Networking Parallel Web3 Metaverses for Interoperability

Yuanfang Chi, Haihan Duan, Wei Cai, Z. Jane Wang, and Victor C. M. Leung

Abstract

Parallel Web3 metaverses play a vital role in preventing monopolistic markets and fostering fair and profound user experiences. Meanwhile, ensuring interconnections and interoperability among these metaverses is crucial, allowing users to seamlessly transition between different Web3 environments while maintaining their digital identities and assets. In this tutorial paper, we provide an overview of the significance and current landscape of interoperability in parallel metaverses. Furthermore, we identify key challenges in achieving interoperability in parallel Web3 metaverses within the blockchain industry, including the technical complexities and practical business considerations. Then, we suggest that decentralized knowledge inference can be used as a potential solution for facilitating knowledge sharing among parallel metaverses. Finally, we outline the technical and economic approaches of decentralized knowledge inference to inspire future research in this field.

Introduction

The digital world stands on the brink of a historic transformation with the rise of Web3. This new era, driven by advanced technologies such as blockchain, smart contracts, and artificial intelligence, emphasizes decentralization and user empowerment. In particular, Web3 promises to give users greater control over their data and identity. With their own digital identity, users can now verify ownership and transfer data between applications with explicit consent, eliminating the need for intermediaries. Furthermore, the Web3 metaverse, built upon blockchain technology, offers the characteristics of persistence and unity, creating an innovative virtual realm [1]. As such, as a Web3 application, the Web3 metaverse provides unprecedented opportunities for metaverse residents to interact with each other and their digital assets in a fair, transparent, and secure manner [2]. The Web3 metaverse has sparked a new wave of entrepreneurship and excitement within the industry.

However, it is vital to recognize that the monopolization of the Web3 metaverse contradicts its decentralized nature, as excessive control by a single entity can lead to the abuse of power. Consequently, the emergence of parallel digital worlds on different blockchains within a unified Web3 framework, or the coexistence of multiple parallel metaverse projects within the same blockchain ecosystem, is inherent to the decentralized and anti-monopoly essence of Web3. In fact, the industry has already embraced this concept, with multiple metaverse projects coexisting on various blockchain platforms such as Ethereum, Polygon, and Binance Smart Chain. Prominent examples include Decentraland, Voxel, and The Sandbox. These metaverse projects foster diversity within the metaverse ecosystem, providing users with abundant choices and promoting a thriving environment.

Nonetheless, multiple parallel metaverses should strive to establish a comprehensive community interconnection system that enables users to seamlessly transit between different virtual worlds. Such an interconnected system would allow users to explore a unified digital realm while safeguarding the integrity of their identity and the value of their assets [3], ultimately fostering a more profound social immersion. Thus, ensuring interoperability for collaborations between parallel metaverses is crucial, which primarily encompasses two key aspects: 1) Interoperability of identity and assets, and 2) Interoperability of information and knowledge. In this context, "identity" signifies the inherent essence of a user's being. "Assets" denote valuable entities associated with a specific identity. "Information" encompasses the raw data produced by identities and/or assets. Lastly, "knowledge" is defined as the comprehension of facts derived from this information, perceived in a multi-dimensional framework.

Unfortunately, the current state of industry development highlights a lack of comprehensive interoperability between parallel metaverses. While there have been advancements in achieving interoperability for identity and tokenized assets, the same cannot be said for non-tokenized assets and information and knowledge. This predicament can be attributed to existing technological challenges in the blockchain industry, including 1) Interoperability issues arise from data heterogeneity, which impedes the seamless exchange of on-chain open data, and 2) barriers exist concerning off-chain, non-open data due to technological limitations within the blockchain industry and practical business considerations.

This tutorial paper summarizes the challenges faced by collaboration between Web3 metaverses and outlines recent methodologies proposed. The

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contributions of our research can be summarized as follows:

- We summarize the necessity, types, and industry landscape of interoperability between parallel metaverses, analyzing the technical difficulties and business challenges associated with achieving interoperability for collaborations.
- We discuss how knowledge graphs can be applied in metaverses and how decentralized knowledge inference techniques can be used to share knowledge without sharing raw data among Web3 parallel metaverses. Then, we discuss the current achievements and future research directions in this field.

Parallel Web3 Metaverses

Web3 Metaverse: The Background

The concept of the metaverse is not new in the digital world, but the decentralized metaverse under the Web3 paradigm brings a fresh perspective. Unlike the traditional notion of the metaverse as a digital world accessed through virtual reality goggles, the Web3 metaverse is grounded in the principles of decentralization. It leverages blockchain technology and smart contracts to create a new form of digital world, where residents can trust that it exists independently of third-party organizations. Meanwhile, metaverse residents possess the freedom to create user-generated content (UGC) in the form of digital assets, which can be traded through smart contracts within the decentralized crypto space without the fear of unwarranted deprivation [4].

