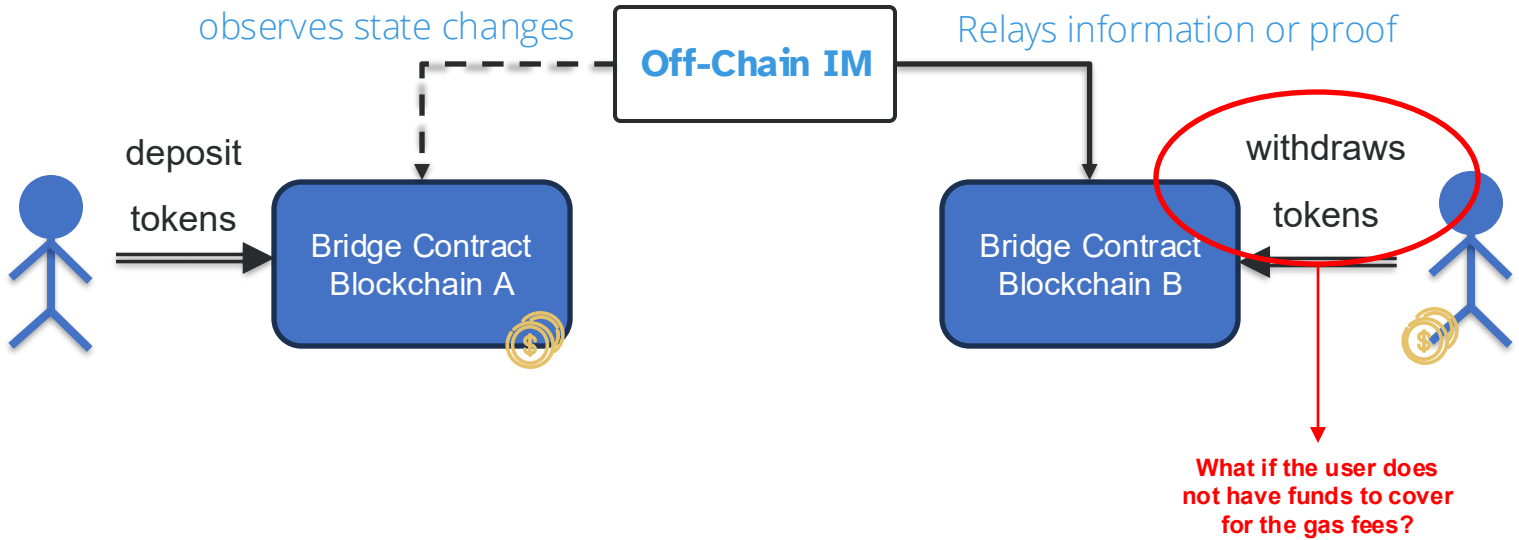
# Anomaly 1


Fraud Proof Window Violation (Deposits in the Nomad Bridge)
Fraud Proof Window Time (30 mins)
5 invalid CCTXs accepted by the Nomad Bridge
CCTX Value (USD)
$100,000,000
$1,000,000
$10,000
$100
$1
$0.0100
$0.0001
100
1,000
10,000 (2.78 hours)
100,000 (1.16 days)
1,000,000 (11.57 days)
10,000,000 (115.74 days)
CCTX Latency (seconds)
Unmatched SC_ValidERC20TokenDeposit
CCTX_ValidDeposit

# Anomaly 2


Matched vs. Unmatched Withdrawal Events in T (Nomad Bridge)
Number of Events
300
250
200
150
100
50
0
2022–02
2022–04
2022–06
2022–08
Date
Transferred Value (USD)
$1M
$5M
$10M
$15M
$20M
Matched
Unmatched

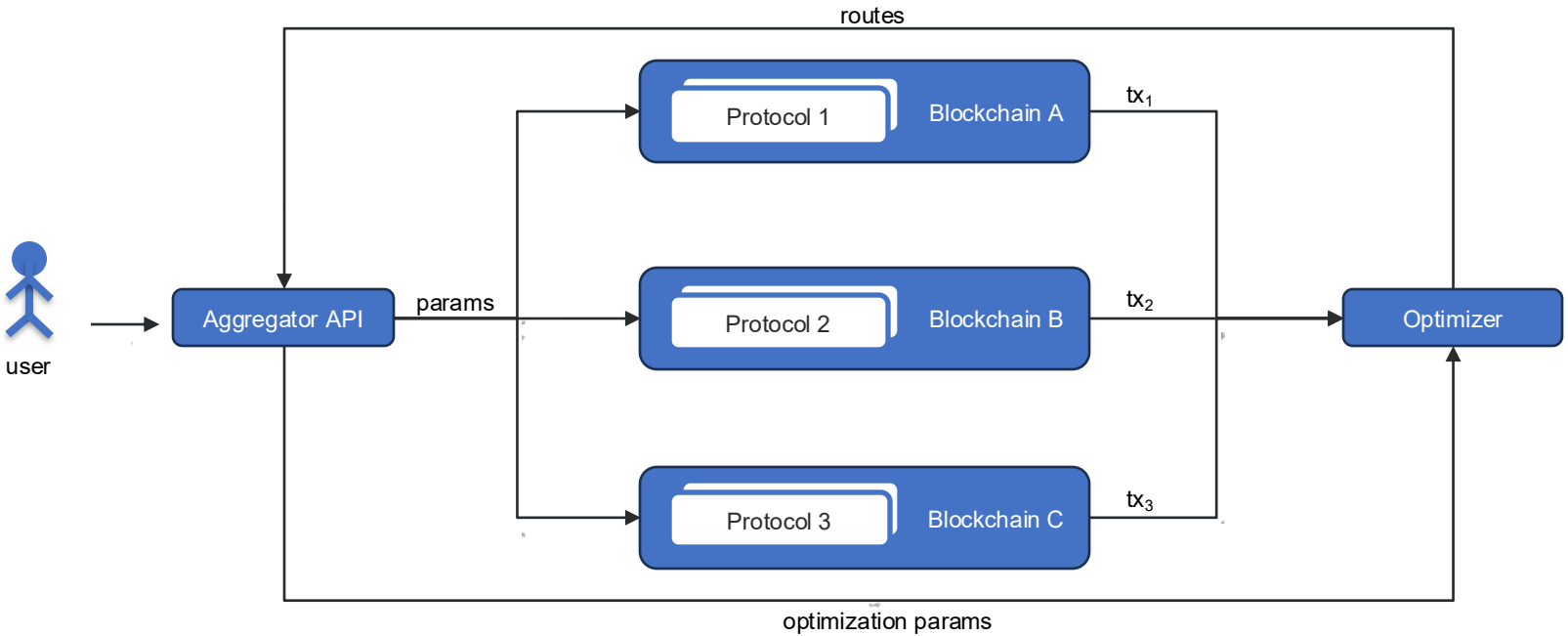
# Example: how does a token bridge work?



# Outline

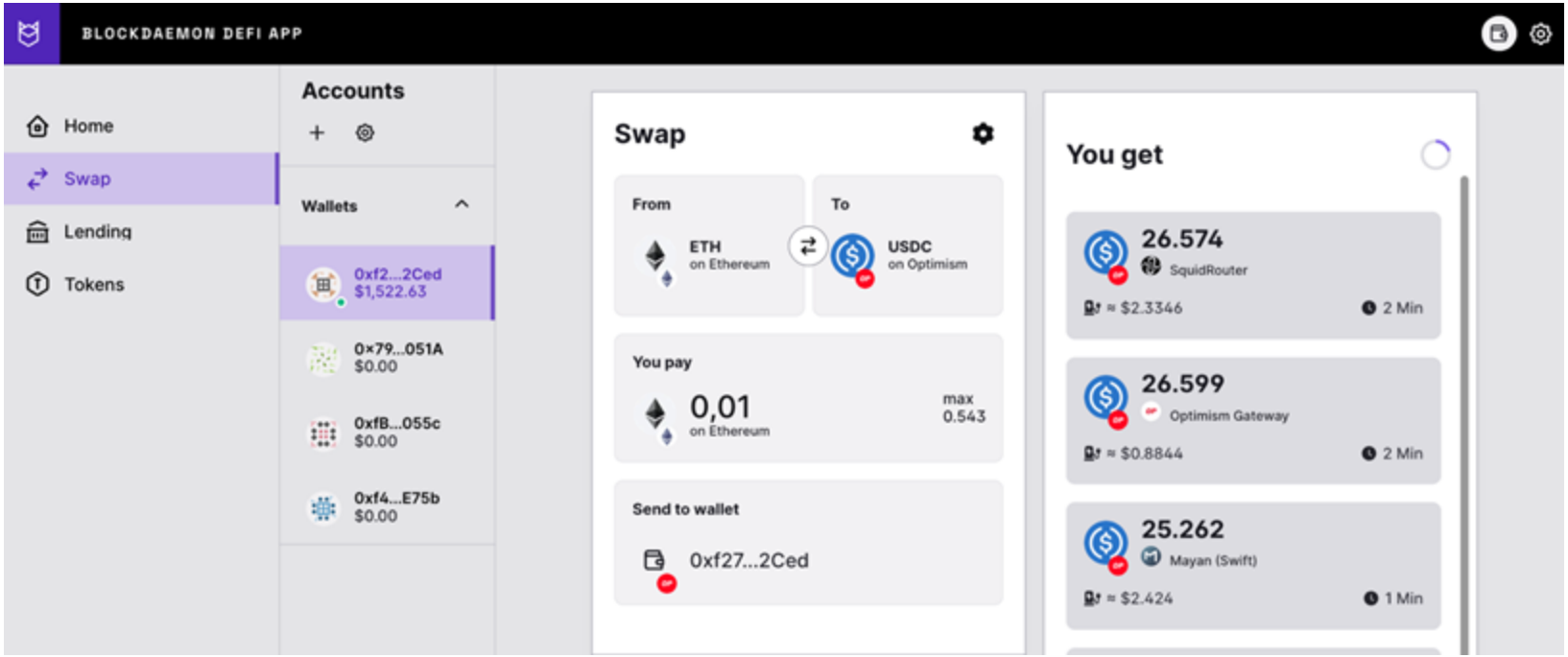
- ~~Motivation (Why?, How?, What?)~~
- ~~Blockchain Interoperability and Interoperability Mechanisms~~
- ~~Security and Privacy of Interoperability Mechanisms~~
- ~~Securing interoperability solutions: Hephaestus and XChainWatcher~~
- Future Research Directions

# Bridge Aggregators

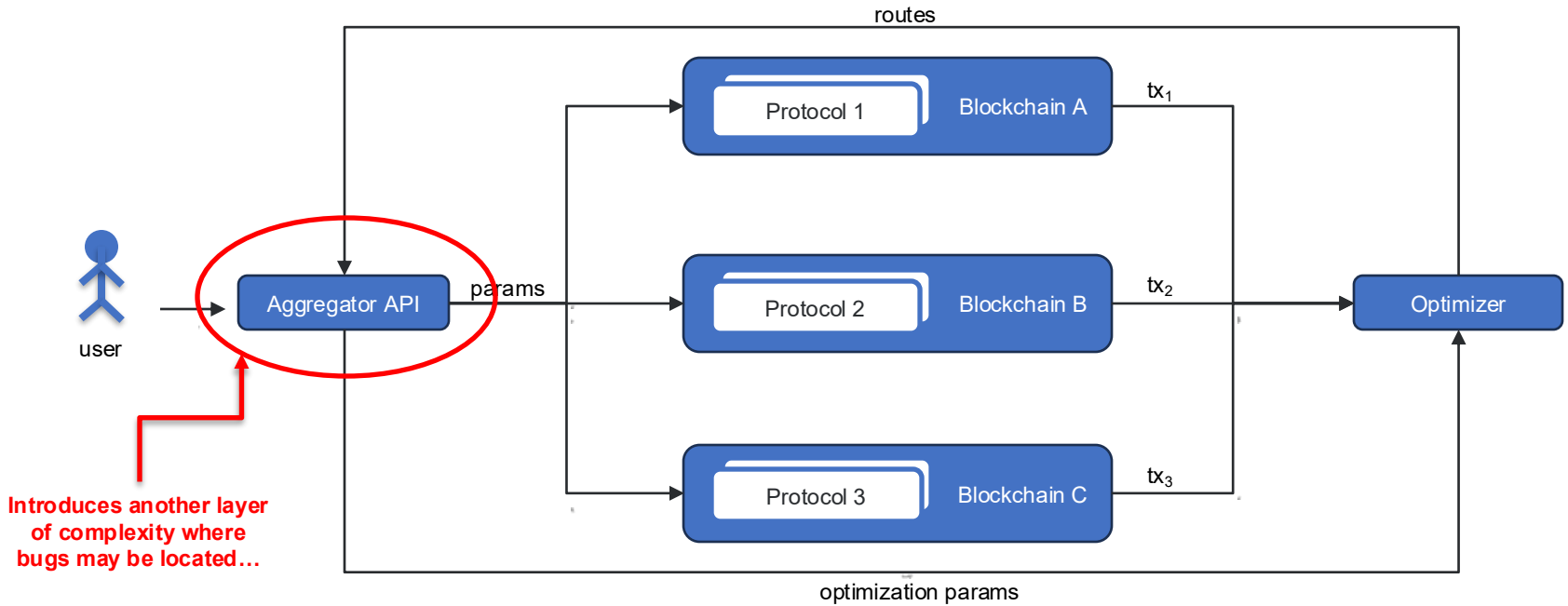



Subramanian, Shankar, et al. "Benchmarking blockchain bridge aggregators." *2024 IEEE International Conference on Blockchain (Blockchain)*. IEEE, 2024.

