How to Cross the Bridge: Interoperability among Blockchain Systems

Short Paper

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Abstract

Blockchain research tends to focus on technical improvements and their potential for efficiency and productivity, repeatedly at the cost of comprehending the complex reciprocal interaction between social and technical aspects. One of the technical challenges for blockchain systems is scalability. Interoperability has proven effective in addressing scalability by offloading transactions via bridges, enhancing flexibility and portability for, e.g., tokens. As a result, we investigate how interoperability is organized in blockchain systems and what implications it might bring. In this research, we develop an on-ledger analytics prototype, which facilitates the examinations of NFT bridges and theorizes about the dimensions of interoperability. Practical implications reveal that hiding a token's track in an otherwise supposedly transparent system is possible. We provide evidence that current research may only consider a subset of a token's history among blockchain systems. Ultimately, we claim that interoperability among blockchain systems can lead to decreased transparency.

Keywords: Blockchain, Interoperability, Transparency, Tokens, Information Systems

Introduction

The ongoing digital transformation made technology an integral part of all areas of public and private life. Technology is no longer just an add-on that organizations use to gain competitive advantages but is an endogenous part of economic and societal processes of how we work and deal with each other (Vial 2019). Many organizations are looking at blockchain technologies as they enable new ways of interacting and collaborating. Blockchain is a transaction-based append-only database distributed in a peer-to-peer network (Beck et al. 2017). Blockchain systems are, in nature, dispersed (decentralized) networks operated by several peers. As peers in the network can verify the code and data, everyone can agree and contribute to forming a consensus. Once executable code is deployed to the blockchain network, often referred to as protocols (Szabo 1997) or smart contracts (Buterin 2014), it can execute autonomously when predefined conditions are met.

Research on blockchain has shifted toward a focus on technical improvements and their potential for efficiency and productivity, repeatedly at the cost of comprehending the complex reciprocal interaction between social and technical aspects in those information systems (Sarker et al. 2019). One of the technical challenges often highlighted for blockchain systems has been scalability (Rossi et al. 2019), as transactions through-put might be limited by, e.g., the chosen consensus algorithm. One way to solve this challenge without changing the consensus mechanism is interoperability among blockchain systems by offloading transactions to other blockchains via bridges. As a result of offloading transactions, system flexibility and portability to, e.g., tokens, are added.

With the rise of blockchain systems, the potential for new value creation and capture in networks increased (Schwiderowski et al. 2023b), as the reciprocal relations in networks are upheld by coded rules in protocols and smart contracts. As blockchain systems are rapidly embraced by platforms and users, supplying the backbone not only for the metaverse (Duan et al. 2021) but for all types of blockchain typologies (Beck et al. 2018), those blockchains (ledgers) provide a wealth of information from within the system. On-ledger data analytics (ledgerlytics) is already used to detect criminal activities for different cryptocurrencies (Sun Yin et al. 2019) and has become increasingly prevalent, and so has the need to understand how platforms and users operate within the systems. Several tools already exist that help conduct in-depth investigations within a system, such as, Dune[1], Chainalysis [2], and Etherscan[3], to understand on-ledger activities by tracking transactions, detecting events, or associating external information with wallets or even users (Jørgensen and Beck 2022). As a result, analyzing transactions across blockchain systems remains challenging, as adequate research tools are still missing.

To provide a comprehensive analysis of interoperability for cryptographic tokens (Schwiderowski et al. 2023a) among different systems, research tools for data analysis should be able to examine blockchain transactions that occur across ledgers (Buterin 2016). Such tools have to account for the intertwined relationship between effects on an individual and network level (Madsen et al. 2023), which have not been studied in depth so far. Given the growth of blockchain systems and the variety in use, a holistic investigation of tokens among blockchain systems become increasingly complex. Hence our research envisions to provide a theoretical framework (Burton-Jones et al. 2021) by applying, integrating, and combining data allowing us to generate a holistic and comprehensive audit trail for interoperability among blockchain systems. Thus, this research aims to answer the following: *How is interoperability organized among blockchain systems?*

In the following, we develop a prototype as a part of a design science research (DSR) approach. The focus of this short paper is on bridges between blockchain systems exchanging non-fungible tokens (NFT). First, background information and theoretical considerations on interoperability will be provided, and then we continue to describe the approach in the methodology section. Second, we present the current status of the research and some preliminary findings. Lastly, we conclude and point to our future work for a substantial theoretical contribution.