In fact, the development of the Web3 metaverse has undergone a series of shifts in community perception over the past few years. Initially, the industry focused on building visually immersive three-dimensional spaces on the blockchain, primarily through building virtual parcels of land and constructing unique digital experiences with them. Representative projects in this area include Decentraland, Voxels, and The Sandbox. Subsequently, attention shifted to implementing digital identities. Notable projects in this category include domain name systems like Ethereum Name Service (ENS) and avatar-based non-fungible tokens (NFT) projects such as CryptoPunks, BAYC, and mfers. Currently, the emphasis is on constructing decentralized autonomous organizations (DAOs) within the metaverse, as an increasing number of Web3 metaverse participants are emphasizing the formation and evolution of societies within the digital world.

In summary, humanity now has a parallel digital world that coexists with the physical world. This digital realm encompasses virtual spaces, digital identities, and organizations built on unified protocols, creating a unified and integrated domain.

The Necessity and Inevitability of Parallel Metaverses

However, a unified metaverse does not mean allowing monopoly or dominance. In fact, the concept of Web3 has been against the monopolistic tendencies and privileges since its inception. In other words, the fundamental principle of decentralization in Web3 necessitates the existence of parallel metaverses.

Meanwhile, the nature of digital assets make the existence of parallel metaverses inevitable. Artificial scarcity, created through smart contracts, attracts early investors but requires strong consensus to sustain rising prices. Without parallel metaverses to prevent monopolistic markets, high prices can hinder new user groups from entering, posting negative impact on ecosystem development and reducing activity in that metaverse. Thus, the emergence of new metaverses becomes inevitable to cater to the specific digital world needs of these user groups, ensuring a dynamic and inclusive ecosystem.

> Multiple parallel metaverse should strive to establish a comprehensive community interconnection system that enables users to seemlessly transit between different virtual worlds.

Hence, the market will ultimately decide the long-term coexistence and development of multiple parallel metaverses. While Bitcoin and Ethereum currently hold dominant positions in terms of market capitalization at the infrastructure blockchain layer of Web3 metaverses, other competing chains still have opportunities for growth. Similarly, in the realm of upper-layer metaverse ecosystem projects, whether spatial or identity-focused, coexistence and competition remain constant themes.

The Needs of Interoperability Among Parallel Metaverses

However, parallelism does not imply fragmentation. On the contrary, interconnection and collaboration among Web3 metaverses are essential, and parallel metaverse projects should have the ability to connect in various ways, ultimately embracing the concept of a unified digital world. In fact, as long as they adhere to the same underlying protocol, users should have the freedom to seamlessly move and transition between parallel metaverses. For example, in the example shown in Fig. 1, resident (A) of The Sandbox can migrate to Decentraland and interact with resident (B), who can then move to Voxels and interact with resident (C).

In general, the interconnection of parallel metaverses should be approached from two aspects:

1) Interoperability of Identity and Assets: Users can use a unified public address as their personal identity or represent their identity through forms such as domain names and avatar-based NFTs. This enables them to easily traverse various metaverses with one recognizable identity or even with the same appearance. Additionally, metaverse residents should have the freedom to smoothly transfer their assets, including NFTs and cryptocurrencies, from one metaverse to another. In other words, the value of digital assets should be preserved within the metaverse.

2) Interoperability of Behavior and Relationships: Meanwhile, content serves as a fundamental element within the metaverse, providing immersive experiences through well-structured narratives and user-generated events [5]. In fact, user movements, character behaviors, and avatar personas play a crucial role in behavioral modeling when establishing interactions between metaverse residents and non-player characters (NPCs). Additionally, hidden relationships based on causal connections between events and

We discuss how knowledge graphs can be applied in metaverses and how decentralized knowledge inference techniques can be used to share knowledge without sharing raw data among Web3 parallel metaverses

themes contribute to the development of coherent storyline progression, crafting rich narratives without conceptual conflicts. Therefore, relationships and interactions among residents, along with their past experiences and preferences, should be shared among metaverse operators, allowing for a deeper understanding of residents to tailor immersive experiences to meet their needs.

Drawing from a wide range of information and knowledge, including user identity, digital assets, user behavior, and relationships, the Web3 metaverse industry has the opportunity to create innovative application models that elevate the user experience. Meanwhile, utilizing this valuable information, operators of new projects in the Web3 metaverse industry can implement innovative strategies such as token and NFT airdrops to attract high-quality users who meet specific criteria [6]. By leveraging such techniques, these operators can achieve remarkable outcomes in project marketing and organizational governance while keeping costs at a minimum cost.

Networking Parallel Metaverses: Industrial Practice

The interoperability of parallel metaverses in the current Web3 ecosystem can be roughly illustrated in Fig. 2, which can be divided into four scenarios:

1) One Metaverse Project on Different Blockchains: Achieving interconnectivity in the Web3 metaverse can be accomplished through centralized servers or cross-chain bridges. For instance, in Matrix World, users have the ability to convert and circulate digital assets between Ethereum and Flow using the centralized servers maintained by the operator. Similarly, The Sandbox enables token and NFT interoperability between Ethereum and Polygon through a cross-chain bridge. These projects, whether through centralized servers or cross-chain bridges, facilitate the circulation of digital assets across different blockchains. In the Web3 metaverse context, such projects can effectively identify and utilize digital assets across various blockchains, thereby achieving seamless asset interoperability and enhancing the overall user experience.