# Bridge Aggregators (Example)



# Bridge Aggregators

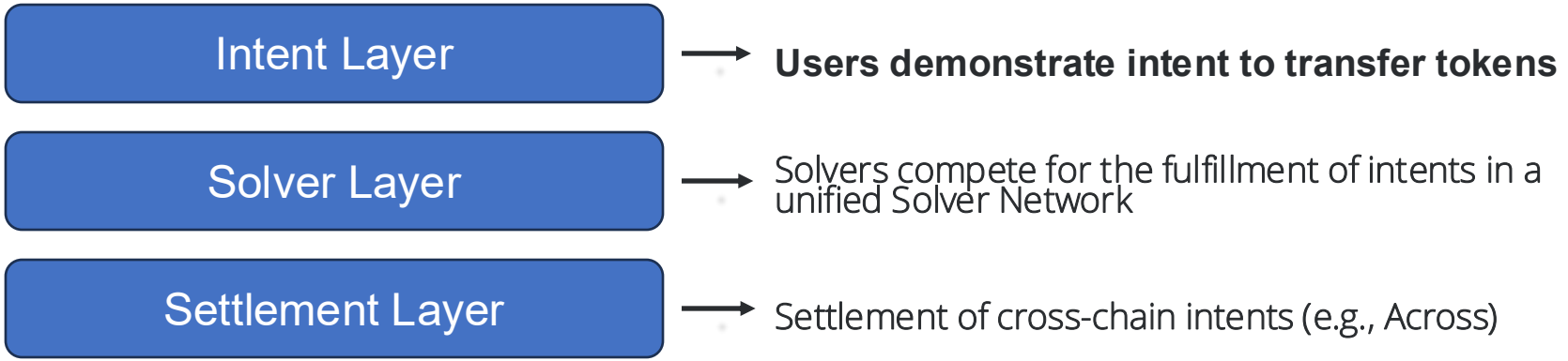



Subramanian, Shankar, et al. "Benchmarking blockchain bridge aggregators." *2024 IEEE International Conference on Blockchain (Blockchain)*. IEEE, 2024.

# ERC-7683 Cross-Chain Intents

**Focus on user experience**, fulfilling immediately users' orders

Shift risk to a 'Network of Solvers'



# Current Interoperability Challenges

**Weak monitoring** of
cross-chain solutions

**Layer 2s are**
majorly **centralized**

Sometimes **large time windows** to
withdraw funds (e.g., 7 days)

**Awful user experience** when
interacting **with cross-chain protocols**

# Standardization Efforts


**EEA Distributed Ledger Technology Interoperability Specification Version 1.0**

EEA Publication 19 September 2024

ENTERPRISE ETHEREUM ALLIANCE

**This Version:**

https://entethalliance.org/specs/dlt-interop/v1/

# Understudied Interoperability Layers


https://interoperable-europe.ec.europa.eu/collection/nifo-national-interoperability-framework-observatory/solution/eif-toolbox/6-interoperability-layers

# Materials for further studying

Hyperledger Cacti workshop (3h) - https://www.youtube.com/watch?v=TM-dnP2yzRM&t=4410s

DLT Interoperation: Implementing IETF Secure Asset Transfer Protocol in Hyperledger Cacti: https://www.youtube.com/watch?v=hmkK2lxhhFw

R. Belchior et al., “A Brief History of Blockchain Interoperability” Communications of the ACM (CACM), 2024 - https://dl.acm.org/doi/pdf/10.1145/3648607

M. Hargreaves et al., “Secure Asset Transfer Protocol (SATP)”, Internet Engineering Task Force Internet Draft draft-ietf-satp-core-04, May 2024 - IETF draft

# References


Belchior, R., Riley, L., Hardjono, T., Vasconcelos, A., & Correia, M. (2023). Do you need a distributed ledger technology interoperability solution?. *Distributed Ledger Technologies: Research and Practice*, *2*(1), 1-37.

Belchior, R., Vasconcelos, A., Correia, M., & Hardjono, T. (2022). Hermes: Fault-tolerant middleware for blockchain interoperability. Future Generation Computer Systems, 129, 236-251.

Belchior, R., Dimov, D., Karadjov, Z., Pfannschmidt, J., Vasconcelos, A., & Correia, M. (2023). Harmonia: Securing cross-chain applications using zero-knowledge proofs. Authorea Preprints.

Belchior, R., Somogyvari, P., Pfannschmidt, J., Vasconcelos, A., & Correia, M. (2023). Hephaestus: Modeling, analysis, and performance evaluation of cross-chain transactions. *IEEE Transactions on Reliability*.

Belchior, R., Vasconcelos, A., Guerreiro, S., & Correia, M. (2021). A survey on blockchain interoperability: Past, present, and future trends. Acm Computing Surveys (CSUR), 54(8), 1-41.

Augusto, A., Belchior, R., Correia, M., Vasconcelos, A., Zhang, L., & Hardjono, T. (2024, May). Sok: Security and privacy of blockchain interoperability. In *2024 IEEE Symposium on Security and Privacy (SP)* (pp. 3840-3865). IEEE.

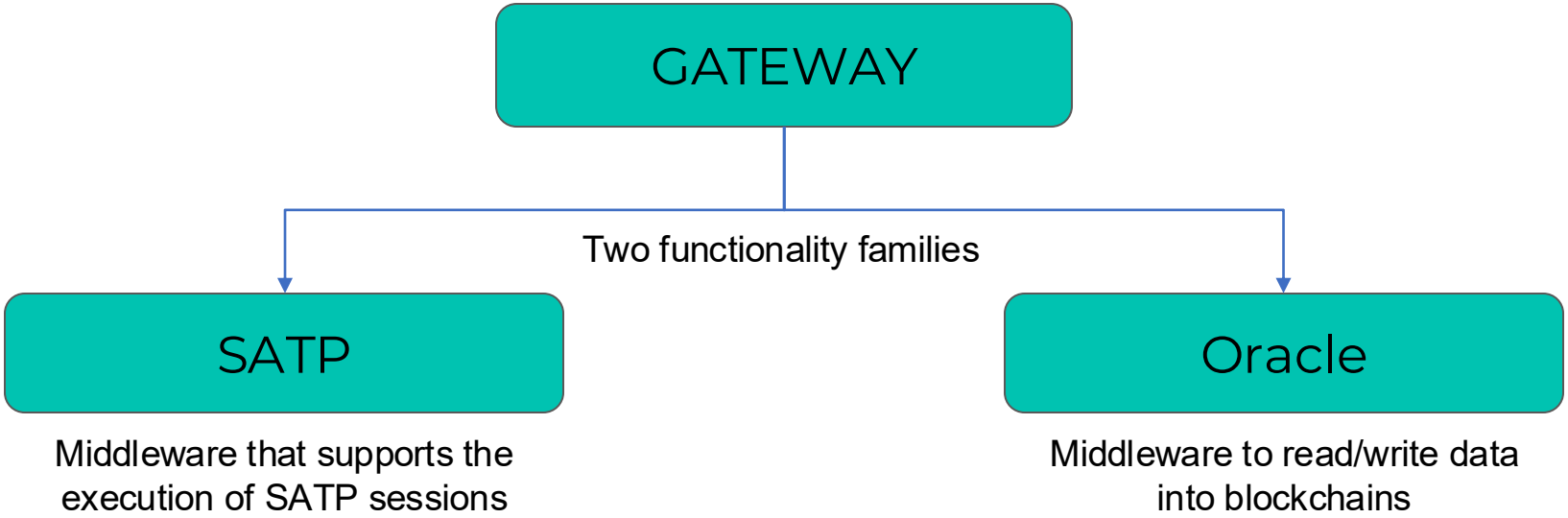
Augusto, A., Belchior, R., Pfannschmidt, J., Vasconcelos, A., & Correia, M. (2024). XChainWatcher: Monitoring and Identifying Attacks in Cross-Chain Bridges. *arXiv preprint arXiv:2410.02029*.

Subramanian, S., Augusto, A., Belchior, R., Vasconcelos, A., & Correia, M. (2024, August). Benchmarking blockchain bridge aggregators. In 2024 IEEE International Conference on Blockchain (Blockchain) (pp. 37-45). IEEE.

# Part 2: Practice

# We will use…

Docker image: **aaugusto11/cacti-satp-hermes-gateway:215ad342b-2025-05-29**




Implementation in: https://github.com/hyperledger-cacti/cacti/tree/4a9e5dab04ca59367208bdab33a42cf5671547da

# The Secure Asset Transfer Protocol (SATP)


HYPERLEDGER

BLOCKDAEMON

IETF®


MIT Connection Science

the technology of innovation



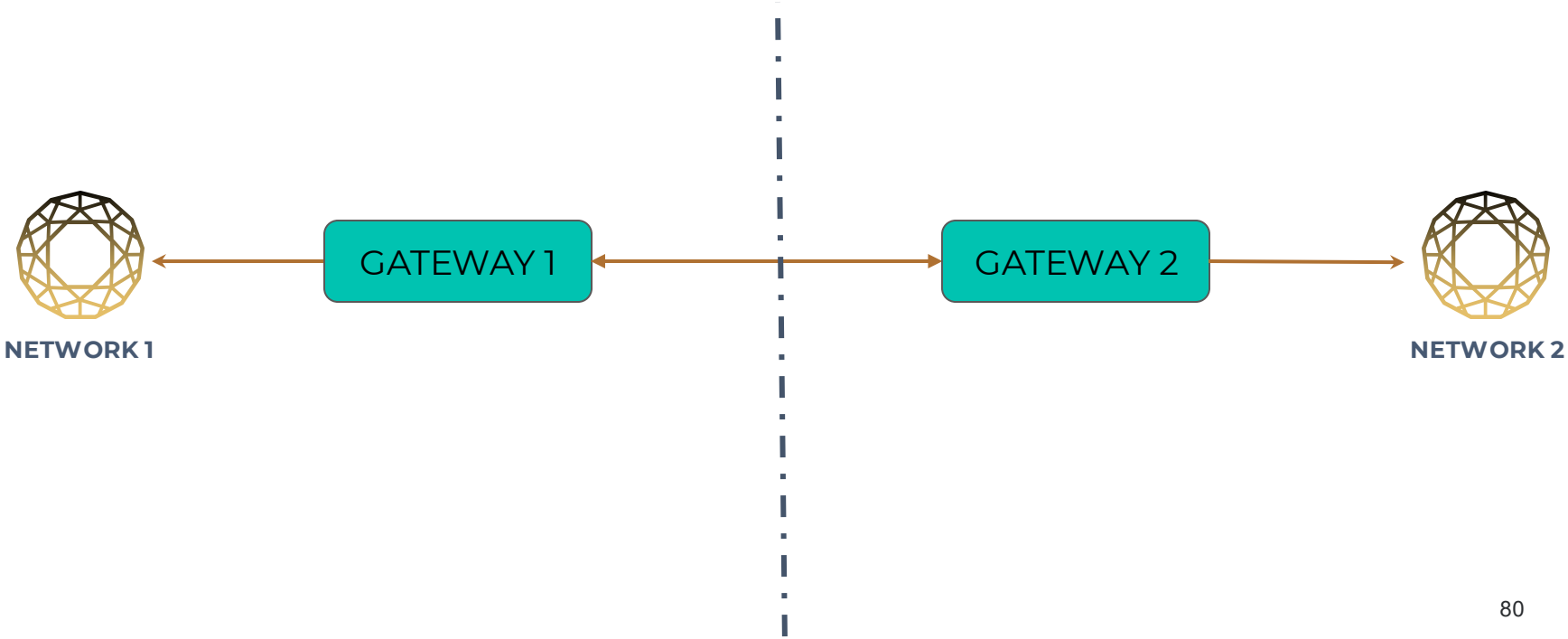
https://datatracker.ietf.org/doc/draft-ietf-satp-core/