Theoretical Foundation

We are interested in the interoperability aspects of digital assets, in this case NFTs, as types of cryptographic tokens in and among blockchain systems. Cryptographic tokens form socio-technical systems through embedded reciprocal interactions with their underlying blockchain system, where tokenization allows for the creation and capture of value in the form of new assets by securing ownership, representation, and transferability (Schwiderowski et al. 2023a). Simultaneously, tokens enable new socio-economic systems for future cash flows to be generated within a blockchain system in the form of, e.g., interest rates, dividend payout, and royalty fees (Kugler 2021). Royalties are a fee (often percentage) of the saleprice paid to the creator every time the NFT is resold.

Interoperability is the capacity of software components to interact regardless of code, interface, and system (Wegner 1996). A successful exchange among two or more systems is measured by the ability to understand and interpret the information transferred. The concept and importance of interoperability has been researched within IS (Chau and Tam 1997; Ure et al. 2009; Valk et al. 2021). However, as blockchain systems are immutable (and decentralized), it is hard to change the system once it has been implemented. The

[1]https://dune.com/home
[2]https://www.chainalysis.com/
[3]https://etherscan.io/

fact that numerous blockchain systems have been deployed over the last couple of years has fragmented the blockchain space (Belchior et al. 2021). As a result, several methods have been proposed to ensure interoperability among the many blockchain systems in operation (Chard and Fletcher-Smith 2022; Gangwal et al. 2023; Gaži et al. 2019; Hardjono et al. 2018; Kiayias and Zindros 2020; Liu et al. 2019; Shevkar et al. 2021; Tyagi and Kathuria 2021). Nevertheless, all suggested interoperability methods require some aspect of integration or alteration to the system. This is specifically of importance as any data exchange has to consider both social and technical cohesion on an individual and network level to ensure the value of interoperability among blockchain systems, which is why interoperability is typically discussed along technical, syntactic, semantic, and organizational dimensions.

Technical interoperability is often associated with hard- and software components, which enable machine-to-machine communication on a network level (Van Der Veer and Wiles 2008). More specifically, technical interoperability related to blockchain consists of both internal and external interoperability. When a blockchain system reaches consensus, internal technical interoperability is achieved, e.g., via proof-of-work, proof-of-stake, or proof-of-authority, as the data is agreed upon and distributed to the network participants. However, external technical interoperability among different blockchain systems requires the involved systems to reach consensus via bridges in all the networks on the data exchanged (Pillai et al. 2022), like XP Bridge[4], Polkadot[5], Xclaim (Zamyatin et al. 2019), and Hathor[6].

Syntactic interoperability defines the code, format, and classes of data, primarily on a machine-to-machine communication level (Kubicek et al. 2011). In relation to blockchain systems, syntactic interoperability focuses on the protocols and smart contracts within the system infrastructure that facilitates and operates the communication (Ibrahim and Hassan 2010). In order to understand and investigate syntactic interoperability within blockchain systems, characteristics like data structure, data exchange, and connectivity are all factors that contribute to a successful information transfer (Veltman 2001).

Semantic interoperability focuses on the interpretation rather than the machine code and structure (Benson et al. 2021). The exact meaning of exchanged information and its value, from an individual´s perspective, need to be commonly understood among the systems involved in the transfer in this dimension (Micheni et al. 2014).

Organizational interoperability is the ability to exchange and execute the exact meaning of information influencing other systems. The relationship between the information exchange and function execution can be constructed in two ways: unidirectional or bidirectional (Belchior et al. 2021). Unidirectional only triggers in one direction, e.g., when a transaction in a blockchain system executes a function that may update its own state based on another, or a service that allows various blockchain systems to interact through an oracle (Sober et al. 2021). In comparison, bidirectional are transactions where, e.g., two participants in different blockchain systems can exchange tokens if and only if they both complete the transaction (Pillai et al. 2022).