2) Different Metaverse Projects on One Blockchain: Token interoperability is primarily facilitated through exchanges. For instance, platforms like The Sandbox and Decentraland on the Ethereum blockchain enable the trading of their respective native tokens, *$SAND* and *$MANA*, through decentralized exchange platforms such as Uniswap. However, due to the unique characteristics of each NFT, achieving interoperability in the NFT market through decentralized exchanges and automated market makers (AMMs) is challenging. Particularly, while claiming to be decentralized, Sudoswap can only facilitate NFT AMM transactions based on the floor prices of the NFT. Thus, the liquidity of NFT trading is significantly lower compared to fungible tokens (FTs), which makes the decentralized exchange of NFTs between different metaverses currently not feasible. In practice, users typically need to monetize their NFTs on specific metaverse marketplaces like OpenSea and then transfer the value of their digital assets between parallel metaverses through FT transactions.

3) Different Metaverses on Different Blockchains: As mentioned above, FTs can be used to facilitate value transfer between different metaverses. Since data on different blockchains are not directly interchangeable due to the nature of the chains, interconnectivity can only be achieved through tokens on centralized exchanges or cross-chain bridge exchanges. For example, if a user of The Sandbox on Ethereum wants to experience the metaverse project Avagotchi on Polygon, the user needs to exchange their holdings of the *$SAND* token on Ethereum for the *$GHST* token

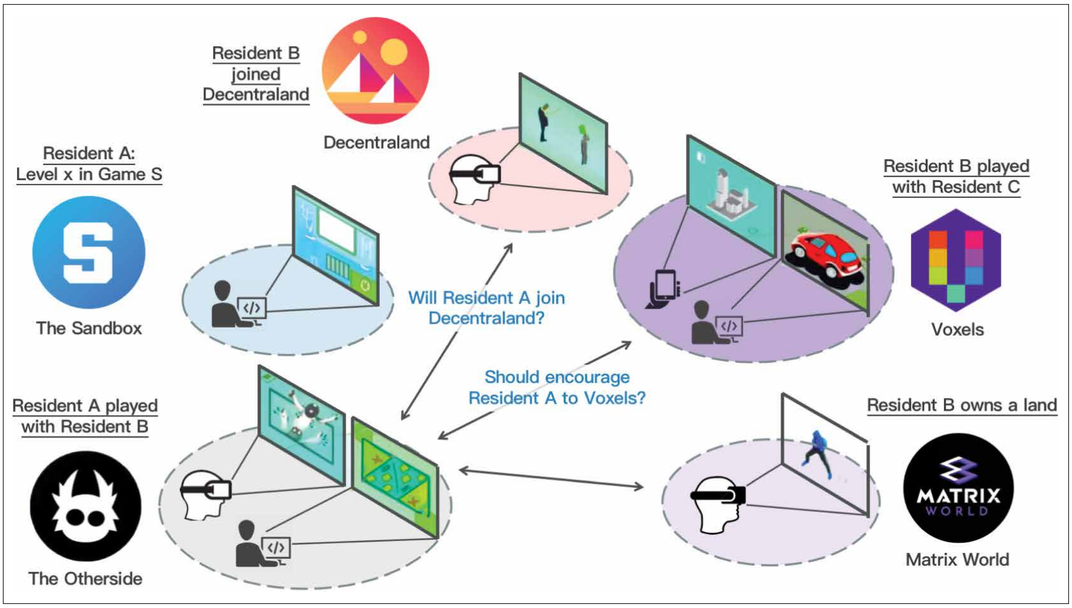

FIGURE 1. Example of parallel metaverses collaboration.

