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A Survey on Decentralized Metaverse using Blockchain and Web 3.0 technologies, Applications, and more.

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ABSTRACT

This survey delves into the convergence of blockchain, Web 3.0 technologies, and the decentralized metaverse, analyzing their combined effects on virtual experiences. The study meticulously examines the decentralized metaverse's architecture, intrinsic properties, and transformative potential. Central to our analysis is the role of blockchain technology in addressing scalability issues and presenting practical applications in virtual real estate, gaming, and social interactions. Furthermore, we explore consensus mechanisms such as Proof of Work (PoW) and Proof of Stake (PoS), emphasizing their significance in the decentralized framework. The survey also investigates governance models and exceptionally Decentralized Autonomous Organizations (DAOs) and identifies associated challenges, including data security threats and possible mitigation strategies. By incorporating case studies on platforms like Decentraland, Vault Hill, and The Sandbox, we illustrate real-world implementations and emerging trends within the decentralized metaverse. This research highlights the profound implications of decentralized technologies on digital interactions, economies, and governance, marking a pivotal shift towards the Web 3.0 era. It underscores the potential for these technologies to redefine ownership, identity, and social engagement in virtual environments. Moreover, the paper outlines future research opportunities, encouraging further exploration into the integration and advancement of decentralized systems within the metaverse. The survey provides a comprehensive overview of the decentralized metaverse, supported by blockchain and Web 3.0 technologies. It offers valuable insights into the challenges and opportunities within this rapidly evolving domain, paving the way for innovative applications and research directions to shape the future of digital interaction and governance.

INDEX TERMS

Decentralized Metaverse, Blockchain Integration, Web 3.0, Consensus Mechanisms, Non-Fungible Tokens (NFTs), Smart Contracts, Decentralized Autonomous Organizations (DAOs), Self-Sovereign Identity (SSI)

I. INTRODUCTION

The metaverse, an amalgamation of the transcendental "meta" and the expansive "verse," has captivated the imagination by envisioning a universe where virtual environments, social interactions, and economic systems intertwine seamlessly. Neal Stephenson's "Snow Crash" may have introduced the term, but the concept has evolved beyond fiction, encompassing descriptions like "Second Life," "3D Virtual Worlds", and "life-logging" [1]. Central to its essence is an immersive shared domain, bridging the realms of the tangible, human, and digital. This era, unfolding in the wake of the Web and mobile internet revolutions, beckons users to embrace their digital nature and engage in alternate realities.

The rapid strides of blockchain and Web3 technologies have ushered in the emergence of decentralized metaverses, propelling the metaverse concept into a new era [2], [3]. This transformation, rooted in security, transparency, and autonomy, addresses the limitations of the traditional metaverse paradigm. Centralized metaverses grapple with limited user control, security vulnerabilities, and interoperability con-

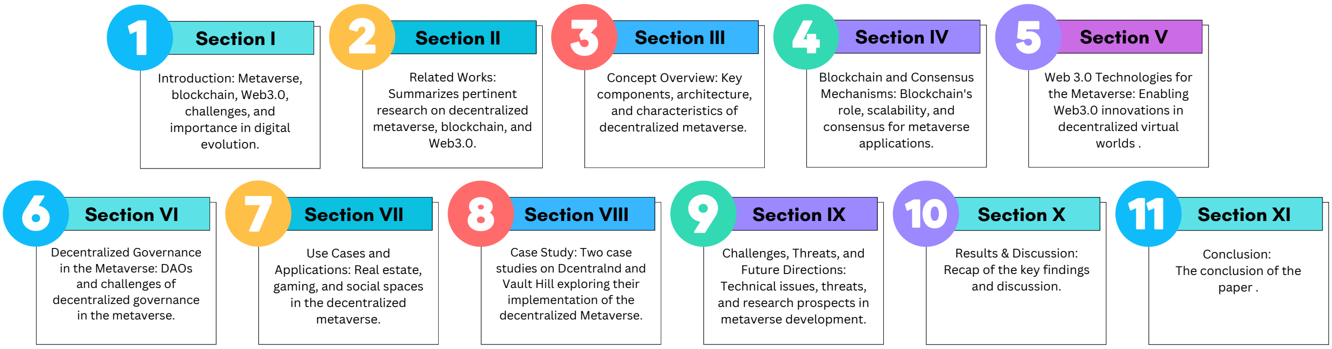

FIGURE 1: Sections of the paper.

straints. Recent projections foresee a lucrative market with an estimated worth of $87 billion by 2030 [4]. This compels us to explore decentralized alternatives that offer augmented user autonomy, fortified security, and cross-platform adaptability. Furthermore, centralized metaverses contend with challenges tied to data ownership, censorship vulnerability, and dependence on singular authorities [5]. Understanding these multifaceted problems is indispensable to fostering inclusivity and user-centeredness within the metaverse.

Currently, attempts to address the shortcomings of centralized metaverses are marred by inefficiencies and limitations. While some centralized platforms partially integrate distributed ledger technologies, the reliance on centralized servers remains a stumbling block, leading to concerns of single points of failure, opacity, and potential censorship [2]. The proprietary nature of these platforms curtails interoperability and curbs users' control over their virtual assets and identities [6]. The quest for decentralized metaverses, leveraging blockchain and Web 3.0 technologies, stems from the need to transcend these restrictions and enhance user experiences.

The limitations of current metaverse approaches have driven interest in decentralized alternatives. Blockchain and Web 3.0 advancements have expedited this shift, enabling benefits like user control, transparent transactions, cross-platform communication, and reduced intermediary reliance [7]. This change can entirely revolutionize various industries, including gaming, entertainment, education, and commerce [8].

This survey paper investigates the potential of utilizing Web 3.0 and blockchain technology to develop decentralized metaverses that address the limitations of centralized metaverses. By leveraging the inherent characteristics of decentralization, transparency, and consensus mechanisms offered by blockchain, decentralized metaverses empower users with greater control over their virtual assets, enhance security and privacy measures, enable seamless interoperability across different metaverses, and reduce transaction costs. Additionally, integrating smart contracts with decentralized governance models fosters trust, user-driven decision-making, and the development of a thriving metaverse ecosystem [9].