Methodology

In this research, a software artifact is created following design science research (DSR) to study and theorize about interoperability among different blockchain systems transferring NFTs. We apply a problem-centered DSR approach (Peffers et al. 2007) that subsequently allows for theorizing from design science (Beck et al. 2013). The developed ledger data analytics prototype allows for studying different NFT bridges and theorizing about the types of interoperability as well as subsequent implications for NFT owners.

The problem and motivation for this research is inspired by the interoperability of NFTs among different blockchain systems. Contrary to the transfer of tokens such as cryptocurrencies between two or more blockchains, due to the nature of NFTs being unique and non-fungible, the question arises how different bridges available actually perform interoperability and, subsequently, which rights are actually transferred. For example, how can it be that identical NFTs exist at the same time on different blockchains, if they are truly unique? As this contradicts the principle of NFTs, how do we establish consensus on the original (not

[4]https://bridge.xp.network/
[5]https://wiki.polkadot.network/docs/learn-xcm
[6]https://hathor.gitbook.io/hathor/fundamentals/atomic-swap

fake) via audit of transactions and related tokens among the blockchain systems? This research set out to shed light on the problem of NFT transfers between blockchains to systematically analyze how NFTs are transferred and what it actually means.

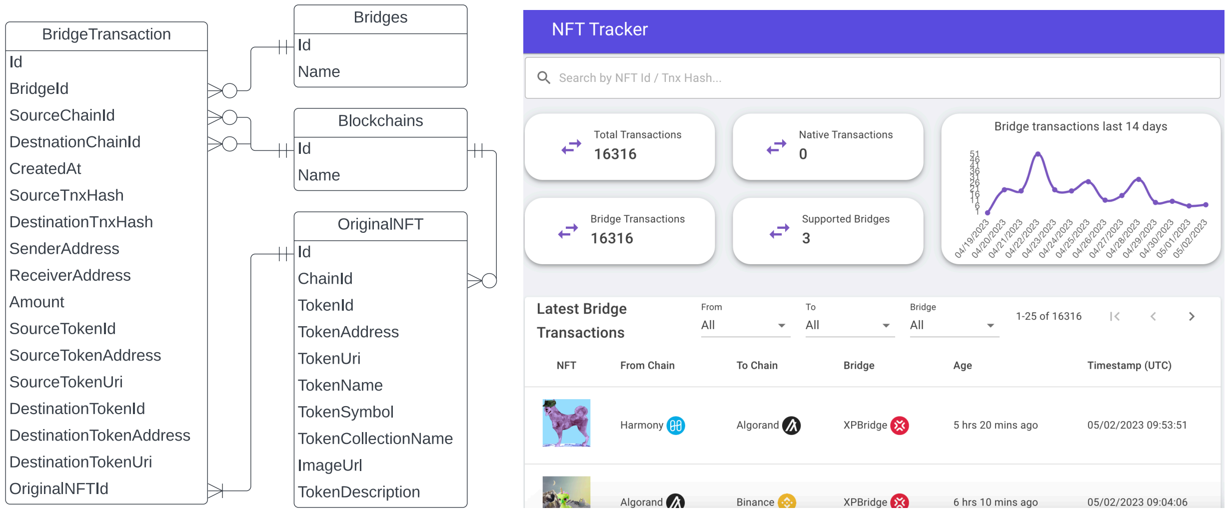
The objectives of the solution is to construct an on-ledger data analytics tool to visualize and enable us to analyze tokens among blockchain systems. The prototype must allow visualization and investigation of NFT transfers to gain insights. The prototype allows us to explore the dimension of organizational interoperability and whether the exact meaning of the NFT is preserved when exchanged among blockchain systems, e.g., does a successful exchange of an NFT ensure the mechanism of royalties (Wang et al. 2021) or dividend payout being sent to the *correct* wallet in a different blockchain system? Future research will incorporate and examine further characteristics to gain more holistic insights and perspectives on the actual meaning of what is bridged between different blockchains. The developed on-ledger analytics tool considers compatible blockchain systems based on EVM, which guarantees that there is only one canonical state executing the rules for each new block. Future research should investigate how the exact meaning of NFTs is preserved (or is changed) if bridged between numerous heterogeneous blockchain systems not based on EVM. As a result, the overall functionalities of the prototype in this short paper are defined as: a) The ability to contain data from multiple blockchain systems. b) The data has to be dynamic and up-to-date by adding new transfers in real-time as they occur. c) The prototype has to come with a user interface (UI) that allows for querying NFT transfers and a transaction record of all related transfers from the systems involved.