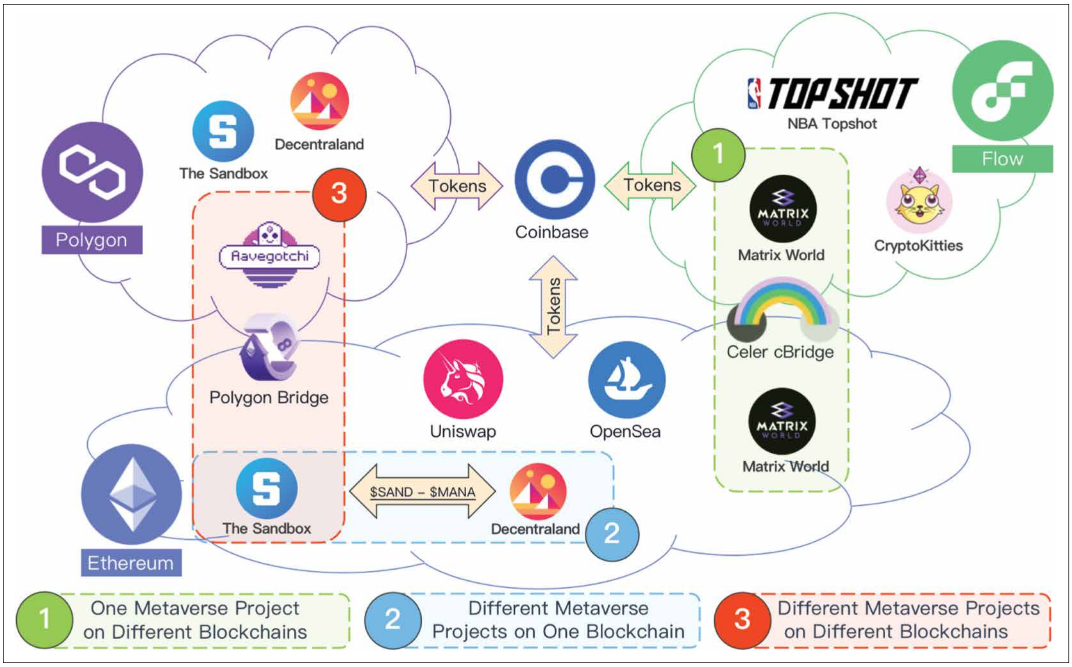

FIGURE 2. The state-of-the-art industrial practice of parallel Web3 metaverses.

on Polygon through a centralized exchange, e.g. Coinbase, or a cross-chain bridge, thereby completing the conversion of digital assets between different metaverses on different blockchains.

4) Interoperability within One Metaverse on One Blockchain: A metaverse on a particular blockchain may have sub-metaverses, and the networking among sub-metaverses can be achieved through a unified project interface for on-chain assets interoperability. Representative projects with the feature of interoperability within one metaverse on one blockchain include GALA and TreasureDAO. In this paper, we select GALA as an exemplary case, as it has a relatively mature architecture and ecosystem to enable FT and NFT interoperability. In Fig. 3, we illustrate a detailed description of the data and value exchange process in GALA. Facilitated by Project GYRI, a node network for blockchain-based data exchange, the Gala Games is a decentralized platform for Web3 games, which nowadays are considered as the pioneering prototypes of Web3 metaverses. In other words, the Web3 games on Gala Games platform are sub-metaverses within the GALA metaverse and they are able to communicates with each other through the GALA platform. Since digital assets on the Gala platform are stored on the GYRI blockchain and can be publicly accessed by other sub-metaverse projects within the platform, it is possible to achieve value exchange of digital assets between different metaverses in Gala Games. For example, if a player owns a magical sword in a Gala game, which is a verifiable asset on the blockchain, they can use it in the game or trade it with other players. In fact, Gala Games encourages developers to create new games that utilize this magical sword, thereby promoting the reuse, sharing, and circulation of assets. Therefore, GALA can be seen as a typical example of FT and NFT interoperability among metaverses. However, Gala Games currently does not support the exchange of information and knowledge such as user behavior and relationships.

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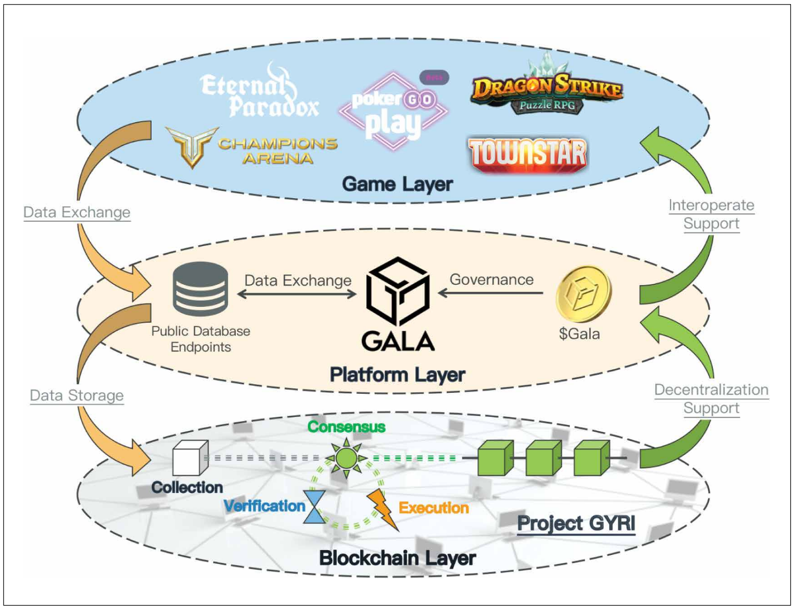

FIGURE 3. Data exchange workflow of *Gala Games*.

Parallel Web3 Metaverse Users: State-of-the-Art

Fig. 4 shows how the user count changes over time in representative Web3 metaverse projects. Based on the assumption that each blockchain address represents a user, we fetch the addresses associated with multiple land NFTs from different projects to identify the users participating in multiple parallel metaverses. The data show a