TABLE 1: Table of Acronyms

Term	Full Form
AR	Augmented Reality
AXS	Axie Infinity Shards
BFT	Byzantine Fault Tolerance
CDNs	Content Delivery Networks
CPU	Central Processing Unit
DAO	Decentralized Autonomous Organization
DDoS	Distributed Denial-of-Service
DLT	Distributed Ledger Technology
DPoS	Delegated Proof-of-Stake
DeFi	Decentralized Finance
DID	Decentralized Identity
ERC	Ethereum Request for Comment
GPU	Graphics Processing Unit
GRT	The Graph Token
ILP	Interledger Protocol
IPFS	InterPlanetary File System
MANA	Decentraland's virtual token
MSF	The Metaverse Standards Forum
NFT	Non-fungible Token
OMI	Open Metaverse Interoperability Standards
OMG	Open Metaverse Interoperability Group
P2E	Play-to-Earn
PoA	Proof-of-Authority
PoH	Proof-of-History
PoS	Proof-of-Stake
PoST	Proof-of-Space-Time
PoW	Proof-of-Work
SSI	Self-Sovereign Identity
USD	US Dollar
VR	Virtual Reality
W3C	World Wide Web Consortium
X3D	Extensible 3D
XR	Extended Reality
ZKP	Zero-Knowledge Proof

The impetus for this effort comes from the flaws in the existing metaverse development techniques pointed out in the preceding paragraphs, which underline the need for decentralized alternatives. Decentralized metaverses can provide unmatched advantages by adopting blockchain and Web 3.0 technologies, such as user sovereignty, transparent and auditable transactions, seamless cross-platform interactions, and a decreased reliance on intermediaries. Several businesses, including gaming, entertainment, education, and commerce, stand to benefit from these developments.

According to industry reports, the global blockchain mar-

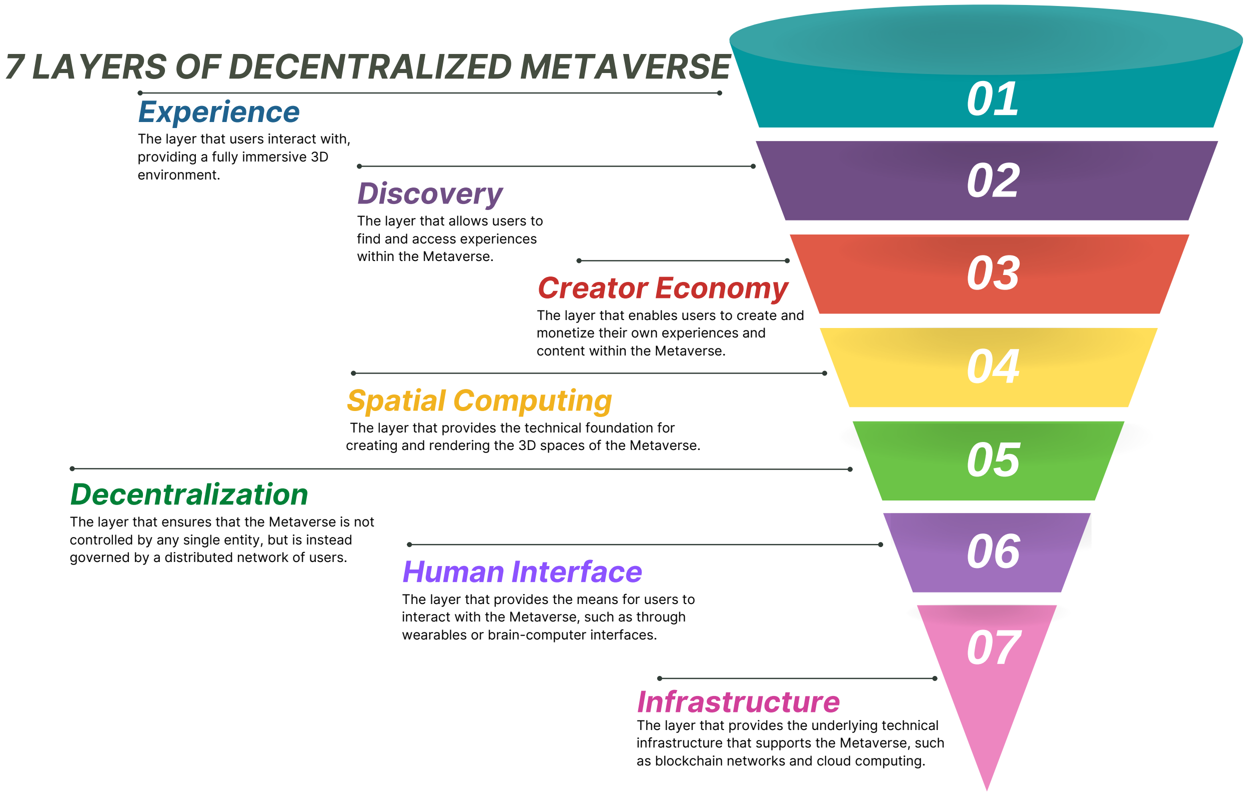

FIGURE 2: Sections of the paper.

ket is expected to reach \$1431.54 billion by 2030 [10]. This exponential growth signifies the immense potential and motivation to harness decentralized metaverses as the future of immersive virtual experiences. The metaverse can fulfill these desires by providing a dynamic and interactive digital environment.

The potential of decentralized metaverses to disrupt conventional business models and unlock novel economic avenues is undeniable [3]. The tokenization of virtual assets enables secure ownership, transferability, and monetization [8], ushering in a decentralized economy where users can create, trade, and profit from virtual possessions [2]. This paradigm shift can reshape economic landscapes and empower individuals in unprecedented ways.

Furthermore, decentralized metaverses wield the power to counteract censorship and content moderation concerns [11]. This atmosphere of openness and inclusivity cultivates diversity and innovation within the metaverse ecosystem.

Given these advantages, decentralized metaverses stand poised to redefine the trajectory of digital interactions [12]. By combining the strengths of blockchain and Web3 technologies, they offer a decentralized, secure, and immersive milieu that empowers users and forges novel avenues for social, economic, and cultural interactions.

Thus, the imperative to enhance current centralized metaverse architectures through decentralized principles underpinned by blockchain and Web3 technologies becomes evident.