# Example: The Secure Asset Transfer Protocol (SATP)

NETWORK 1

NETWORK 2

# Example: The Secure Asset Transfer Protocol (SATP)



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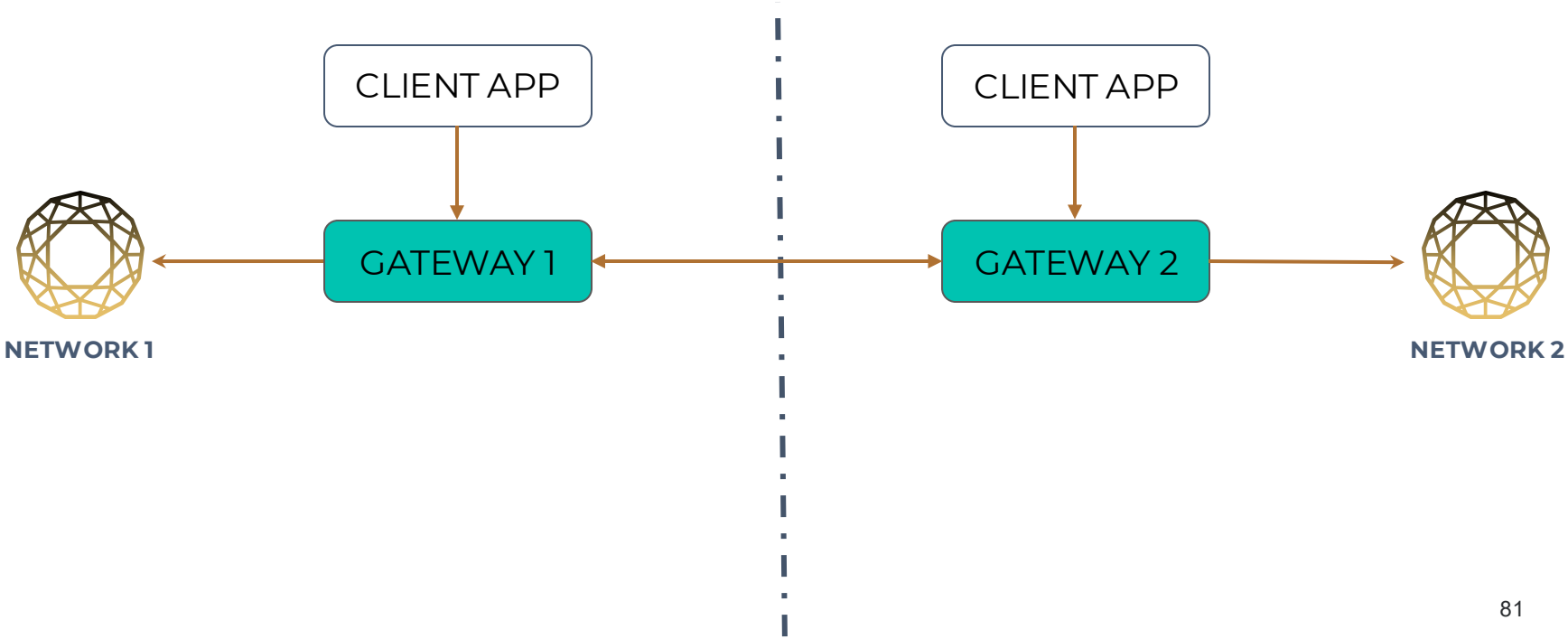

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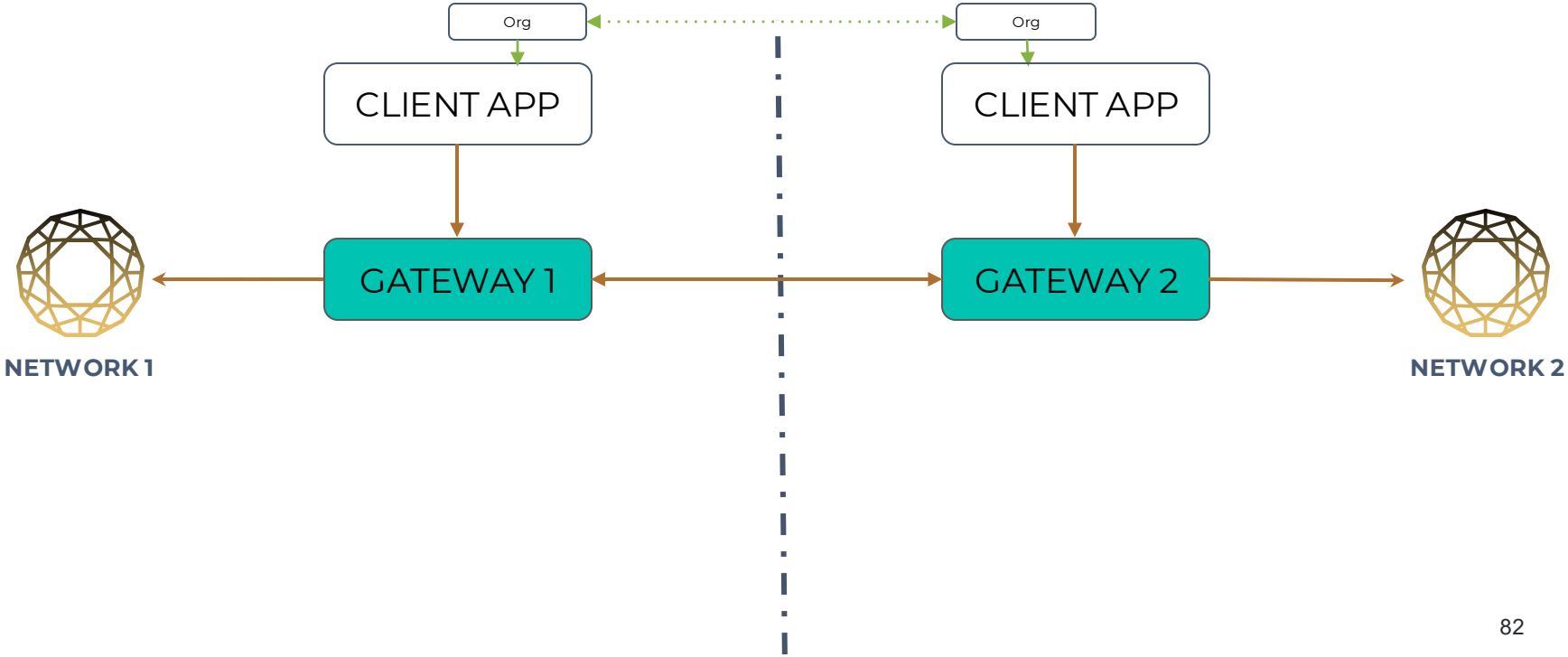

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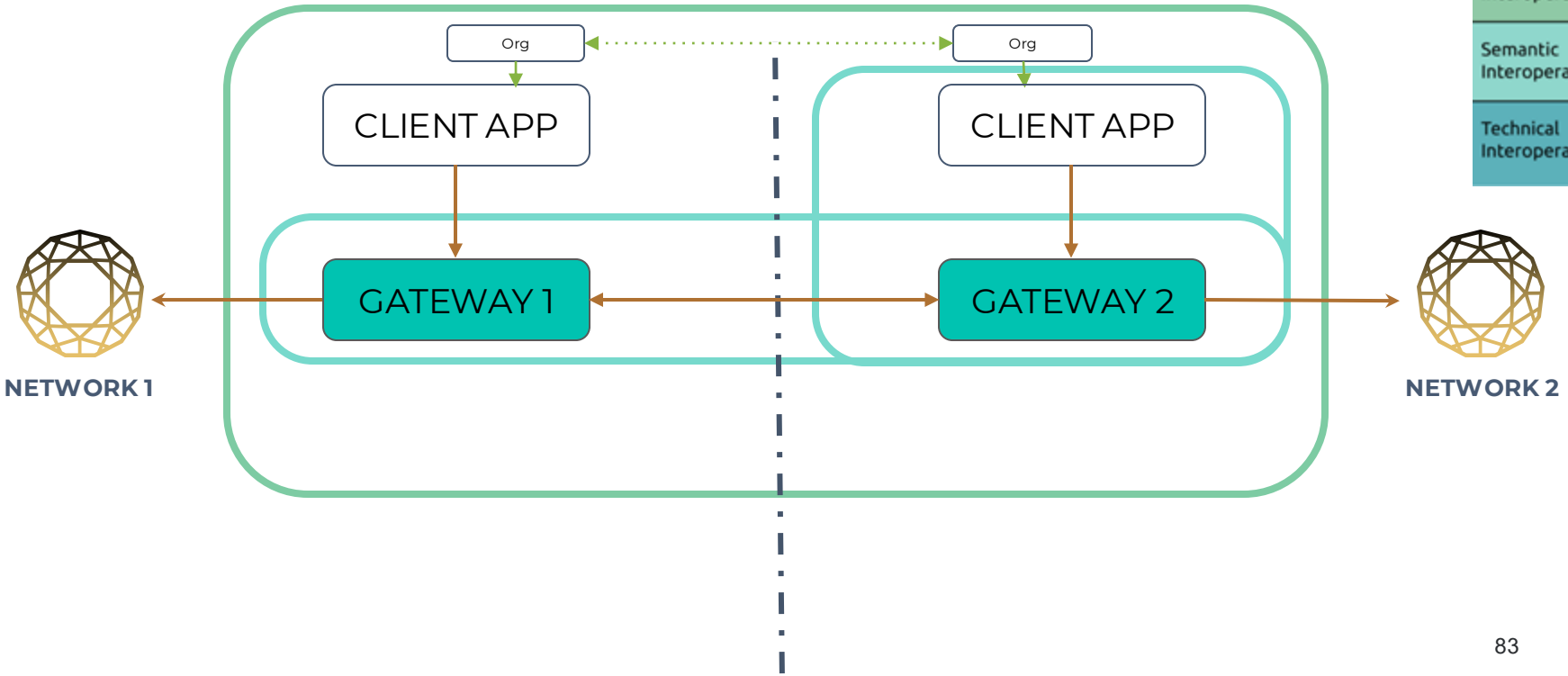


Legal Interoperability

Organizational Interoperability

Semantic Interoperability

Technical Interoperability

# Secure Asset Transfer Protocol (SATP)

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# Secure Asset Transfer Protocol (SATP)

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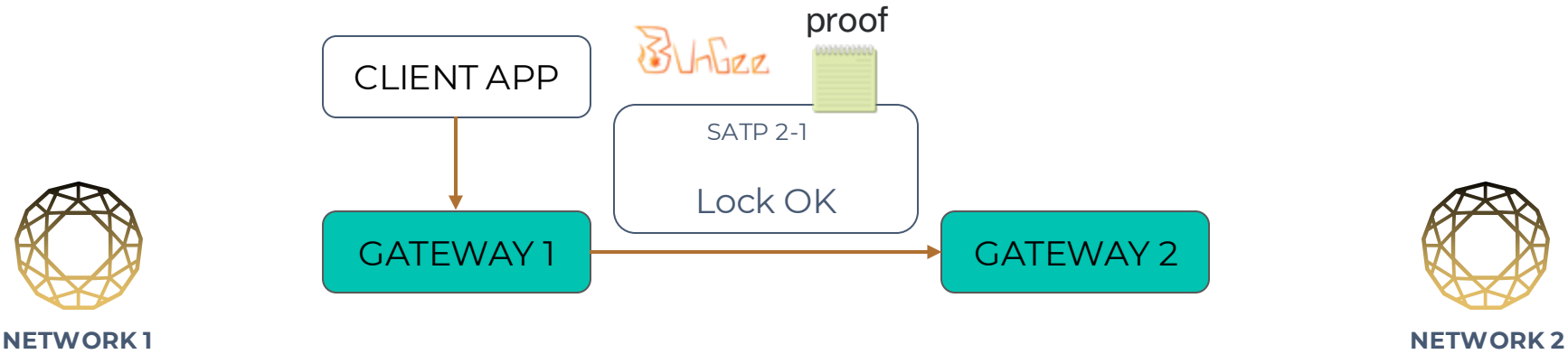


**Proving Systems:**

SNARK-based
Merkle Proofs
...