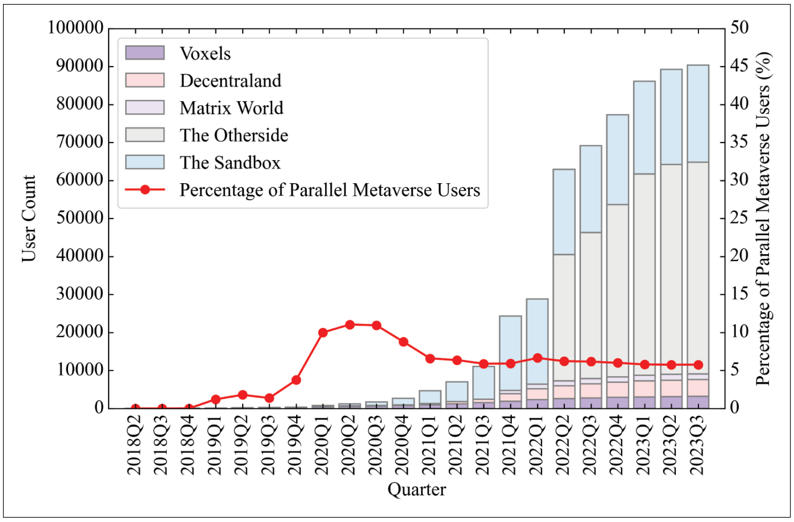

FIGURE 4. Number of active users in different metaverses.

significant increase in the percentage of these parallel metaverse users since Q4 of 2019, indicating the Web3 users' strong interest in the interoperability of parallel metaverses. It is worth noting that many active metaverse users without land NFTs are unrecorded, while a large amount of addresses solely holding metaverse tokens are also absent in the results because a significant portion of them are pure investors. Therefore, we argue that the number of parallel metaverses users may be much larger than presented in the graph. Meanwhile, another interesting phenomenon after the Q3 of 2021 is that the user count keeps growing, while the proportion of addresses participating in multiple parallel metaverses has decreased. The possible reasons behind this are: 1) the unreasonable high prices of land NFTs during this metaverse bubble period suppressed the active users from purchasing more land NFTs from multiple projects; 2) the state-of-the-art metaverse projects are hardly interoperable, providing limited parallel metaverse experience for users, which is also the motivation of this work.

The Challenges of Interoperability

However, the collaboration between parallel metaverses faces two significant challenges:

1) Data Interoperability Issue: The primary challenge lies in achieving data interoperability, which stems from the inherent heterogeneity of such data, including on-chain open data and off-chain non-open data. In this section, we use on-chain open data to discuss the data interoperability issue.

On one hand, different metaverses may support diverse formats for digital assets, resulting in a prevalence of various data formats within the metaverse ecosystem. While the formats for ownership and asset transaction records of FTs and NFTs tend to be standardized within a specific blockchain, the formats and contents of metadata can vary significantly. For instance, NFTs possess unique asset attributes encompassing text descriptions, images, videos, 3D point cloud models, and more. Given the immense possibilities within the metaverse realm, designing a universal standard format that caters to all types of digital assets in the Web3 world presents a considerable challenge.

On the other hand, different metaverses operate with distinct interaction logics, value systems, artistic styles, and more, contributing to their unique metaverse worldview. Many metaverse projects employ separate economic systems with different tokens or currencies. When users acquire tokens within one metaverse, the real value of those tokens should be transferable to another metaverse, regardless of differences in the economic system. Currently, token prices across different metaverses are determined by the market, and arbitrageurs play an active role in maintaining stable values by monitoring price disparities in various liquidity pools in real-time. However, the situation becomes more complex when it comes to NFTs, which possess special attributes as digital assets. Achieving consistent attribute values for NFTs in different metaverses requires standardization of various attributes such as gender, material, rendering, and functionality across all metaverses. This necessitates a careful design and the establishment of a common protocol agreed upon by all metaverse operators, which can often be a challenging undertaking [7].

As a result, integrating dynamic and heterogeneous data from different metaverses in the creation and operation of metaverses is difficult because of the lack of interoperability between digital models of various metaverses. Considering the heterogeneity of data, it is necessary to perform consistent integration and analysis of data collected from different sources to understand user interactions. Therefore, instead of sharing raw data, a more effective approach is to share knowledge within the Web3 metaverse for collaboration.

2) Barrier Posed by Off-Chain Non-Open Data: The second challenge lies in the barrier posed by off-chain non-open data. This challenge primarily arises from the existing technological limitations of blockchain and is influenced by practical business considerations in the real world.

On one hand, the distributed storage and consensus mechanisms of blockchain systems inherently result in high storage costs [8]. As a result, existing blockchains become prohibitively expensive for metaverse applications that involve rich multimedia content in the long term. Consequently, many metaverse projects opt to host and execute their content on centralized servers instead of the blockchain, due to this technological limitation of the blockchain in practical industry scenarios.

On the other hand, there is an ongoing debate surrounding the capabilities of centralized servers to open-source data and programs, which brings to light an important aspect: the real-world business considerations of project operators. The decision not to open-source off-chain data and programs is often driven by the intense competition faced by metaverse developers and operators. While this may appear contrary to the ideals of open sharing in Web3, it is crucial to recognize that developers and operators bear the costs of program development and system maintenance. Complete open-sourcing of projects, eliminating technical barriers and data moats, could potentially hinder their ability to generate legitimate profits and sustain the project in the long term. Hence, in the current Web3 industry, it is widely accepted that project operators can adopt a partially non-open or delayed open-source approach to ensure the successful operation of decentralized projects.