This research's primary contributions encompass:

– **Holistic Integration:** Synthesizing the components of decentralized metaverses, from concepts to Web 3.0 technologies, blockchain applications, and governance models, delivering a comprehensive panorama.
– **Decentralization Exploration:** Defining and applying decentralization principles within the metaverse, unraveling their transformative influence on governance, ownership, and decision-making.
– **Risk Mitigation Insights:** Identifying and proposing solutions to technical challenges and security threats in decentralized metaverse implementations, providing actionable risk-mitigation strategies.
– **Future-Forward Direction:** Focusing on emerging trends and research trajectories, presenting a roadmap for future innovations in the dynamic realm of decentralized metaverse technology.

This paper delves into decentralized metaverses, exploring their architecture, the role of blockchain, and the potential benefits of decentralized governance models. Fig. 1 summarizes the structure of the paper. It covers various applications, including virtual real estate, gaming, collaborative spaces, and Decentraland, Vault Hill, and The Sandbox case studies. Fig. 2 depicts the seven layers of a decentralized metaverse and presents the detailed taxonomy by briefly explaining all the seven layers. The paper also addresses challenges, emerging technical hurdles, and data security innovations. Table 1 lists all the acronyms used throughout the paper. The summary highlights the results and underscores the transformative role of the metaverse in the Web 3.0 era. The references section provides the foundation for this exploration. Join us on this journey of discovery as we explore the nexus of decentralized metaverse, blockchain, and Web 3.0.

II. RELATED WORKS

Numerous studies have delved into the possibilities of utilizing blockchain and Web3 technologies to create decentralized metaverses. In this section, we outline the current research and emphasize their efforts in comprehending and enhancing the realm of decentralized metaverses. The concept of decentralized metaverses has gained significant attention in recent years. Researchers have proposed various architectural designs and frameworks to leverage blockchain and Web3 technologies for creating decentralized virtual environments.

To ensure a comprehensive understanding of the evolving landscape of decentralization of the metaverse, we have conducted a thorough literature review encompassing a broad timeframe (1992-2024). Scholarly databases like ACM Digital Library, IEEE Xplore, SpringerLink, ScienceDirect, and more were utilized alongside Google Scholar, relevant industry news reports, and well-known blogs. This multifaceted approach aims to capture the full spectrum of research and developments in the field, from its early conceptualizations to its current applications. Table 2 summarizes the research work reviewed below.

Daniel Mawunyo Doe *et al.* [13] proposed an incentive mechanism to foster sustainable growth within blockchain networks integral to the metaverse. Their work underscores the importance of incentive structures in promoting active participation and resource contributions from users while mitigating centralization risks. By aligning individual interests with the collective goals of the network, this approach enhances the economic viability and democratization of the metaverse. Furthermore, the authors conducted a comparative analysis of existing incentive mechanisms in blockchain systems, showing that their proposed mechanism increases the blockchain network's utility by 48.48% to 54.52% and reduces the users' cost by 38.46% to 62.5%, highlighting the novel aspects of their proposal and its potential impact on creating a more inclusive and resilient decentralized virtual environment.

Vu Tuan Truong *et al.* [2] provided a comprehensive analysis of blockchain's systemic impact on the metaverse, focusing on decentralized governance and data management solutions. Their study explores technical and socio-economic implications, including user autonomy and content moderation trade-offs inherent in designing inclusive metaverse platforms. Additionally, the authors conducted case studies of existing decentralized governance models in blockchain networks, analyzing their effectiveness in ensuring platform transparency and user trust. These insights offer valuable guidance for designing governance structures tailored to the unique needs of decentralized virtual environments.

Taras Maksymyuk *et al.* [14] introduced a groundbreaking framework for future metaverse applications in their article. The framework involves synchronized data flows from multiple operators through various wearable devices, each with unique quality requirements. It presents a novel service quality model incorporating customizable utility functions for individual data flows. This approach relies on dynamic, fine-grained data flow allocation and service selection facilitated by non-fungible tokens (NFTs) traded on the blockchain within a decentralized mobile network environment. This innovative system allows seamless interaction and cooperation among users and operators, paving the way for efficient and versatile metaverse experiences.

Yuchuan Fu *et al.* [15] investigated the metaverse's evolution, design, and significant tendencies, including its integration with blockchain and intelligent networking technologies. Their research explores the technical feasibility of integrating these technologies and evaluates their impact on user experience and platform scalability within decentralized virtual environments. The authors offer valuable insights into designing robust and scalable metaverse infrastructures by conducting comparative analyses of different networking architectures and consensus mechanisms. Additionally, their exploration of blockchain's role in addressing metaverse demands and challenges sheds light on potential collaborations between blockchain and intelligent networking technologies, informing future research directions and industry practices.

Rui Quin *et al.* [16] introduced an article that reanalyzed DAOs, providing a precise definition of Decentralized Autonomous Organizations and Operations. They explored fundamental principles, requirements, and a five-layer intelligent architecture based on CPSS and parallel intelligence. Governance mechanisms and incentive structures for humans, robots, and digital humans were discussed, serving as a stepping stone for future DAO research and development. The article proposed a five-layer intelligent architecture, closed-loop equation, and new function-oriented intelligent algorithms for DAOs. It also discussed incentive mechanisms for humans, robots, and digital entities in the context of DAOs, which can all be implemented in the decentralization of the metaverse.

Yuntao Wang *et al.* [17] delved into the complexities of distributed metaverse architectures, exploring their potential impact on security, privacy, and user trust. Their research analyzes existing security and privacy threats in metaverse systems and proposes effective countermeasures to mitigate these risks. The authors offer valuable insights into designing resilient and trustworthy metaverse platforms by conducting comparative analyses of different security architectures and their effectiveness in safeguarding user data and plat-