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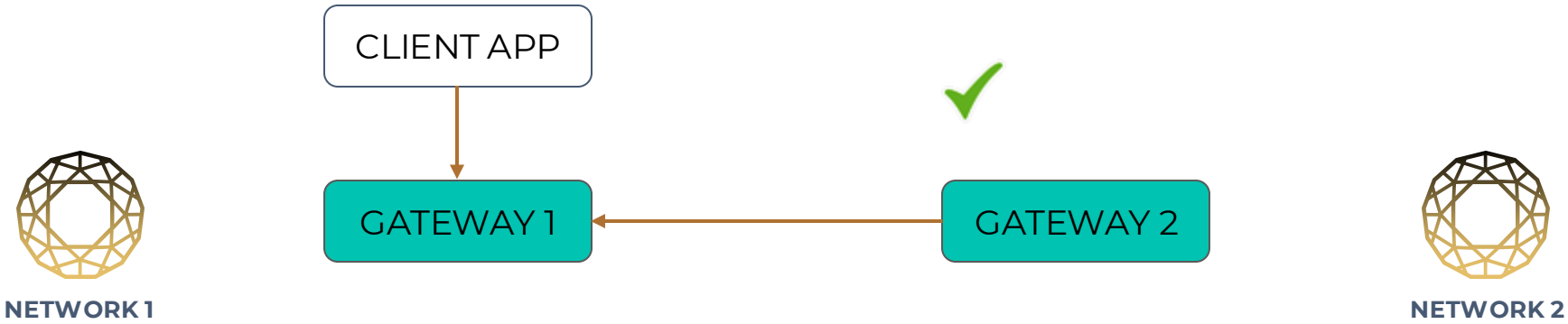

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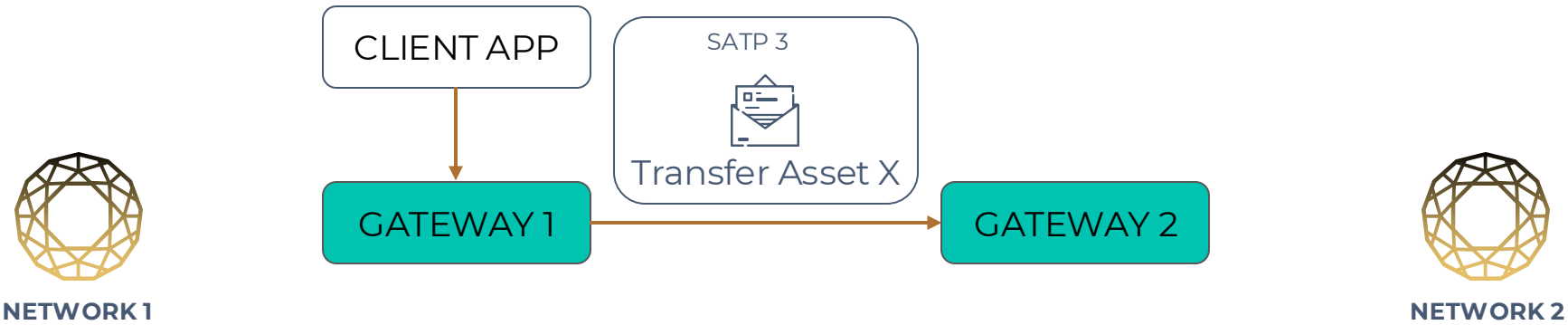

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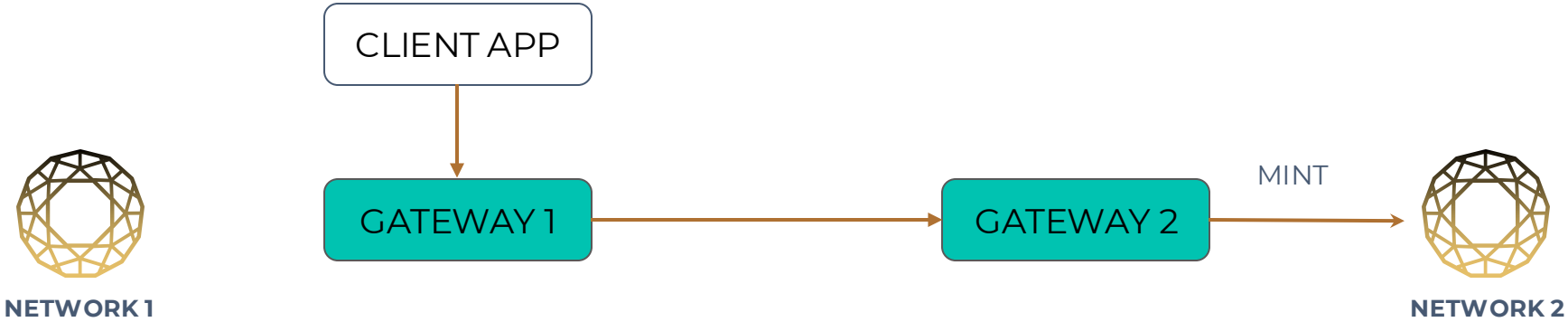

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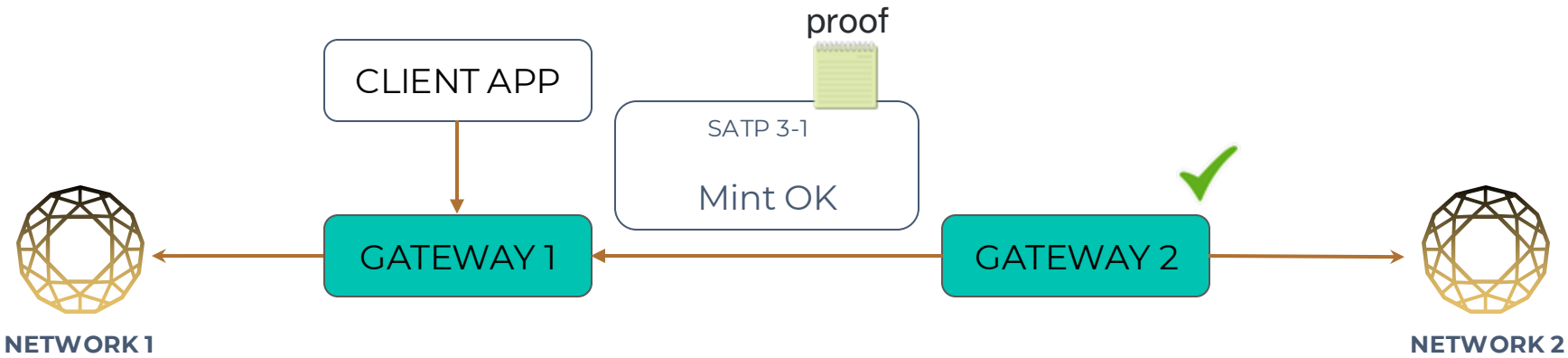