Considering these factors, it is evident that the barrier issue of off-chain non-open data will persist among parallel metaverses in Web3 for the foreseeable future. The research community plays a vital role in exploring technical solutions that facilitate knowledge sharing without compromising developers' interests or directly accessing raw data. For instance, within a metaverse, operators discern a user's inclination towards specific puzzle types through off-chain analysis. These insights can be conveyed to other metaverses to enhance gameplay, optimizing user engagement without delving into granular user data. Another use case can be content filtering: if a metaverse identifies a user as a minor, it can notify other metaverses, ensuring the user is shielded from inappropriate content. Additionally, comprehensive research on incentive strategies is essential to foster cooperation among stakeholders, including parallel metaverse developers and operators. By addressing these challenges, the industry can strive towards achieving greater interconnectivity and collaboration among parallel metaverses in the Web3 ecosystem.

Last but not least, the heterogeneity issue found in on-chain open data also exists in off-chain non-open data, which also poses challenges to the interoperability of off-chain non-open data.

Future Research Directions

The ability to share information and knowledge is the key to achieving interoperability. To tackle the data heterogeneity issue, knowledge graphs (KGs) have been studied and applied in many industries [9]. In addition, to tackle the interoperability issue of off-chain non-open data, in other words, to be able to achieve knowledge sharing without accessing raw data, distributed and decentralized knowledge inference techniques are studied. In this section, we discuss the application of KGs in metaverses. Then, we discuss the technological and economic approaches of knowledge inference techniques that achieve knowledge sharing to address the interoperability challenges among parallel Web3 metaverses.

Knowledge Graphs for Heterogeneous Data

Presently, significant attention is being directed towards large language models (LLMs) within the realm of natural language processing, owing to their remarkable capacity for managing broad knowledge domains. Nonetheless, despite the notable successes achieved across various applications, LLMs have faced scrutiny regarding their factual knowledge proficiency [10]. Specifically, LLMs exhibit a tendency to memorize facts exclusively from the training corpus of general knowledge, leading to instances of factual inaccuracy in their generated statements—an issue commonly referred to as "hallucination." Moreover, these models encapsulate knowledge implicitly within their parameters, effectively functioning as opaque black-boxes. Consequently, a key drawback emerges, as LLMs lack the capability to interpret or validate the knowledge they derive.

To address these limitations, researchers have proposed the integration of Knowledge Graphs (KGs) into LLMs. KGs are renowned for their adeptness at managing domain-specific knowledge through a predefined, structured representation—an enhancement that significantly bolsters interpretability. Essentially, KGs facilitate the conceptualization of information and knowledge as ontologies, meticulously designed by domain experts. In the context of Web3 metaverses, ontologies serve as the bedrock for representing knowledge pertaining to software components, digital models, transactions, and user interactions, as highlighted by MetaOntology [11]. The establishment and consensus upon an information structure usher in the potential for diverse metaverses to harness KGs as their primary data source.

Decentralized Machine Learning Techniques

Enabling the exchange of information while upholding data privacy stands as a pivotal necessity in realizing seamless interoperability for off-chain non-open data. This imperative for privacy-preserving data sharing has garnered extensive attention across various industries. Particularly, federated learning techniques have captured considerable interest due to their ability to train machine learning models using decentralized data, all without necessitating the exchange of local data. In the framework of federated learning, each participating entity trains on its respective local dataset. Following each training iteration, the model parameters are harmonized among the different participants, thereby facilitating the sharing of accumulated knowledge. This iterative process ensures the assimilation of individual expertise into a cohesive, shared model. Furthermore, numerous researchers have strongly advocated for the adoption of transfer learning, which leverages acquired knowledge from a prior task to enhance the overall generalization for another task. Nevertheless, these decentralized machine learning techniques often struggle when confronted with knowledge graphs that contain general knowledge or heterogeneous data.

Decentralized Knowledge Inference for Knowledge Graphs

Similarly, data in KGs can be shared through reasoning models [12]. In addition, decentralized knowledge inference methods can obtain preferences or infer scenario lines from multiple independent knowledge graphs from different metaverses to achieve knowledge sharing.

1) Technological Approach: For decentralized knowledge inference techniques in parallel Web3 metaverses, the following objectives should be achieved: *i) Data Integrity:* In practice, KGs are used in scene rendering or scenario provisioning. An effective knowledge-sharing technique should be able to utilize the KG directly without requiring the stakeholder to process the data into other formats. *ii) Scalability:* The Web3 metaverse is expanding quickly with more residents, scenes, and UGCs. Also, new metaverses are being