The design and development of the prototype was conducted in iterative steps with a specific focus on how the data is collected. The developed software artifact first assembles the database schemata that allow storing blockchain data from different systems, and to ensure a dynamically updated feed of transactions. Once this functionality was developed, a user interface was designed to display and update data continuously.

The first iteration was to create a common database based on the data structures of different blockchain systems' documentation. The relational database was built via a normalization process (Codd 1972) of combining the different system data structures into a unified database schema. We realized, when transforming the data that the nested transactions in a block had to be separated into their own tables with reference to their context. Thus, we populated the transaction data with a block_hash attribute as a foreign key pointing to the corresponding block's hash in the blockchain system. Similarly, we identified multiple bridging (interoperable) transactions, like XP Bridge, that also needed their own tables in the entity relationship diagram (see fig.1a) with a token (ID system), sender (wallet system), and receiver (wallet system) reference along with a from attribute (source system) and to attribute (destination system). The dynamic data feed into the database was enabled by the use of Corn Jobs. The scheduled job in Cron was configured to execute at a fixed interval to check for the delta of new bridge transactions that occurred among the blockchain systems. As a consequence, the scheduled job would write the new data entries (transactions) discovered into the database.

The second iteration concentrated on the UI search and data visualization. Besides a *BridgeTransaction* table from the first iteration (see fig.1a), we learned that if we wanted to represent the original NFT displayed, it would require an *OriginalNFT* table. The reason was that we wanted the original token, as opposed to being wrapped when transferred via a bridging transaction. OriginalNFT was the earliest record collected of a uniquely identified NFT (Id). As a result, we could store the original details, like image URL and metadata, and display the information historically for each stage as the combination of systemid, tokenid, and token address enabled a unique identification within each blockchain system. Ideally, a full NFT collection search would be possible by combining the systemid and token address. To emphasize the data visualization, a dashboard was constructed to gain an overview of the number and frequency of NFTs transferred for the last 14 days. Moreover, we aggregated the total number of analyzed bridge transactions and bridges supported in this prototype. Finally, we displayed the actual transfers reflected as live data from the database being processed continuously (fig.1b).

The evaluation of the data analytics tool will be based on how well it addressed the dimensions of interoperability among blockchain systems in the case of NFTs. This part is research in progress, as the testing of the solution's usefulness to expand the prototype in future iterations has not been conducted yet. However, the



(a) **(b)**

Figure 1. The ERD for bridging transactions (a) and the frontend UI (b)

intention is to store search activities on the software artifact to gather insights on, e.g., the uniqueness and number of lookups conducted on specific NFTs. Furthermore, multiple NFT case studies will be performed to validate and compare the accuracy of NFT interoperability using the software artifact.

The communication of this research and future work is achieved by abstracting and theorizing from this research, providing high-level explanatory insights into the nature of interoperability among blockchain systems as part of this ongoing research. Other researchers interested in joining forces are welcome to help investigate and theorize on the legal, ethical, and economic implications of bridging tokens.

Preliminary Findings

This section analyzes the preliminary findings based on the prototype creation related to the four dimensions of interoperability outlined in the theoretical foundation. Based on the evaluation and communication of the prototype, we further discuss shortly how it is utilized in a practical manner. In so doing, this research also sheds light on the rather opaque tracing of transactions among blockchain systems based on the exchanges of data.