TABLE 2: Related Works

Authors, Reference & Year	Summary
Daniel Mawunyo Doe *et al.* [13] (2023)	Explored the role of blockchain in Web 3.0 and Metaverse through incentive mechanism and contact theory.
Vu Tuan Truong *et al.* [2] (2023)	Described how blockchain can shape the metaverse from a system perspective, including decentralized governance and data management solutions.
Taras Maksymyuk *et al.* [14] (2022)	Proposed a framework for metaverse applications with synchronized data flow from wearable devices and quality requirements.
Yuchuan Fu *et al.* [15] (2023)	Explored blockchain and intelligent networking technologies for addressing metaverse demands and challenges.
Rui Quin *et al.* [16] (2023)	Explored the potential of decentralized autonomous organizations (DAOs) in revolutionizing blockchain and Web3 structures.
Yuntao Wang *et al.* [17] (2023)	Discussed security, privacy threats, and countermeasures in metaverse systems.
Bisenghui Tao *et al.* [18] (2022)	Focused on modeling blockchain transaction networks based on structural identity representation.
Akbobek Abilkaiyrkyzy *et al.* [19] (2023)	Identified critical requirements for successful metaverse platforms, while highlighting the need for advancements in blockchain and AI.
Ramirez-Masferrer *et al.* [20] (2024)	Explored teaching in free metaverses, gaming adaptations, and future educational trends.
Our work (2024)	Explored previous research and provided a comprehensive survey of the decentralized metaverse, integrating blockchain and Web 3.0 technologies, while addressing challenges, governance models, use cases, and future directions.

form integrity. Additionally, their exploration of blockchain's cryptographic primitives and their role in enhancing security and privacy within decentralized virtual environments inform future research directions and industry best practices.

Bisenghui Tao *et al.* [18] introduced a new approach to analyzing blockchain transaction networks that emphasizes structural identity. They analyzed three metaverse-related systems (ETH, BTC, and NFT) and conducted complex network analysis to obtain new insights. Their research suggested a technique for representation learning called SVRP. It employs graph neural networks (GNNs) to acquire the network's latent representation and structural identity. The results show that their proposed method outperforms existing methods in multiple tasks, achieving high accuracy in node classification and link prediction. In short, this paper provides a new approach to modeling and understanding blockchain transaction networks using complex network analysis and representation learning.

Akbobek Abilkaiyrkyzy *et al.* [19] investigated the essential qualities that underpin successful metaverse platforms. They acknowledged the existence of numerous metaverse platforms, each boasting distinct strengths and weaknesses. To achieve widespread adoption, the authors established ten critical requirements that a metaverse platform should strive to satisfy. Interoperability, seamless user migration between platforms, and security safeguarding user data were identified as two paramount requirements. The article underscores the necessity for further advancements in fields like blockchain technology and artificial intelligence to bolster the capabilities of metaverse platforms.

Ramirez-Masferrer *et al.* [20], in their recent study, compared the variations in teaching possibilities within these virtual environments. Their research focused on free metaverses, considering factors like the changing landscape of available platforms, hardware requirements, teacher and student preparedness, and the potential for immersive learning experiences. The study also investigated the repurposing of entertainment or gaming metaverses for educational purposes, highlighting the advantages and challenges of such adaptations. Furthermore, they explored the possibility of creating or utilizing existing virtual spaces to partially substitute real-life experiences, creating a more immersive learning environment. By analyzing these trends, the authors offer predictions on the short-term, medium-term, and long-term future of educational possibilities within the metaverse. Even though most of their research focused on the educational opportunities provided by the metaverse, decentralization may be able to address some problems they found.

While the reviewed literature provides a foundation for understanding decentralized metaverses, a more critical analysis is warranted to elucidate their strengths, weaknesses, and how they align with our manuscript's unique contributions. Our work aims to address the following shortcomings identified in the current research landscape:

- *Limited Comparative Analysis:* Existing studies often lacked in-depth comparisons among decentralized metaverse platforms. Our work will address this gap by comparing prominent platforms and highlighting their distinct features, advantages, and limitations. This analysis will be crucial for discerning which platforms are best suited for specific applications and user demands.
- *Shallow Exploration of Blockchain's Impact:* While sev-

eral works acknowledge the role of blockchain technology, they often provide a superficial exploration of its specific contributions to decentralized metaverses. Our manuscript will delve deeper into this aspect, detailing how blockchain empowers various functionalities within these virtual environments. We will illustrate how blockchain fosters decentralization, transparency, security, and user ownership within the metaverse.

Our survey aims to provide a more comprehensive and nuanced understanding of decentralized metaverses by addressing these critical aspects. Our comparative analysis and in-depth exploration of blockchain's influence will offer valuable insights for researchers, developers, and stakeholders invested in the future of this evolving technological domain.

In conclusion, the related works section provides valuable insights into the progress, challenges, and potential of decentralized metaverses using blockchain and Web 3.0 technologies. We have identified critical areas for further exploration and emphasized how our work will address the limitations of existing research by providing a more nuanced analysis and focusing on the transformative potential of blockchain technology within these virtual environments.

III. CONCEPTS OVERVIEW

This section provides a comprehensive background study of the concepts, components, and standards related to the metaverse, decentralization, blockchain, and Web 3.0 technologies. We explore the existing standards, metaverse architecture, key characteristics, enabling technologies, and the principles of decentralization. Additionally, we delve into the evolution of Web 3.0, the role of blockchain, and smart contracts in shaping the metaverse.

A. THE CONCEPT OF THE DECENTRALIZED METAVERSE

- *Decentralized Metaverse: Definitions and Characteristics* Several experts and researchers have offered valuable insights into the concept of the decentralized metaverse. Understanding these definitions is crucial as we explore this social and technological development.
  One perspective, presented by Decentraland [21], emphasizes the metaverse as a virtual world powered by Web3 and blockchain technologies. This approach highlights the ownership of virtual assets within this decentralized environment. Lik-Hang Lee *et al.* [22] take a more progressive view, outlining a three-phase evolution:
  1) Mirroring the Real World: This initial stage focuses on replicating aspects of our physical reality within the virtual space.
  2) Creating Native Content: As the metaverse matures, it moves beyond mirroring to encompass the development of original experiences and content unique to the virtual world.
  3) Self-Sustaining and Surpassing: In the final phase, the metaverse becomes a self-sufficient entity, potentially surpassing the capabilities and offerings of the real world.