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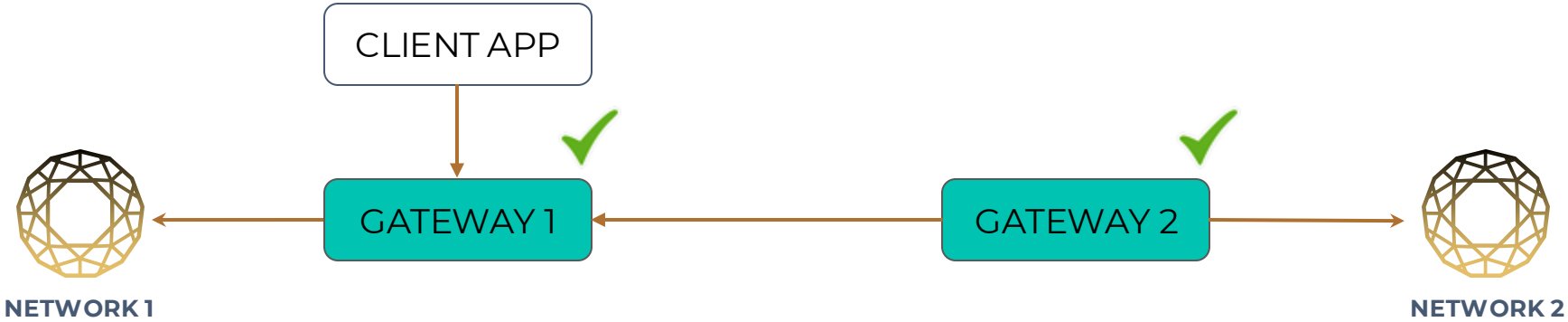
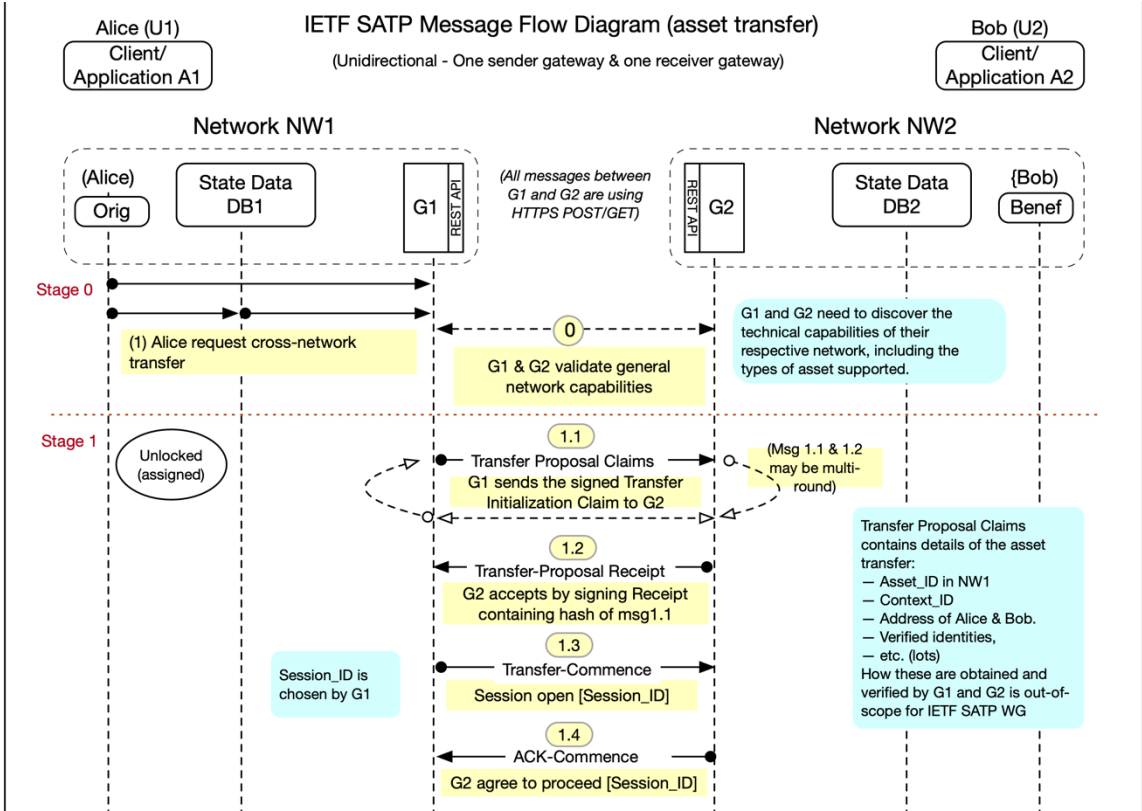
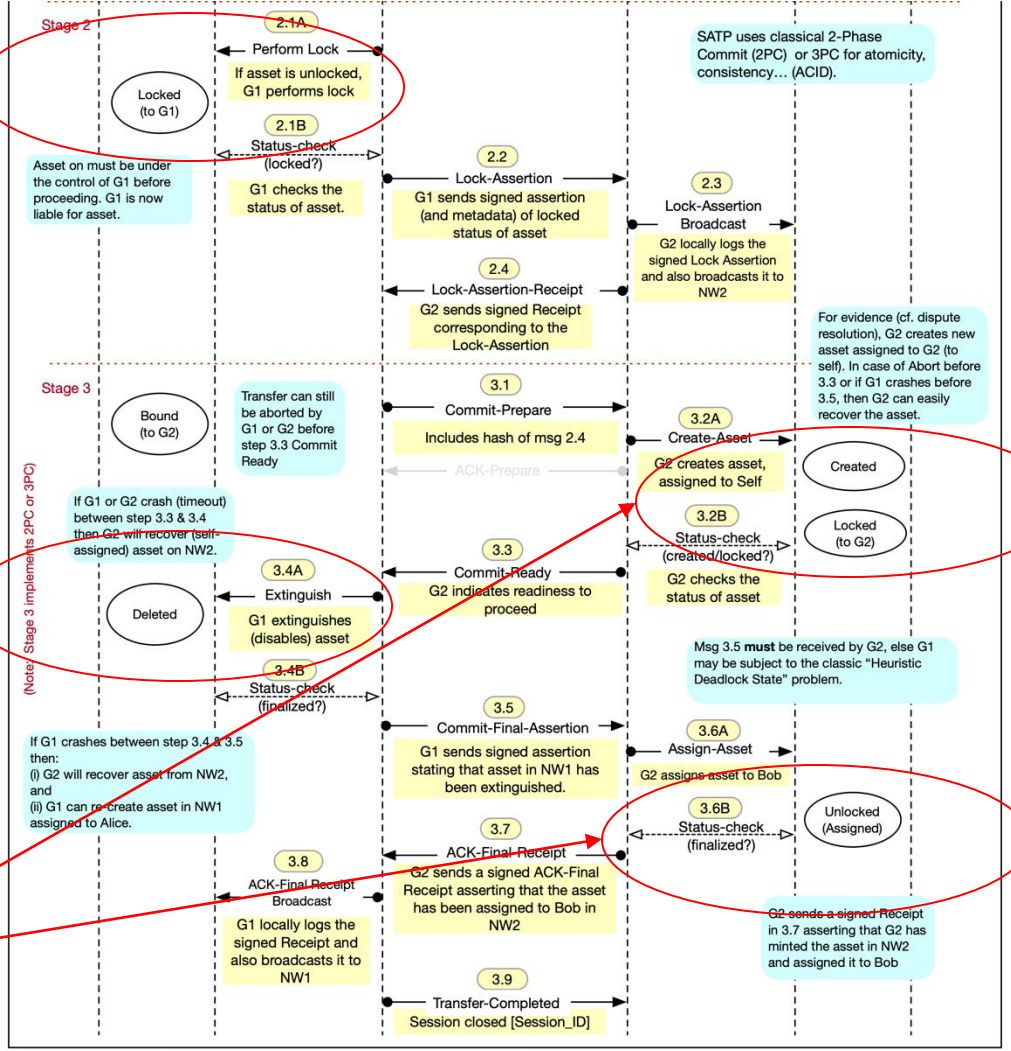


# Sequence Diagram (1/2)




https://github.com/ietf-satp/figures/blob/main/gateway-message-flow-asset-transfer-v19PNG.png

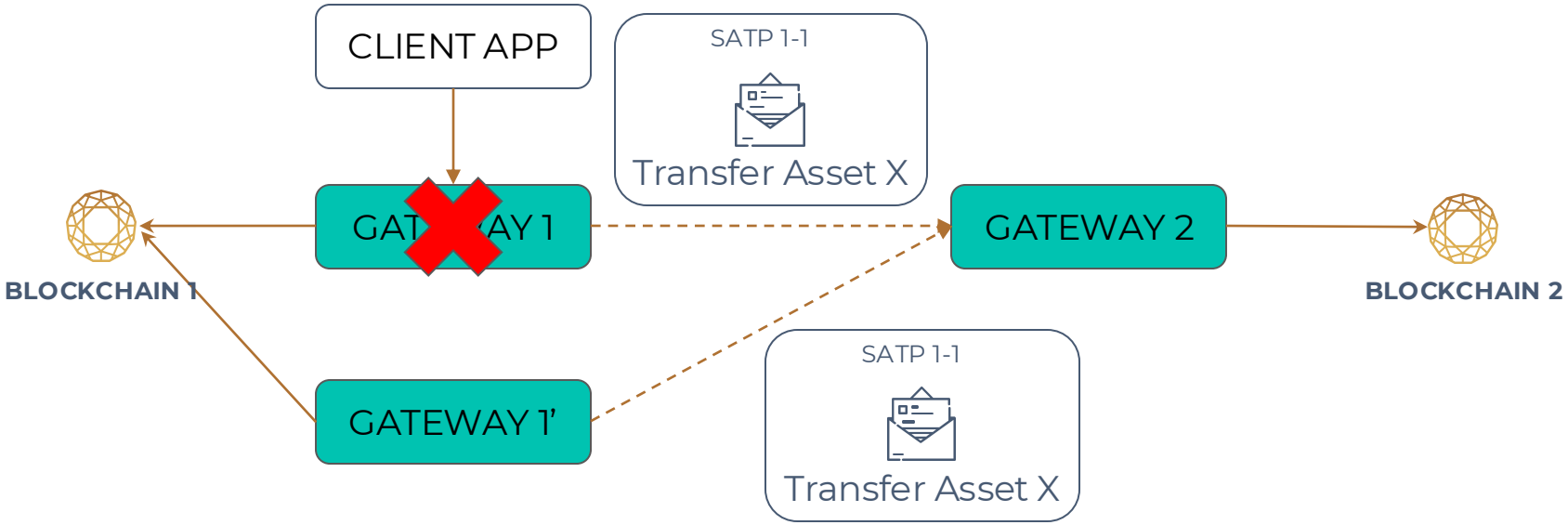
# Sequence Diagram (2/2)




Critical Operations

https://github.com/ietf-satp/figures/blob/main/gateway-message-flow-asset-transfer-v19PNG.png

# Crash Recovery Protocol




https://datatracker.ietf.org/doc/draft-belchior-satp-gateway-recovery/

# Gateway Configuration File (1/2)

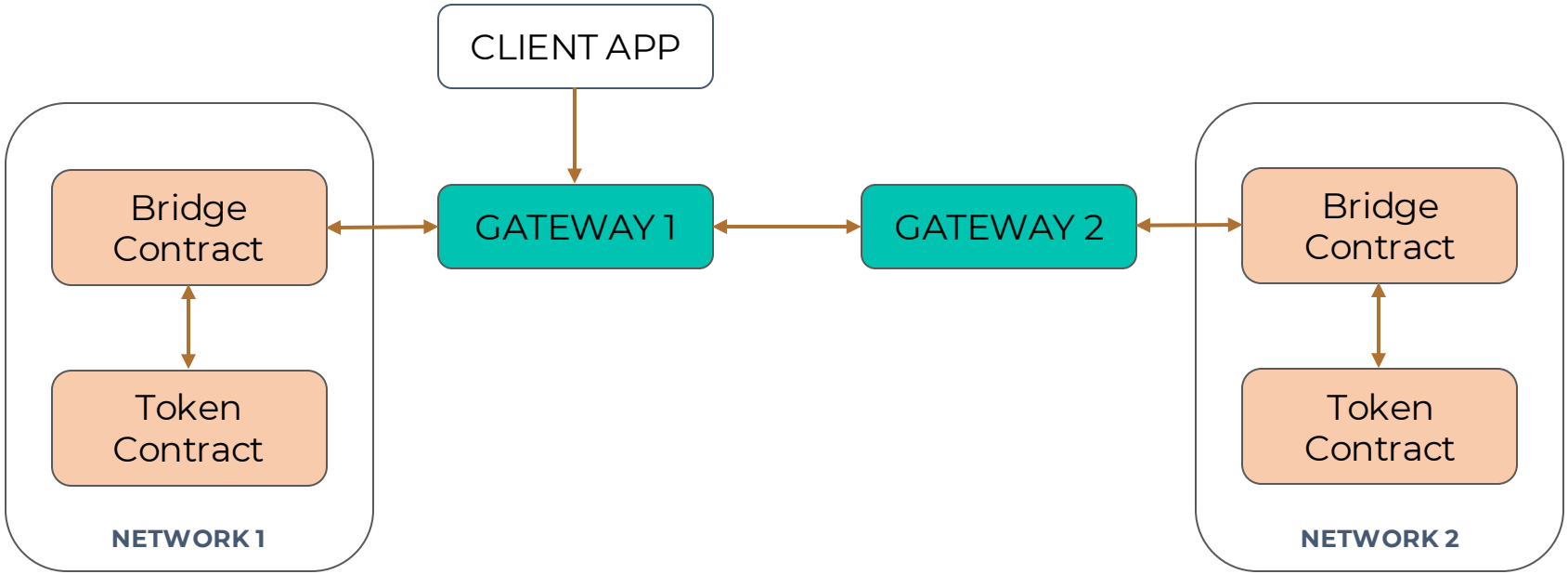
```
{
  // configuration for the gateway to be created
  "gid": {
    <GATEWAY_CONFIG>
  },
  "logLevel": "TRACE",
  "counterPartyGateways": [
    // configuration for other existing gateways, such that they can communicate with one another
    <COUNTERPARTY_GATEWAY_1_CONFIG>,
    <COUNTERPARTY_GATEWAY_2_CONFIG>,
    ...
  ],
  "localRepository": {
    // configuration for the local database used to store logs from the execution of SATP
    <DB_CONNECTION_1>,
    }
  },
  "remoteRepository": {
    // configuration for the remote database used to store logs from the execution of SATP
    <DB_CONNECTION_2>,
  },

  ...
```