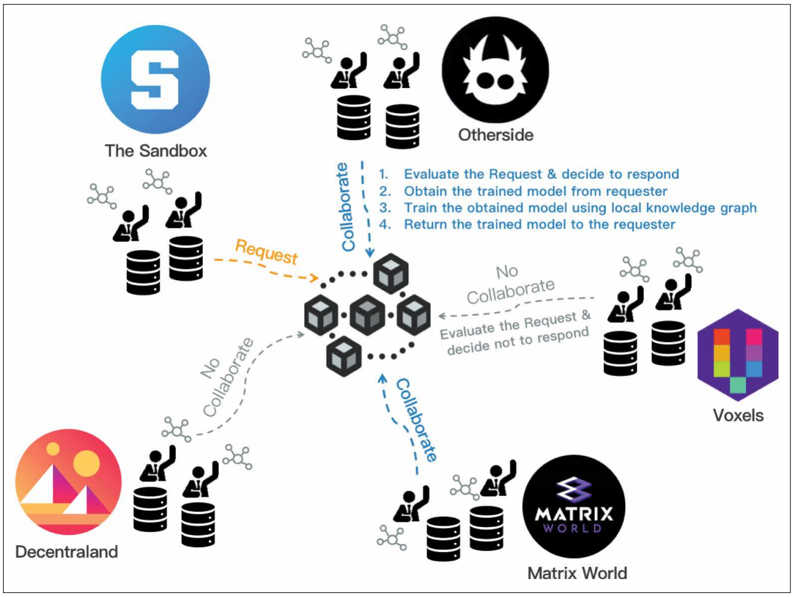

FIGURE 5. Decentralized knowledge inference for parallel metaverses.

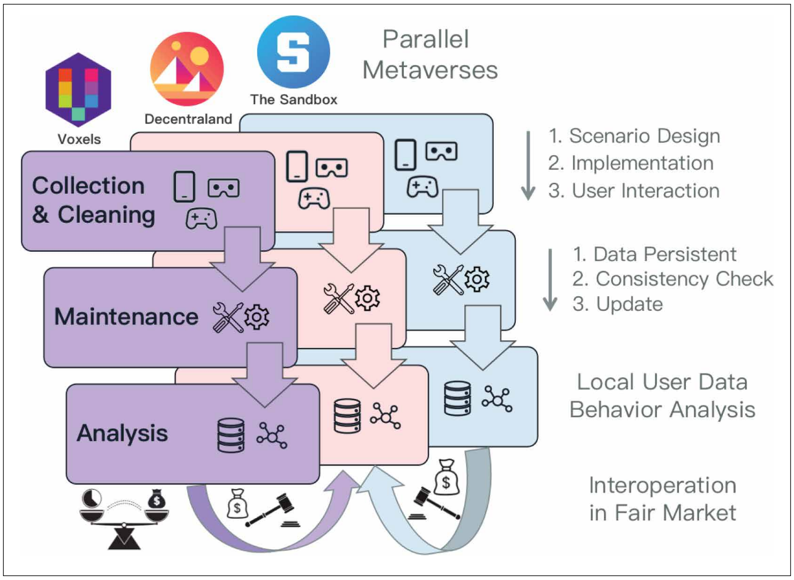

FIGURE 6. Process of knowledge management.

introduced to the market at an unprecedented rate. The knowledge inference mechanism should be able to scale up as the metaverse expands. However, distributed or decentralized knowledge inference with knowledge graphs for Web3 metaverse has not been studied at the time of the preparation of this tutorial paper. Thus, we discuss the distributed knowledge inference framework proposed in [13] with the expectation to inspire future research in this area. The framework proposed achieves the *Data Integrity* and *Scalability* objectives. Specifically, the framework employs a distributed path-based algorithm to reason over paths scattered in multiple KGs. After a stakeholder has trained its reasoning model with its local knowledge graph, a central coordinator will transfer the trained model to another stakeholder, which will start training the trained model with its local KG. The proposed framework can be adopted in the Web3 metaverse since a similar paradigm can be found. As a metaverse resident switches between metaverses, their interactions, and experienced events can be maintained in KGs in different metaverses. Thus, to deduce the preference or new scenario lines for a resident, it is beneficial to have the ability to infer across different KGs without sharing the data directly. Nevertheless, a decentralized collaboration for Web3 metaverses should not involve a central coordinator. Fig. 5 shows an envisioned framework of decentralized knowledge inference in the context of the parallel Web3 metaverses. The requestor could broadcast its request via the blockchain. Then, others can respond to the request after they evaluate their ability to contribute to the request. In this case, the following issues should be addressed: 1) how to utilize the smart contract and blockchain to facilitate automatic, anonymous, and traceable knowledge sharing; 2) how to determine the usefulness of knowledge and the ability of contributing knowledge.

2) Economic Approach: Valuable insights can be derived from user interactions and preferences to help develop operation mechanisms and attract new users to metaverses [14]. However, stakeholders must acknowledge the value of shared knowledge and carefully consider the associated costs in incentivizing its exchange. In this section, we explain the related costs of knowledge management and discuss how incentivization should also serve as a mechanism for promoting honesty among stakeholders.