Transparency is a vital foundational aspect of blockchain as it allows for the validation of authenticity by the history of the token and tracking its past transactions. The prototype allows us to explore the dimension of interoperability and whether the exact meaning of the NFT is preserved when exchanged among blockchain systems, e.g., does a successful exchange of an NFT ensure the mechanism of royalties (Wang et al. 2021) being sent to the *correct* wallet in a different blockchain system? In theory, blockchain technology allows for a transparent and immutable system where transactions can be observed and analyzed. In practice, evaluating and monitoring transactions is cumbersome, especially as on-ledger analytics tools are still in their infancy. The prototype revealed that transactions generated from bridging an NFT do not, by default, indicate the destination blockchain in the transaction on the source blockchain systems and vice versa to ensure a historic audit trail. As a consequence, blockchain systems become black boxes that can only be understood by a few experts. This undermines the raison d'etre of blockchains, namely the promise of transparency that allows everyone to understand and validate transactions on blockchain systems (Yang et al. 2019).

A shared network communication bridge is required to achieve (technical) interoperability between blockchains. In this research, three types of bridges have been identified along with their characteristics to allow for interoperability among blockchain systems: a) Clone bridges (see A in fig.2), like XP bridge, are smart contracts deployed between blockchain systems to lock or burn the token sent from the original system and then cloned (minted) in the destination system. The clone bridges are mostly operated centralized using an off-

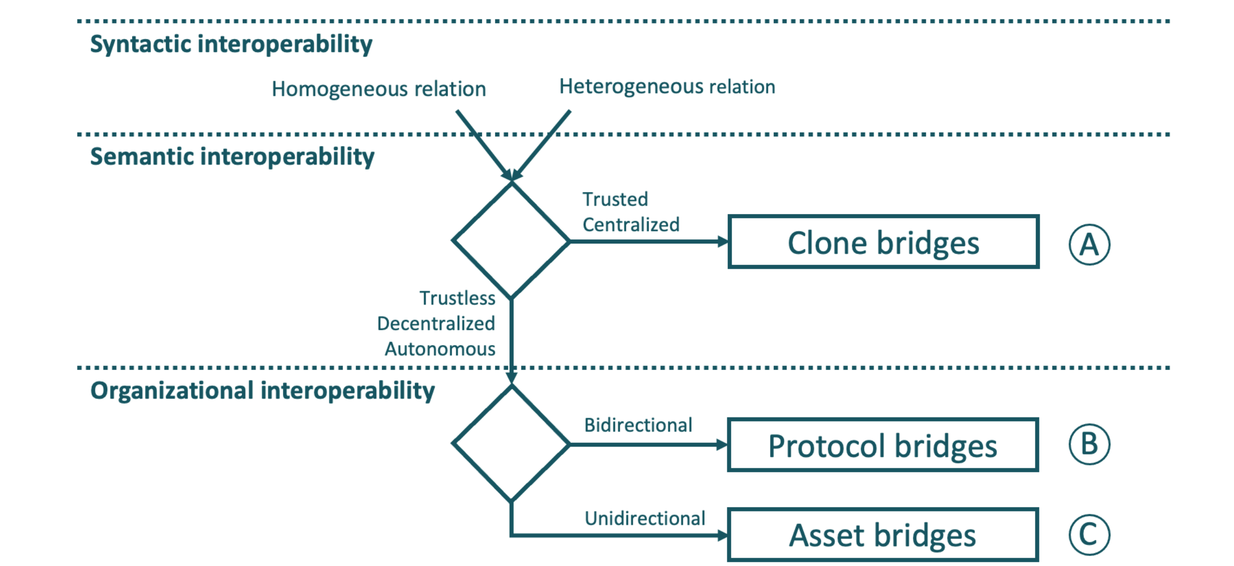


Figure 2. How and which bridge to cross

ledger intermediary. b) Protocol bridges (see B in fig.2) are implemented into the design of the underlying network protocol, as in the case of Polkadot, where a cross-consensus message component communicates with a relay blockchain system handling the exchange of information. c) Asset bridges (see C in fig.2), like Xclaim (asset-backed), utilize the asset from the original system as collateral, where a smart contract issues another (potentially wrapped) token in the destination system. Another asset bridge, Hathor (atomic asset swap), creates a locking contract between sender and receiver each depositing assets in different blockchain systems simultaneously, and when the exchange conditions are met, the assets are swapped.