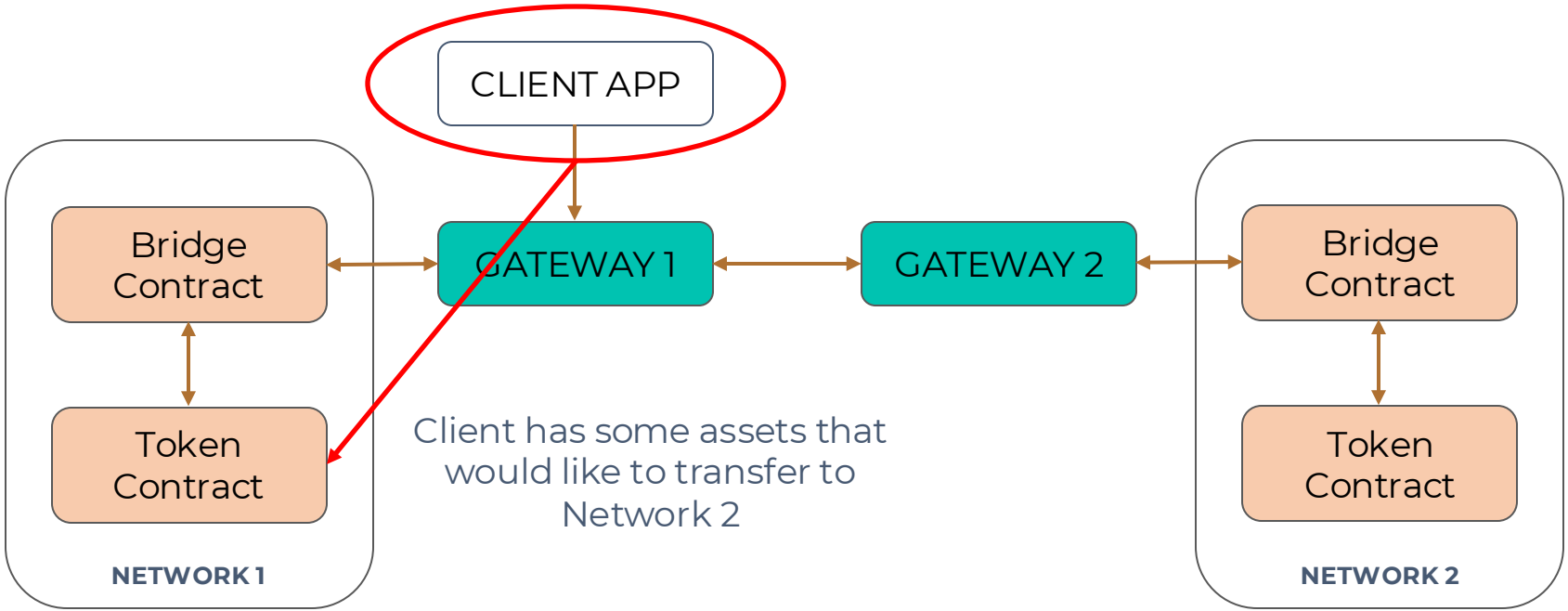
# Gateway Configuration File (2/2)

```
...
  "ccConfig": {
    "bridgeConfig": [
      // configuration for the usage of SATP related endpoints
      <NETWORK_CONFIG_1>,
      <NETWORK_CONFIG_2>,
      ...
    ],
    "oracleConfig": [
      // configuration for the usage of Oracle related endpoints
      <NETWORK_CONFIG_1>,
      <NETWORK_CONFIG_2>,
      ...
    ]
  },
  "environment": "development",
  "enableCrashRecovery": false,
  "ontologyPath": "/opt/cacti/satp-hermes/ontologies"
}
```

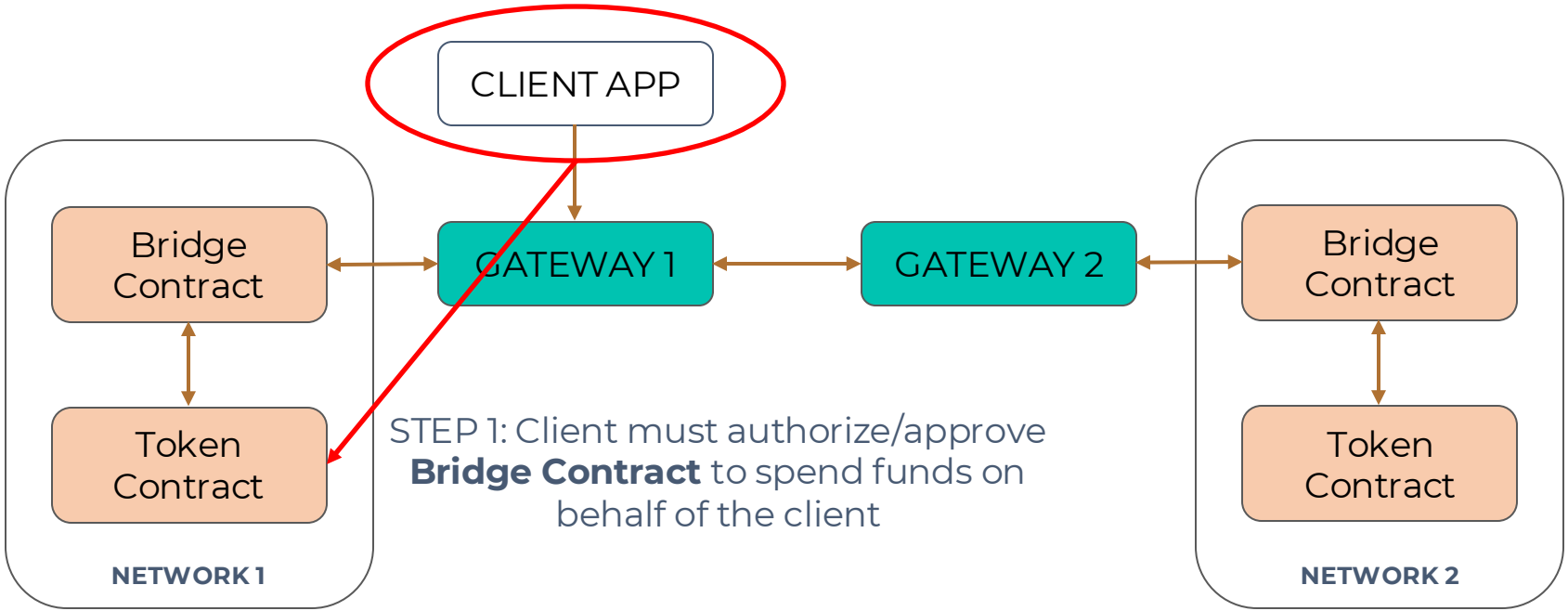
# On-Chain Implementation



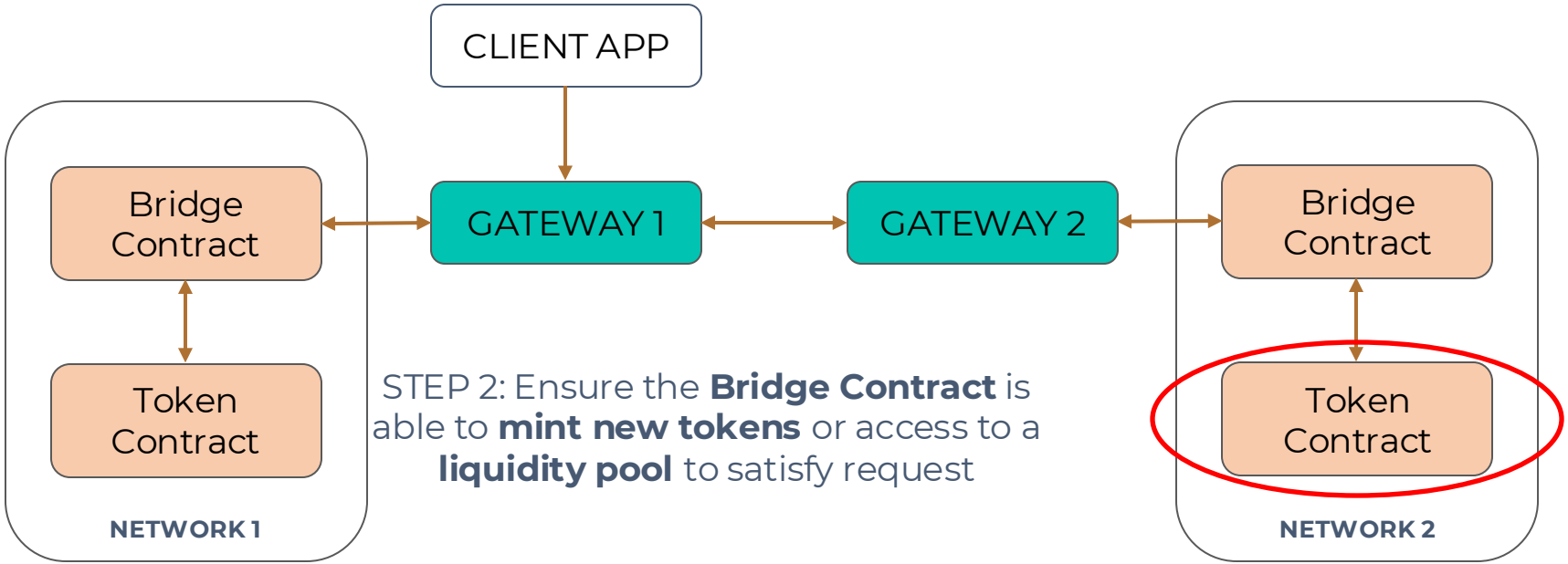
# Protocol Requirements



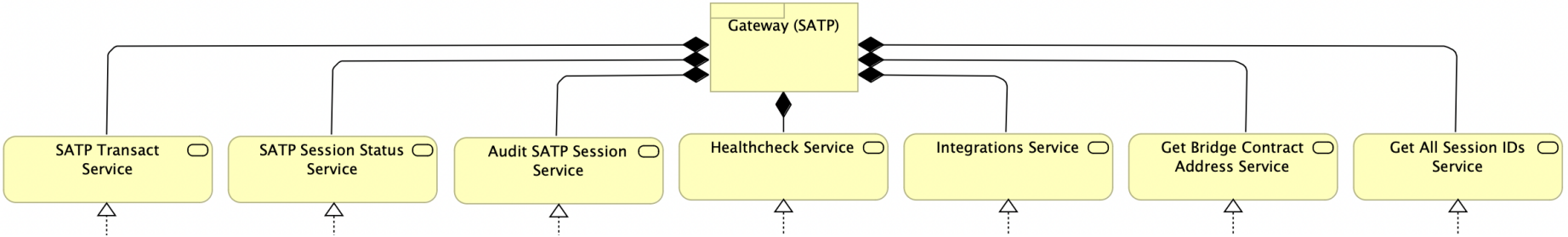
# Protocol Requirements (Step 1)



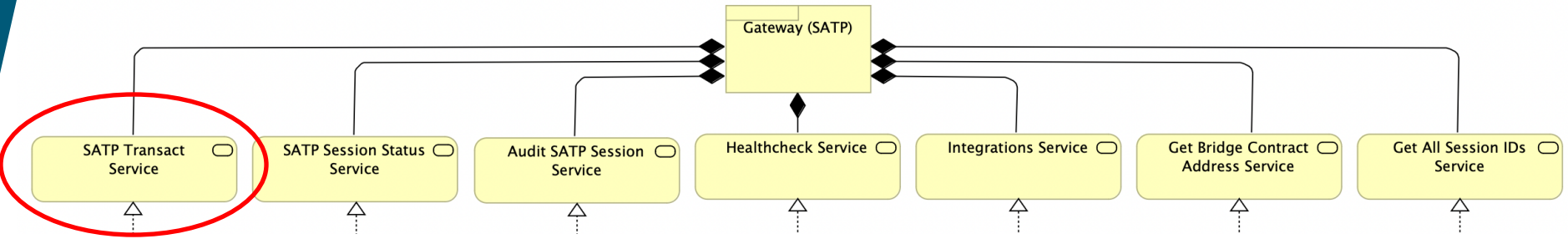
# Protocol Requirements (Step 2)



...so, what are exactly the services offered by the gateway?