Fig. 6 outlines the knowledge management process, where data collected from Internet of Things (IoT) devices, such as personal computers, gaming terminals, and virtual reality gear that facilitate user interaction, are cleaned, maintained, and analyzed into knowledge to be shared among metaverses. Particularly, it is essential to consider the following associated costs: *i) Behavior Analysis:* It is necessary to consider the cost associated with engaging an expert to develop and implement behavior analytic models to capture user preferences. *ii) Consistency Check and Update:* User interests are subject to change over time, necessitating regular reviews of the knowledge stored in KGs to rectify any errors and maintain up-to-date information. Furthermore, abrupt shifts in user behavior patterns could indicate identity theft or impersonation, emphasizing the need for consistency checks. *iii) Scenario Design:* Unique aspects of user interest revealed from certain scenarios are more valuable when shared among other metaverses. Therefore, when assessing the worth of knowledge, it is important to consider the value derived from its uniqueness and the cost of scenario design and implementation. Nevertheless, incentivization serves not only as a means of compensating costs but also as a mechanism for promoting honesty among stakeholders during knowledge sharing. In fact, data quality could affect the result [15] of knowledge sharing with distributed knowledge inference methods. In our envisioned decentralized knowledge inference paradigm for knowledge sharing among Web3 metaverses, where contributing stakeholders locally train the reasoning models of requesting stakeholders (the stakeholder that initiates a decentralized knowledge inference process) without supervision, the challenge lies in incentivizing stakeholders to truthfully utilize the complete KGs for training and selecting stakeholders who are more likely to contribute their KGs honestly.

Limitations and Open Challenges

KGs offer a structured knowledge representation tailored for domain-specific tasks. However, their construction presents challenges, e.g., addressing data incompleteness. Furthermore, modeling unseen entities and novel facts in extant KGs proves difficult. Ensuring KGs' generalization remains a significant hurdle for the proposed decentralized knowledge inference approach. To address this, future studies might consider the integration of LLM-enhanced KGs.

Conclusion

The Web3 metaverse establishes a decentralized ecosystem that provides immersive experiences with unique data ownership. Within this framework, residents can interact with one another and their digital assets securely, transparently, and equitably. Moreover, parallel metaverses that prevent monopolistic markets are necessary for both metaverse residents and operators. In the meantime, it is crucial for multiple metaverses to foster interconnectivity and collaboration, enabling residents to seamlessly navigate between platforms and explore a multitude of possibilities. In this regard, this tutorial paper has highlighted the challenges inherent in interconnection and interoperability between parallel metaverses. Furthermore, it has explored the advantages and practical implementation of decentralized knowledge inference techniques to facilitate knowledge sharing for decentralized collaborations within the parallel Web3 metaverses.

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References

[1] H. Duan et al., "Metaverse for social good: A university campus prototype," in *Proc. 29th ACM Int. Conf. Multimedia*, 2021, pp. 153–161.

[2] W. Cai et al., "Decentralized applications: The blockchain-empowered software system," *IEEE Access*, vol. 6, pp. 53019–53033, 2018.

[3] V. T. Truong, L. Le, and D. Niyato, "Blockchain meets Metaverse and digital asset management: A comprehensive survey," *IEEE Access*, vol. 11, pp. 26258–26288, 2023.

[4] R. Cheng et al., "Will Metaverse be NextG Internet? Vision, hype, and reality," *IEEE Netw.*, vol. 36, no. 5, pp. 197–204, Sep./Oct. 2022.

[5] S.-M. Park and Y.-G. Kim, "A Metaverse: Taxonomy, components, applications, and open challenges," *IEEE Access*, vol. 10, pp. 4209–4251, 2022.

[6] S. Fan et al., "Altruistic and profit-oriented: Making sense of roles in Web3 community from airdrop perspective," in *Proc. CHI Conf. Human Factors Comput. Syst.*, 2023, pp. 1–16.

[7] W. Hyun, "Study on standardization for interoperable Metaverse," in *Proc. 25th Int. Conf. Adv. Commun. Technol.*, Feb. 2023, pp. 319–322.

[8] Y. Liu et al., "An incentive mechanism for sustainable blockchain storage," *IEEE/ACM Trans. Netw.*, vol. 30, no. 5, pp. 2131–2144, Oct. 2022.

[9] N. Sahlab et al., "Knowledge graphs as enhancers of intelligent digital twins," in *Proc. 4th IEEE Int. Conf. Ind. Cyber-Phys. Syst.*, May 2021, pp. 19–24.

[10] S. Pan et al., "Unifying large language models and knowledge graphs: A roadmap," 2023, *arXiv:2306.08302*.

[11] B. Abu-Salih, "MetaOntology: Toward developing an ontology for the Metaverse," *Frontiers Big Data*, vol. 5, Sep. 2022, Art. no. 998648.

[12] D. Song et al., "DTransE: Distributed translating embedding for knowledge graph," *IEEE Trans. Parallel Distrib. Syst.*, vol. 32, no. 10, pp. 2509–2523, Oct. 2021.

[13] Y. Chi et al., "Distributed knowledge inference framework for intelligent fault diagnosis in IIoT systems," *IEEE Trans. Netw. Sci. Eng.*, vol. 9, no. 5, pp. 3152–3165, Sep./Oct. 2022.

[14] H. Ning et al., "A survey on the Metaverse: The state-of-the-art, technologies, applications, and challenges," *IEEE Internet Things J.*, vol. 10, no. 16, pp. 14671–14688, Aug. 2023.

[15] S. Fan et al., "Hybrid blockchain-based resource trading system for federated learning in edge computing," *IEEE Internet Things J.*, vol. 8, no. 4, pp. 2252–2264, Feb. 2021.

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