When considering syntactic interoperability (see upper part of fig.2) as a starting point for theorizing, we identify different types of data structures among the blockchain systems investigated. As a result, we categorize the data structure as a relation between the systems as either homogeneous or heterogeneous. A heterogeneous relation indicates that the data structures between the systems are different from each other, whereas a homogeneous relation would reveal a similar data structure (Gligor and Luckenbaugh 1984). Hence, systems that are compatible with the EVM handle all the computation and data similarly and are homogeneous. Based on our preliminary findings, we find that among homogeneous blockchain systems, the meaning of information (e.g., business logic established within a smart contract) remains intact (Legner and Lebreton 2007). In the case of NFTs and royalty mechanisms, the royalty is distributed correctly as the wallet identifier (public key) remains the same, whereas this logic breaks between heterogeneous systems.

Within semantic interoperability (see middle part of fig.2), bridges can be constructed as either trusted or trustless. Trusted bridges typically take a more centralized approach when exchanging tokens that often involves an off-ledger process, where the bridge service provider gets possession and control of the token during the transfer. In contrast, trustless bridges utilize a more decentralized approach by establishing predefined conditions for when the transfer is accepted. They then execute simultaneously and autonomously between the systems. If someone opts for a trusted and centralized solution, it means that a clone bridge is chosen that allows for semantic interoperability (see A in fig.2). It must be noted that clone bridges are subject to interpretation: Does the new clone of the token have the exact same representation, ownership, rights, and value as the original, or was it just copied to or minted on the destination system without relation or permission? Additionally, will a clone of a clone be made if the token is transferred back to the original system via a different bridge provider? Further research will have to clarify these questions.

Organizational interoperability (see lower part of fig.2) considers the relationship between the information exchange and function execution as either unidirectional or bidirectional. Unidirectional bridges do not have a function for correcting the corresponding asset-backed token issued on the destination blockchain system in case the collateral disappears or otherwise is withdrawn from the original system. The same aspect applies to atomic asset swaps, as the assets do not have any connections after the transfer. In contrast, bidirectional bridges ensure a more reliable and traceable information exchange as the message passing is confirmed by all the involved systems and causes interdependence between the assets transferred. However, the implementation process of a protocol bridge is also often more complex compared to a clone- or asset bridge.

Conclusion and Future Work

The on-ledger data analytics artifact for exploring bridges used to transfer NFTs, along with the preliminary findings in this research in progress, provide the foundation for analytically more advanced research and allow for richer explanatory theorizing in subsequent steps. The prototype can be understood as a scientific tool or method, that provides the base for further research. The artifact has already demonstrated practical relevance in relation to homogeneous blockchain systems supporting business logic within the royalty mechanisms of NFTs, whereas heterogeneous blockchain systems do not. Practical implications also reveal that it is possible to hide a token´s origin or destination tracks in an otherwise supposedly transparent system. Future research with practical implications will consider the semantic and organizational consequences for tokens without a full audit trail, e.g., a token might be considered unreliable, or less valuable, or even blacklisted, if a full audit trail is not possible among blockchain systems. Similarly, organizational interoperability will potentially involve measuring the *health* status of blockchain systems to also account for external value created and captured elsewhere.

This study also provides potential research implications based on the preliminary findings. Our research results give rise to concerns that the current methods for how we conduct and limit the scope of blockchain research related to tokens, in general, are inadequate and may result in inappropriate conclusions when only looking at a single blockchain system. This research provides the first evidence that current research so far may only consider a subset of a token's actual history among blockchain systems.

Our research indicates that interoperability among blockchain systems may lead to decreasing transparency. Thus, comprehensive and holistic on-ledger data analytics tools and methods are needed. Our ongoing research will extend the prototype to handle more characteristics, and validate the audit trails using data triangulation from additional data sources. A further developed and improved version of the artifact will extend the collection of blockchain systems to enable a full-scale analysis of numerous token audit trails. It is our intention to discuss the research in progress provided in this short paper to improve the ongoing research, allowing us to make a more substantial theoretical contribution in addition to the preliminary contribution presented in this work.

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