  Adding to this perspective, Chen *et al.* [23] define the decentralized metaverse as a "decentralized, closed-loop society system." Their perspective suggests a virtual society operating independently, with its own economic and social structures.
- *Overview of the Metaverse Concept:* The metaverse concept is an imaginative expansion of our digital interactions, an intricate virtual domain where individuals transcend the confines of physical space to engage, interact, and craft within a communal digital universe [24]–[26]. Within this interconnected sphere, enhanced by technological progress, users effortlessly navigate immersive realms, partake in social endeavors, conduct business transactions, and even establish their digital assets [2]. The metaverse signifies the convergence of virtual reality, augmented reality, and the internet, presenting an expansive canvas for human creativity and interaction [27].
  In their paper "Web3 Metaverse: State-of-the-Art and Vision" [23], Chen *et al.* delve into the concept of the Web3 Metaverse, a novel virtual world built upon the foundations of decentralized technologies. The paper explores the convergence of three distinct communities: immersive convergence, crowd intelligence, and Web3. The Web3 Metaverse aspires to establish a decentralized virtual space that fosters social interaction and economic opportunities by integrating technologies from these areas. The authors propose a framework for dissecting the Web3 Metaverse through the lens of human identity, field of activity, and behavior. This framework serves as a foundation for understanding how these elements coalesce to shape the Web3 Metaverse.
- *Existing Metaverse Related Standards:* The metaverse landscape is guided by a range of evolving standards that govern interoperability, identity management, and virtual asset exchange [17]. For instance, the XR (Extended Reality) standards encompass virtual reality (VR), augmented reality (AR), and mixed reality (MR) experiences, laying the foundation for immersive environments [28], [29], [30], [31]. Moreover, the Open Metaverse Interoperability Group (OMG) [32] has established protocols to facilitate interoperability between different metaverse platforms. Table 3 briefly describes the existing standards. These standards enable seamless interactions and content sharing across diverse metaverse ecosystems.
- *Metaverse Architecture:* The decentralized metaverse architecture is to be constructed upon a stratified foundation. Key components include the immersive user interface, content delivery networks, distributed databases, and interaction protocols [38], [39]. These components combine to create an ecosystem enabling seamless and immersive user experiences. Blockchain

TABLE 3: Existing Metaverse Related Standards

Standard	Description
XR	Xtended Reality(XR) encompasses VR, AR, and mixed reality experiences for an immersive environment [28].
OMG	Open Metaverse Interoperability Group (OMG) focuses on enhancing cross-platform compatibility and standards. [33].
DID	Decentralized Identity (DID) is a W3C standard that focuses on establishing self-sovereign and decentralized identity systems [34].
ILP	Interledger Protocol (ILP) enables seamless and secure payments across different payment networks. [35]
VRML	Virtual Reality Modeling Language (VRML) is a language that pioneered 3D graphics and interactive content in virtual spaces. [36].
X3D	X3D is a successor to VRML, enabling richer, interactive 3D content [37].

and Web 3.0 technologies underpin these layers, ensuring data integrity, decentralization, and secure transactions within the metaverse. The different layers of a decentralized metaverse architecture are visualized according to their hierarchy in Fig. 2.

- *Enabling Technologies:* The decentralized metaverse's realization is fueled by a web of immersive, multi-user, permanent platforms. Cloud computing, augmented reality (AR), virtual reality (VR) [29], [30], and haptic feedback systems synergize to create immersive environments. The integration of blockchain technology and the principles of Web 3.0 underpin the decentralized nature of the metaverse, ensuring secure transactions, identity management, and data ownership [40].

B. CENTRALIZED METAVERSES

In a centralized metaverse, a sole entity has complete control and management authority. However, transparency may be limited as it relies on the reputation of this central authority [41]. Interoperability among platforms may also be hindered, and the economy and ownership of virtual assets are centralized [17], [42]. Despite offering streamlined control, this model poses challenges like transparency and user autonomy. A well-known example of such a metaverse is the video game **Roblox** developed by the Roblox Corporation [43].

C. UNDERSTANDING DECENTRALIZATION

In the world of metaverses, decentralization holds a crucial role in shaping virtual landscapes and interactions. This fundamental concept aims to disperse authority, control, and decision-making away from central entities, fostering a more open and resilient metaverse environment [44]. Table 4 presents the differences between centralized and decentralized metaverses. Several key characteristics of decentralization seamlessly blending into the metaverse concept are:

- **Transparency in Virtual Transactions:** Like decentralized systems, future metaverses will use transparency to log all virtual actions on a public ledger [45]. This will ensure accountability, allowing participants to verify actions and maintain the metaverse's integrity [2].
- **Preserved Unalterable Virtual History:** In the metaverse, data immutability matters [46]. Decentralization will safeguard unchangeable virtual data, establishing trust. This will ensure a dependable history of the metaverse [47].
- **Secured Virtual Realms:** Decentralized metaverses will employ cryptography to boost security. By distributing assets across nodes, risks of unauthorized access will be reduced, guaranteeing secure virtual experiences [2], [48].
- **Resilience Against Glitches:** Future metaverses, thanks to decentralization, will endure glitches without overall failure [9]. Participants will be able to continue immersive experiences despite challenges in specific elements.
- **Trust-Free Virtual Interactions:** In the future metaverse, decentralization will enable trust-free interactions [49]. Smart contracts and consensus mechanisms will cut intermediaries, allowing seamless exploration, interaction, and transactions [50].

D. ADVANTAGES AND LIMITATIONS OF DECENTRALIZATION:

Decentralization has its upsides and downsides. They are briefly explained below:

- **Advantages of Decentralization:** The metaverse capitalizes on the benefits of decentralization to empower users with ownership of virtual assets, democratic governance, and interactions resistant to censorship. These aspects collectively cultivate user trust and facilitate the establishment of diverse, user-driven ecosystems [51].
- **Limitations of Decentralization:** While decentralization bolsters security through distribution, it can inadvertently lead to latency and scalability problems, particularly in rapidly evolving metaverse environments [51]. Additionally, consensus mechanisms needed for decentralized decision-making may introduce complexities impacting real-time interactions [52].

E. WEB3.0 TECHNOLOGIES & BLOCKCHAIN

- **Introduction to Web3.0:** Web3.0, the evolution of the internet, emphasizes decentralization, enhanced user interactions, and seamless data exchange. Its key components include blockchain technology, smart contracts, interoperability, decentralized identity, tokenization of assets, and more [53]. The convergence of blockchain, semantic web, and decentralized protocols creates an ecosystem that aligns with the decentralized metaverse's vision [54].