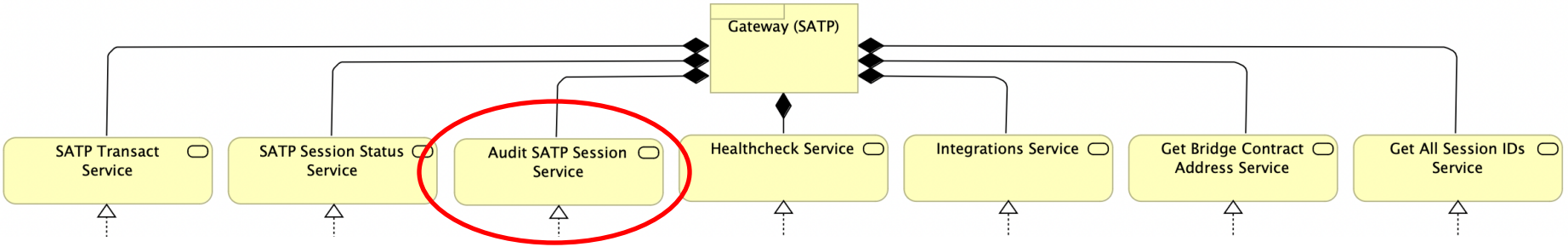


# SATP-Related Functionalities/Services



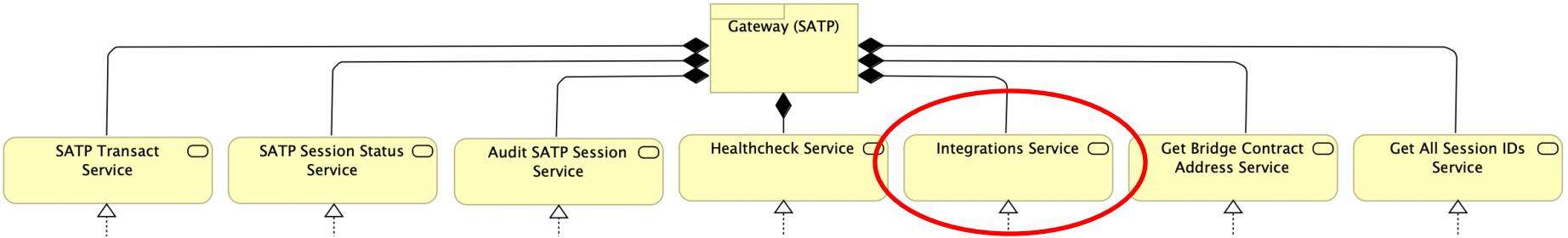

Executes SATP based on the source and destination networks, and source and destination tokens

# SATP-Related Functionalities/Services



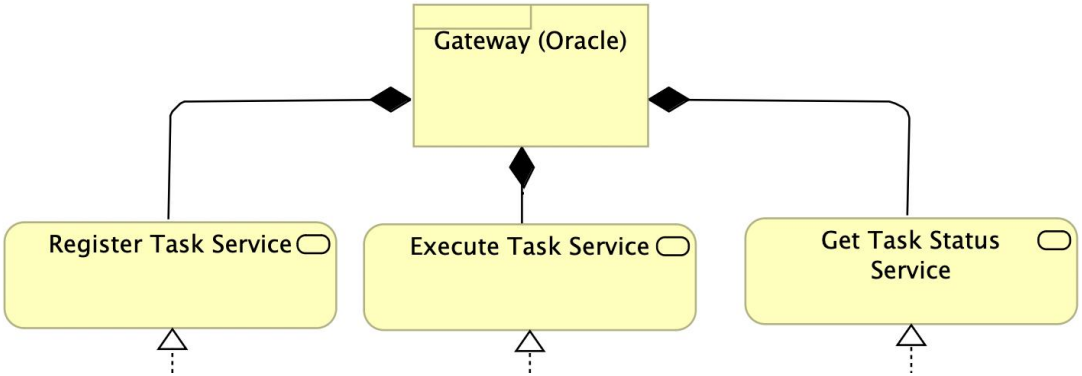

Retrieves all data from all sessions executed in the selected interval

# SATP-Related Functionalities/Services

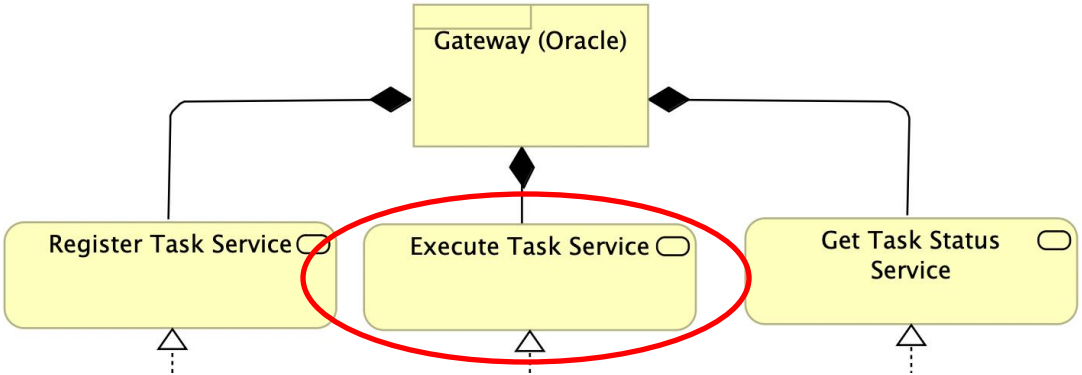



Retrieves all networks to which the gateway instantiated is connected to

# Oracle-Related Functionalities/Services

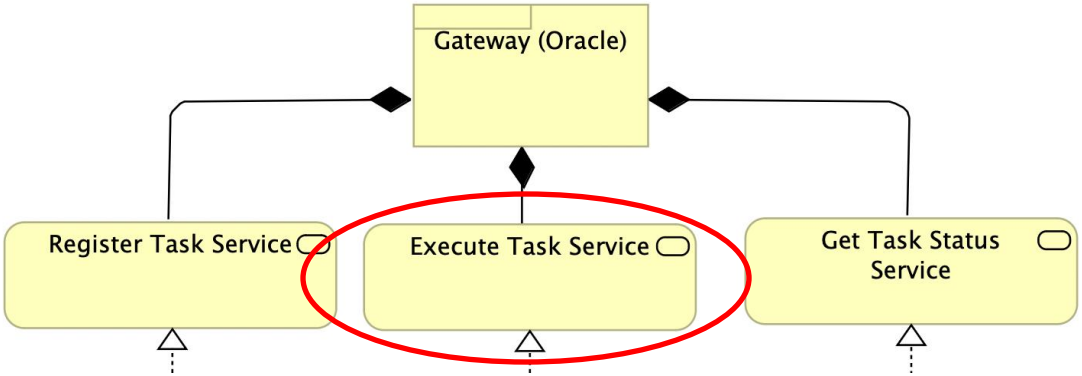


# Oracle-Related Functionalities/Services



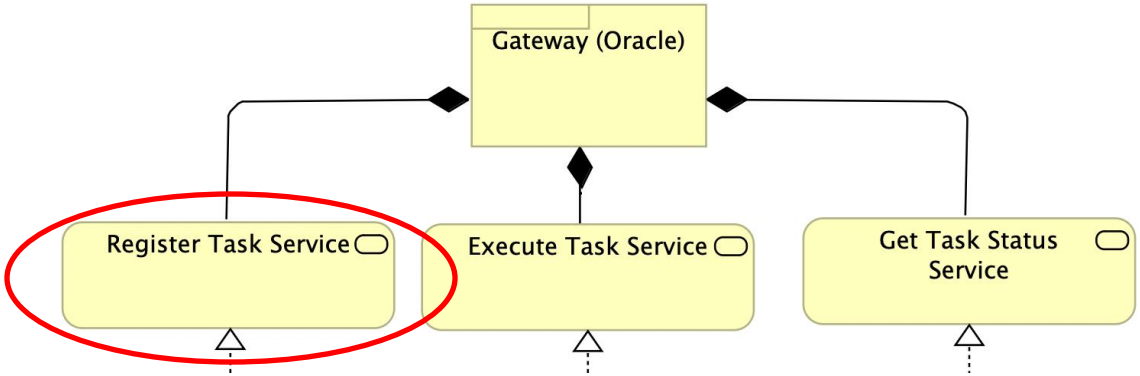

Executes READ, UPDATE, or/and READ_AND_UPDATE tasks in one or more smart contracts

# Oracle-Related Functionalities/Services



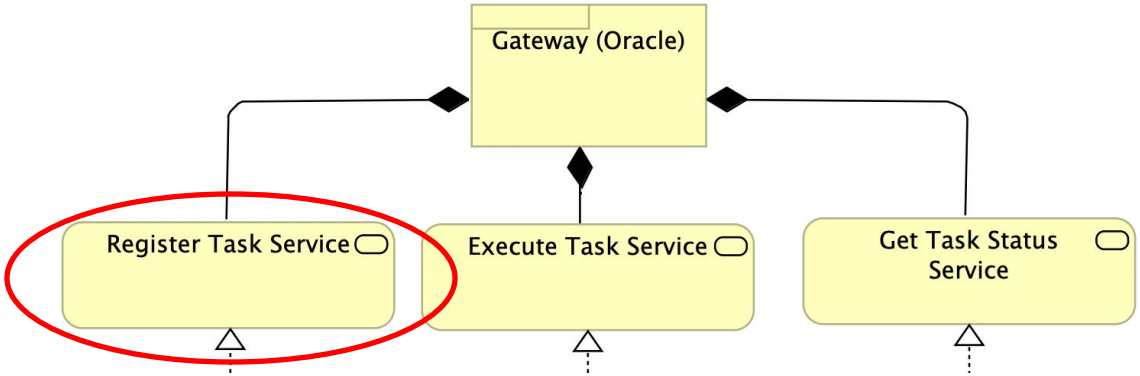

READ_AND_UPDATE tasks allow for reading data from one blockchain and writing in the other automatically – i.e., the gateway manages the whole process

# Oracle-Related Functionalities/Services



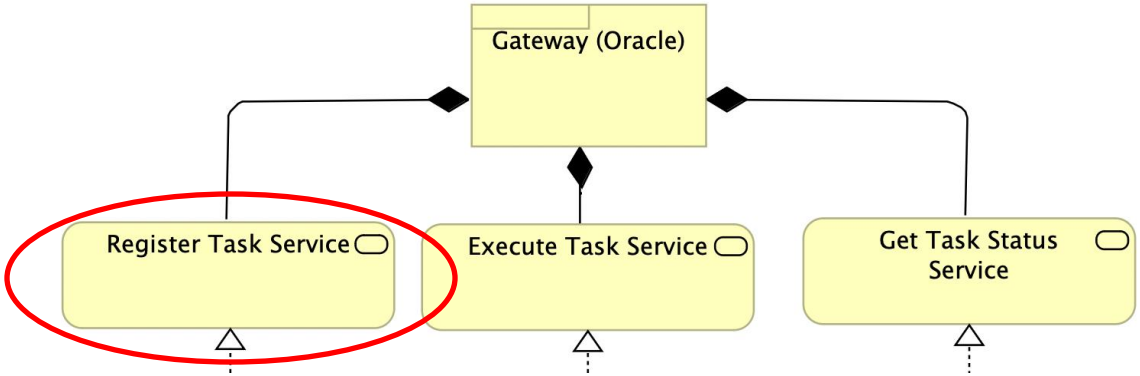

Allows registering a periodic task that is executed when some condition is met. Currently, we have POLLING and EVENT_LISTENING modes.

# Oracle-Related Functionalities/Services




POLLING: The task is executed every *pollingInterval* seconds

# Oracle-Related Functionalities/Services




EVENT_LISTENING: The task is executed whenever an event with *eventSignature* is emitted in a contract

# SATP Experiment (Case 1)

1. Set up two Ethereum test networks
2. Create a configuration file for each gateway
3. Spin up both gateways (that will deploy automatically the **Bridge Contracts**
4. Deploy **Token Contracts** on both networks and mint some tokens to the user
5. Issue a transaction from the user to the **Token Contract** authorizing (*approve*) the **Bridge Contract** on the source blockchain to spend the amount to be transferred on behalf of the user
6. Create a request from the **Client Application** to one of the gateways, triggering the cross-chain transaction. The protocol will be executed!!

# Oracle Experiment (Case 4)

1. Set up two Ethereum test networks
2. Create a configuration file for each gateway
3. Spin up both blockchains
4. Deploy the **Oracle Contract** on both networks
5. Register a task that sets up a listener for a certain event signature on the contract on the source network, and writes the “data” parameter to the destination network.
6. Create a request from the **Client Application** to the gateway, writing data to the source blockchain, which causes the event listener to trigger the write on the destination blockchain.