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TABLE 4: Comparison of Centralized and Decentralized Metaverse

Feature	Centralized Metaverse	Decentralized Metaverse
Ownership Model	Centralized ownership	Decentralized ownership
Control Over Assets	Platform-controlled	User-controlled
Digital Asset Interoperability	Limited across platforms	Enhanced interoperability
Economic Model	Platform-driven economy	User-driven economy
Censorship Resistance	Vulnerable to central control	Resistant to censorship
Privacy	Platform-dependent	User-centric privacy control
Security	Centralized security measures	Enhanced through decentralization
Governance	Platform-centric governance	Decentralized governance models
Monetization	Platform dictates revenue	User-driven monetization models
Content Control	Centralized content control	Distributed content control

- **Blockchain:** Blockchain is a decentralized ledger technology that records transactions across many computers. It serves as the foundational technology for Web 3.0, ensuring data integrity, security, and user empowerment. Its distributed ledger architecture verifies and records transactions, addressing provenance, traceability, and digital asset ownership [44].
- **Interoperability:** Web 3.0 aims to enable seamless communication and data exchange among blockchain networks, creating a unified and connected ecosystem. Interoperability is essential for the decentralized metaverse to function as a cohesive and integrated virtual environment [55]. It allows users to interact across different metaverse platforms, bringing together diverse virtual experiences [56].
- **Smart Contracts and the Metaverse:** Smart contracts, self-executing code embedded in blockchain transactions, play a pivotal role in the decentralized governance and economy of the metaverse [57]. They automate and enforce agreements, from virtual asset exchanges to participatory decision-making within decentralized autonomous organizations (DAOs) [16].

F. DECENTRALIZED METAVERSE INFRASTRUCTURE: CHALLENGES AND REQUIREMENTS

The decentralized metaverse is a vision of a virtual universe that transcends physical boundaries. [25], [26]. However, widespread adoption hinges on addressing critical infrastructure requirements currently lacking in the nascent metaverse landscape. Some of the main concerns are mentioned below:

- **Network Bandwidth Demands:**Supporting thousands of avatars in a decentralized metaverse requires a massive leap from the current streaming bandwidth [58], [59]. Decentralized network solutions are crucial for handling this data surge.
- **Latency:** Decentralized architectures, with data spread across nodes, can introduce latency challenges [59]. Optimizing decentralized network protocols and strategically distributing server clusters can minimize data travel distances and maintain a seamless experience.
- **Hardware Demands:** Currently, the hardware equipment required to access the metaverse, like VR headsets and high-end computers, is quite costly and not readily available [25]. Advancements in technologies involving such hardware are required to make them affordable and available.
- **Storage Demands:** Decentralized metaverses require keeping vast amounts of data. Decentralized storage solutions like Filecoin [60] or Arweave [61] are promising, but their scalability for the metaverse's data volume remains unproven. Large-scale implementation of such metaverses would require extensive research in storage technologies.

These technical challenges faced in realizing a decentralized metaverse are further discussed in detail in Section IX.

In conclusion, this concepts overview section elucidates the components, characteristics, and enabling technologies that define the decentralized metaverse, including the challenges in the infrastructure to implement it on a large scale. By embracing the principles of decentralization and harnessing technologies like blockchain and Web 3.0, the metaverse ecosystem advances toward a future characterized by user-centricity, inclusivity, and digital sovereignty.

IV. BLOCKCHAIN AND CONSENSUS MECHANISMS FOR THE METAVERSE

In this segment, we explore the crucial role that blockchain technology and consensus mechanisms play in influencing the structure and functioning of the decentralized metaverse. As applications within the metaverse become more intricate and expansive, we tackle the vital issues of scalability and efficiency. Furthermore, we carefully analyze how various blockchain platforms are utilized within this immersive digital environment.

A. ROLE OF BLOCKCHAIN IN THE DECENTRALIZED METAVERSE

Integrating blockchain technology into the metaverse ecosystem addresses fundamental challenges concerning transparency, security, and trustworthiness. Through the application of distributed ledgers, Blockchain furnishes an immutable record of transactions, asset ownership, and interactions [11]. This transparency nurtures a sense of user confidence that is indispensable within virtual realms, where the notions of identity and the lineage of assets hold paramount importance [62].

The scalability problem, which often looms over metaverse applications due to the dynamic nature of virtual interactions, can be skillfully tackled via the decentralized architecture of blockchain [14]. By incorporating shard chains, layer-2 solutions, and hybrid consensus mechanisms, congestion problems are minimized, and throughput is increased, resulting in smoother and seamless user experiences.

Decentraland is one of the most well-known metaverses that uses blockchain technology to achieve decentralization. Built on the Ethereum blockchain, it is a virtual world where users can purchase and customize plots of land (parcels), interact with others, and participate in a virtual economy. Land ownership is secured on the Blockchain, ensuring transparency and immutability of ownership records. Transactions involving virtual assets (wearables, avatars) leverage smart contracts, enabling secure and trustless peer-to-peer interactions [63]. The technical details of its implementation and architecture are further discussed in Section VIII.

Beyond the foundational functionalities, let us delve deeper into how blockchain technology specifically enhances these immersive environments:

– **Secure and Transparent Ownership:** Blockchain technology underpins secure and transparent ownership of virtual assets within the metaverse. Assets like virtual land parcels, avatars, wearables, and in-game items are tokenized as NFTs (non-fungible tokens) on the blockchain [64]. This tokenization ensures:
  - **Immutability:** Ownership records cannot be tampered with or forged, as all transactions are permanently recorded on the distributed ledger. This fosters trust and eliminates concerns about fraudulent activities.
  - **Traceability:** The complete ownership history of an NFT is readily available, allowing users to verify the authenticity and provenance of their virtual assets.
  - **Interoperability:** NFTs can potentially be transferred seamlessly across different metaverse platforms built on compatible blockchains, promoting a more unified virtual economy.

– **Decentralized Marketplaces:** Blockchain facilitates the creation of secure and trustless marketplaces within the metaverse. Here, users can buy, sell, and trade their virtual assets directly with each other, eliminating the need for intermediaries. Smart contracts automate transactions, ensuring secure execution and eliminating the risk of counterparty default [65].
  - **Example: The Sandbox Marketplace:** Built on the Ethereum blockchain, The Sandbox Marketplace allows users to trade LAND tokens (representing virtual land parcels) and other NFTs using SAND, the platform's native utility token [66]. This cultivates a vibrant in-game economy where players can monetize their creations and participate in a play-to-earn model [67].