# Try it ourselves

# The Problem: Connecting to Web3 is...

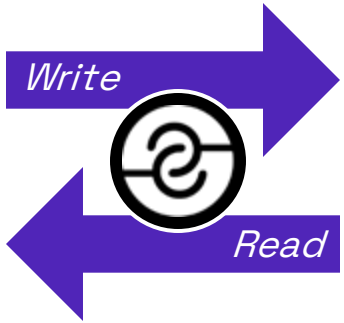
Immense | Fragmented | Constant-Change | Complex | Resource-Intensive | Not Scalable

# The Solution: expand.network | By BLOCKDAEMON

## All Digital Asset Users

Traders | Funds | Wallets

DApps | Analysts | Service Providers




One unified API

## 170+ Endpoints

| | | | |
|---|---|---|---|
| Chains | DEXs | Lending Protocols | RWAs |
| On-Chain Data | DEX Aggregators | Yield Aggregators | Stablecoins |
| Oracles | Fungible Tokens | NFTs | Staking |
| Bridges | Perpetuals | Synthetics | Algos |

# Chain & Protocol Integrations - All of Web3 & DeFi in ONE unified API

## Chains

Ethereum, Binance, Bitcoin, Fantom, Solana, Avalanche, XRP

Algorand, Tron, NEAR, Aptos, Solana, Ton, Cosmos

Stellar, ZKsync, Cronos, Osmosis, Mantle, Kaspa

**L2s**: Arbitrum, Base, Optimism, Starknet, Polygon, Stacks

## DEXs & Aggregators

Uniswap, Sushiswap, Curve, Balancer, Ston.fi, Sologenic, Pancake Swap (v2 v3)

Trader Joe, Ref Finance, sdex, Camelot, Liquidswap, Raydium, Orca

ALEX, Cetus, Osmosis, Mantle, Aerodrome

**L2s**: 0x, Linch, Kyberswap, Jupiter

## Lending Protocols & Yield Aggregators

Aave (v2 v3), Harvest Finance, Yearn Finance

Compound (v2 v3), Pendle, Morpho

## Bridges & Intents

Stargate Finance (v2 v3), Squid Router, Across, Uniswapx, Rango, Wormhole

Allbridge Classic/Core, Linch Fusion+, Bungee, Everclear, Symbiosis

## Oracles

Wink Link, Chainlink

Pyth, RedStone

## Staking & Restaking

Lido, Benqi, Jito

Tonstakers, EigenLayer

COMING SOON

# Appendix

# Interoperability can take multiple forms

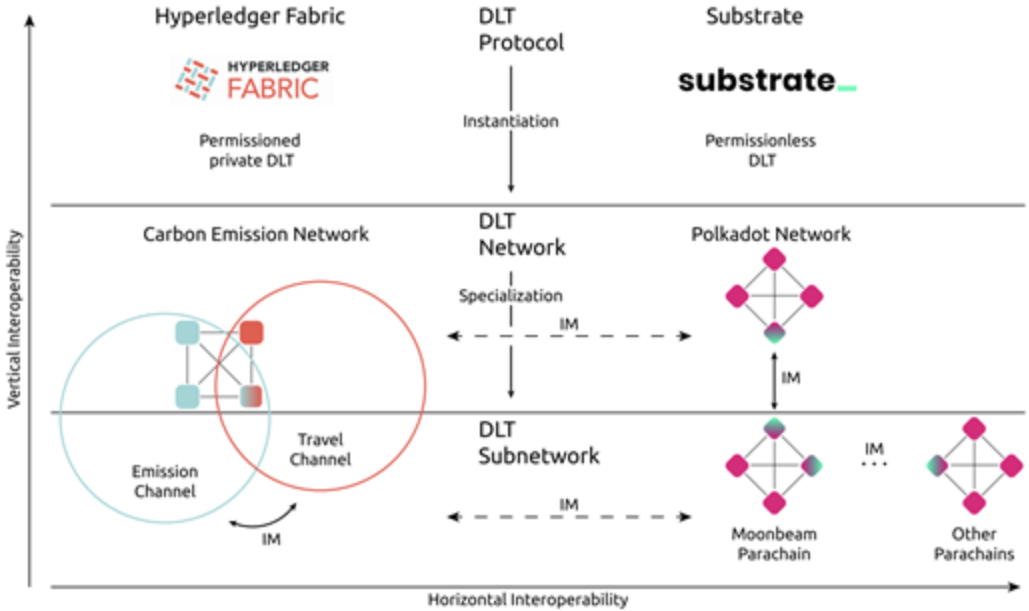
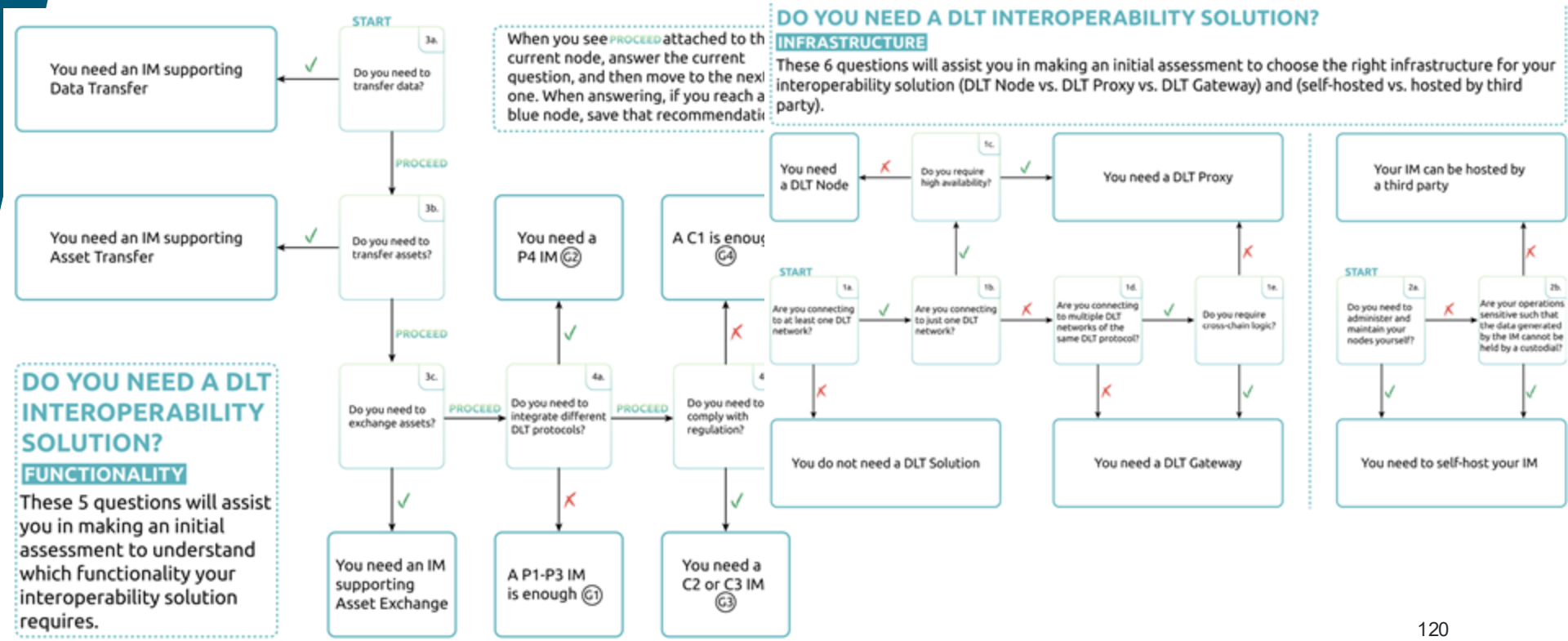



Fig. 2. DLT protocols, networks, and subnetworks.

Rafael Belchior, Luke Riley, Thomas Hardjono, André Vasconcelos, and Miguel Correia. 2023. Do You Need a Distributed Ledger Technology Interoperability Solution? Distrib. Ledger Technol. 2, 1, Article 1 (March 2023), 37 pages. https://doi.org/10.1145/3564532

# Do you need an interoperability solution?



# Interoperability Assessment

Table 3. DLT Interoperability Solution Assessment

| **Potentiality Assessment (PA)** | **Score (0–4)** |
|---|---|
| P1: Interoperation within the same DLT network, same subnetworks | ☐ |
| P2: Interoperation within the same DLT network, different subnetworks | ☐ |
| P3: Interoperation within different DLT networks | ☐ |
| P4: Interoperation within different DLT protocols | ☐ |
| **Compatibility Assessment (CA)** | **Score (0–3)** |
| C1: Provides semantic-level interoperability (shared protocols) | ☐ |
| C2: Provides organization-level interoperability (shared agreements) | ☐ |
| C3: Provides legal-level interoperability (follow regulations) | ☐ |
| **Performance Assessment (PeA)** | **Score (0–3)** |
| PE1: Provides acceptable cross-chain transaction end-to-end latency/throughput | ☐ |
| PE2: Provides acceptable cross-chain transaction end-to-end cost | ☐ |
| PE3: Complies with desirable energetic consumption goals | ☐ |
| **PA + CA + PeA** | **Total (0–10):** |

Interoperability assessment is divided into PE, CA, and PeA assessments. A higher score corresponds to a more interoperable solution.

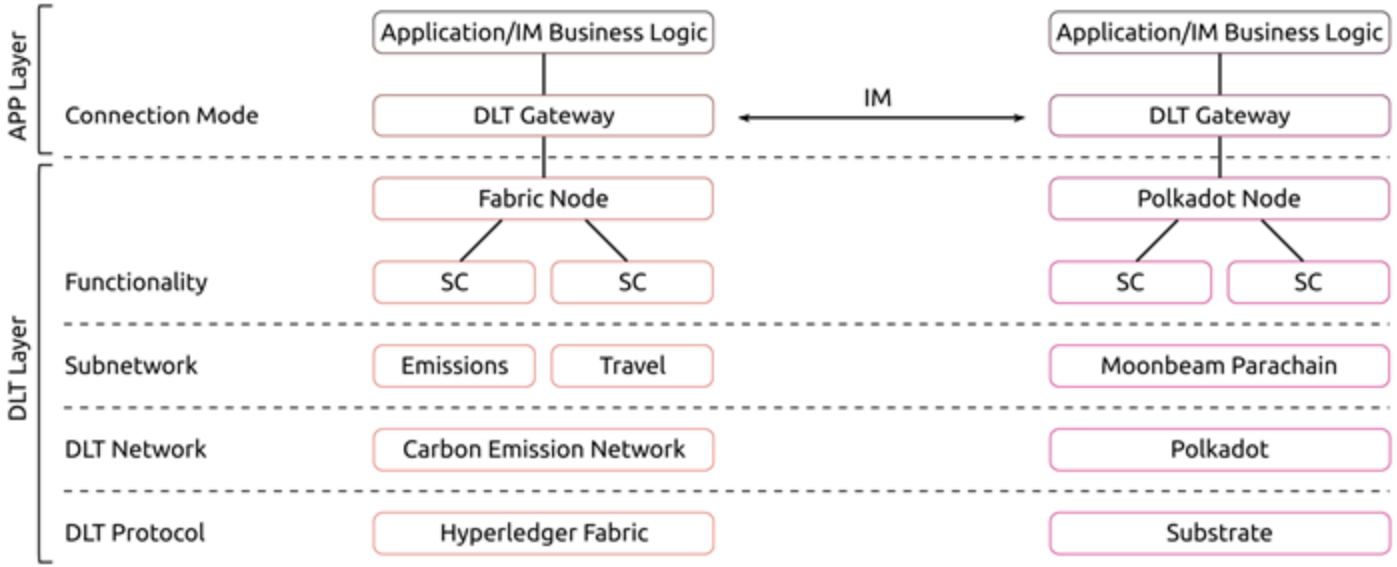



Fig. 12. Example of vertical interoperation in a Hyperledger Fabric network and the Polkadot network. Horizontal interoperability can be achieved via an IM using, for example, a DLT gateway.