– **Play-to-Earn Economies:** Blockchain enables the development of play-to-earn (P2E) experiences within the metaverse. Players can earn tokens or NFTs through gameplay, which can be used within the metaverse or traded for real-world value. This economic model incentivizes user engagement and participation, nurturing a more sustainable metaverse ecosystem [68].
  - **Example: Axie Infinity:** This popular P2E game leverages the Ronin sidechain, a blockchain designed explicitly for the Axie Infinity ecosystem. Players breed, battle, and trade collectible creatures (Axies) represented as NFTs [69], [70]. Ownership of these axes is secured on the Blockchain, and players can earn Smooth Love Potions (SLP) tokens [71] through gameplay. These SLP tokens can be used within the game or cashed out for real-world value [70].

– **Identity Management:** Blockchain offers a potential solution for self-sovereign identity management within the metaverse. Users can manage their digital identities on the Blockchain and use them across various metaverse platforms [10]. This eliminates reliance on centralized identity providers and empowers users with greater control over their data.
  - **Example: ERC-725 Identity Protocol:** Imagine a single digital ID for all your metaverse adventures. No more starting from scratch on each platform. ERC-725, a developing standard, is making this dream a reality on the Ethereum blockchain [72]. The ERC-725 standard on the Ethereum blockchain transforms identity management for the developing decentralized metaverses. It enables users to create self-sovereign identities (SSIs), essentially secure digital passports [73]. These SSIs store user data and credentials issued by trusted sources within the metaverse. Users hold complete control over their SSIs, choosing what information to share with different platforms, fostering privacy and security [72], [74]. This standard paves the way for a more unified metaverse experience, allowing SSIs to function across various platforms built on compatible blockchains.

These are just a few examples of how blockchain technology revolutionizes our interactions with virtual environments. As the metaverse continues to evolve, we can expect even more innovative applications of Blockchain to emerge, shaping the future of this immersive digital landscape.

Real-world instances underscore the indispensability of Blockchain in the metaverse [75]. Various blockchain platforms, like the ones discussed above, are being used to

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support decentralized metaverse experiences, whether by enabling secure ownership of virtual assets or establishing interoperable ecosystems. These platforms underscore the tenets of decentralization, user agency, and secure transactions, all in harmony with the core ethos of the metaverse.

From the above discussion, we observe that blockchain technology plays a vital role in a decentralized metaverse by establishing secure and transparent ownership mechanisms, facilitating decentralized marketplaces, enabling play-to-earn economies, and empowering users with self-sovereign identity management. By addressing these crucial aspects, Blockchain paves the way for a more secure, trustworthy, and user-centric metaverse experience.

As we delve deeper into the metaverse's decentralization, the mechanisms governing interactions and transactions become paramount. Here is where consensus mechanisms come into play, ensuring these virtual environments' smooth operation and security.

B. EXPLORING CONSENSUS MECHANISMS

Within the metaverse, where trust in a decentralized world is crucial, consensus mechanisms reign supreme. These mechanisms, acting as the digital backbone, guarantee that all network participants agree about the validity of transactions and the current state of the virtual world. This shared understanding is essential for establishing a secure and dependable foundation for the ever-expanding metaverse. PoW and PoS are traditional and most commonly used among various consensus mechanisms. A concise comparison between the established Proof-of-Work (PoW) and Proof-of-Stake (PoS) mechanisms is provided below to give insight into their suitability for metaverse dynamics [76].

Proof-of-Work (PoW), known for its robust security through computationally intensive puzzles, poses challenges in energy consumption and scalability. These limitations become especially concerning in the context of the metaverse, where a massive user base and high transaction volume are anticipated [76], [77]. While PoW offers strong security guarantees, the vast amount of computational power required raises environmental concerns and limits the ability of the network to handle a rapidly growing metaverse [78].

Proof-of-Stake (PoS), on the other hand, offers an attractive alternative due to its energy efficiency and potential for higher transaction throughput. In a Proof-of-Stake system, validators are chosen based on the amount of cryptocurrency they hold and have staked in the network [76], [79]. This eliminates energy-guzzling computations and allows the network to handle more transactions more efficiently. This improved scalability is crucial for the metaverse, where a smooth and responsive user experience is paramount [80].

Fig. 3 briefly describes the workings of the consensus mechanisms (PoW and PoS).

Example: Decentraland's Shift to PoS: Decentraland, as mentioned earlier, initially utilized the Proof of Work (PoW) consensus mechanism inherited from the Ethereum blockchain. However, recognizing the limitations of PoW in terms of scalability and energy consumption, Decentraland is transitioning to a Proof of Stake (PoS) based system called the Decentraland Security Module (DSM) [81]. This shift is expected to enhance transaction speed, reduce gas fees, and improve overall network efficiency, paving the way for a more scalable and sustainable Decentraland metaverse.

Ethereum's transition to Ethereum 2.0 with its PoS-based consensus mechanism enhances energy efficiency and scalability for metaverse applications [82].

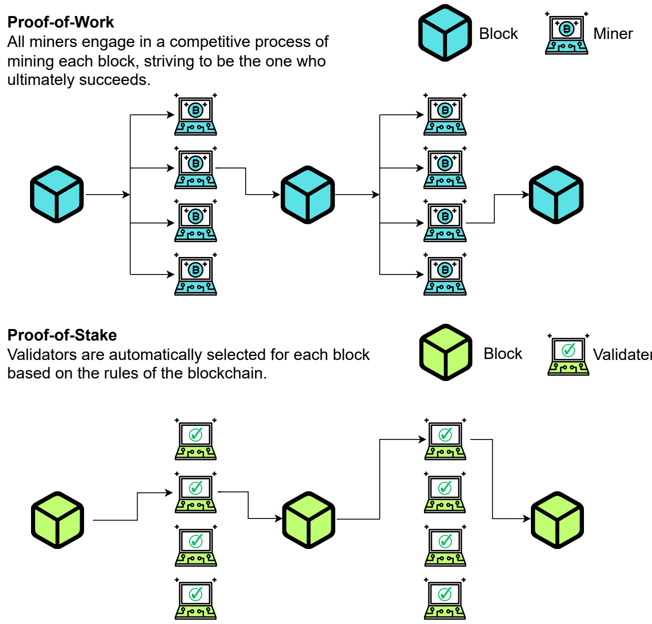

FIGURE 3: PoW vs PoS.

Beyond PoW and PoS, emerging consensus mechanisms are being tailored to the unique requirements of virtual environments. Some prominent ones are as follows:

- **Delegated Proof of Stake (DPoS):** In DPoS, users vote for a fixed number of delegates who are responsible for validating transactions. This approach offers faster transaction speeds than PoS but introduces an element of centralization through elected delegates [9], [57], [83].
  - **Example: EOS and Tron:** These metaverse platforms leverage DPoS to achieve high transaction throughput for their virtual worlds [84]. EOSIO, the software powering EOS, offers a high degree of customization for developers building decentralized applications within the EOS ecosystem. Similarly, Tron utilizes DPoS to facilitate fast and low-cost transactions for in-game assets and functionalities within its Tron network [85].
- **Proof of Space-Time (PoST):** This mechanism utilizes both storage space and time to secure the network. By requiring validators to dedicate storage space, PoST discourages malicious activity while promoting efficient resource allocation [86].

- **Example: Storj:** It is a decentralized cloud storage platform that utilizes PoST. This characteristic could make PoST suitable for metaverse applications with high storage demands for user-generated content or virtual assets [87].
- **Example: Metaverse Filecoin Integration:** As previously discussed, While not currently implemented, Filecoin, a decentralized storage network utilizing PoST, has the potential to be integrated with future metaverse platforms. Metaverse applications could leverage Filecoin's secure and scalable storage for user-generated content, virtual item backups, or even as a platform for storing metaverse world data [60].

– **Proof of Authority (PoA):** In PoA, validators are preselected, trusted entities known for their reputation and identity. This approach offers high transaction speeds and low latency but comes at the cost of reduced decentralization [88]. ConsenSys, a blockchain software company, utilizes PoA in its private blockchain solutions that could be adapted for permissioned metaverse environments [89].

- **Example: AAVE (DeFi Lending Platform):** AAVE is a popular decentralized lending platform in the DeFi (Decentralized Finance) space. It leverages a PoA consensus mechanism to ensure fast and secure transactions for users borrowing and lending digital assets on the platform [90], [91]. While not strictly a metaverse platform, AAVE demonstrates the use of PoA in a blockchain application with transaction requirements similar to those of potential metaverse marketplaces.

– **Proof of History (PoH):** Solana's innovative PoH mechanism relies on a verifiable record of time passage to achieve consensus. This record allows validators to order transactions efficiently, leading to faster transaction speeds and improved scalability [92]. The play-to-earn game CryptoKitties successfully migrated to Solana's PoH-based Blockchain, demonstrating its potential for high-throughput metaverse applications.

- **Example: Star Atlas (Solana-based metaverse game):** Star Atlas is a space exploration and strategy game built on the Solana blockchain. It leverages Solana's PoH consensus mechanism to facilitate real-time in-game actions, NFT trading, and seamless interactions within the Star Atlas metaverse, enabling a more immersive gameplay experience [93].

– **Avalanche:** The Avalanche consensus mechanism utilizes a directed acyclic graph (DAG) structure to achieve high transaction speeds and scalability. In Avalanche, validators can participate in multiple blockchains running simultaneously, improving network efficiency. This makes Avalanche a promising candidate for metaverse applications requiring high transaction throughput and fast confirmation times [94], [95].

These diverse consensus mechanisms not only determine the governance of the metaverse but also impact user experiences by influencing the speed and cost of transactions, the security of virtual assets, and the overall stability of the environment [52], [76]. As the metaverse evolves, selecting an appropriate consensus mechanism becomes essential in achieving an optimal balance between security, efficiency, and user satisfaction.

In conclusion, Blockchain's integration and the choice of consensus mechanism deeply influence the architecture and functionality of the decentralized metaverse [96]. By addressing issues of trust, security, scalability, and user experience, these technologies lay the groundwork for a metaverse that aligns with the values of decentralization and user empowerment.

V. WEB 3.0 TECHNOLOGIES FOR THE METAVERSE

A new era of the internet is being ushered in by Web 3.0, which emphasizes decentralized and user-centric experiences. By utilizing blockchain technology, facilitating peer-to-peer interactions, and encouraging trustless cooperation, it expands upon the principles of Web 2.0 [97]. Fig. 4 illustrates the various components of Web 3.0.

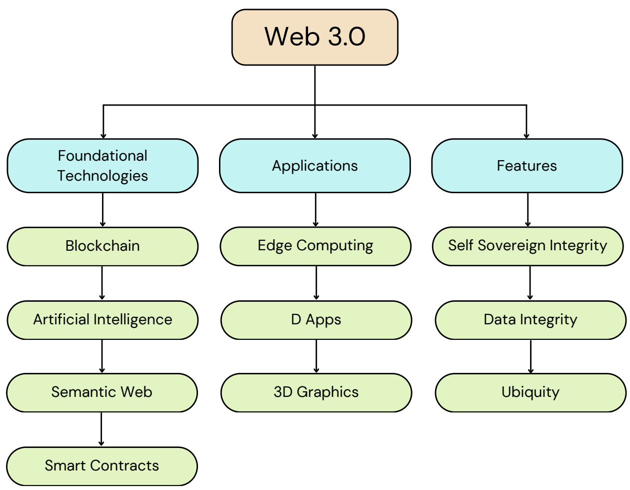

FIGURE 4: Web 3.0 components, applications, and features.

A. FOUNDATIONAL TECHNOLOGIES

Grounded in blockchain and smart contracts, Web 3.0 pioneers decentralized evolution.

– **Blockchain Technology:** At the core of Web 3.0 lies blockchain technology, providing a secure and tamper-resistant foundation for decentralized applications (dApps) and smart contracts. Notable examples include Ethereum [98], a blockchain platform enabling the creation of smart contracts and decentralized applications, and Binance Smart Chain [99], known for its efficiency in processing transactions and hosting a variety of decentralized finance (DeFi) applications [100].

- **Smart Contracts:** Smart contracts, self-executing agreements stored on the blockchain, play a vital role in Web 3.0. Platforms like Chainlink provide decentralized oracle services that enable smart contracts to interact with real-world data securely [101]. This ensures a broader range of applications, from decentralized finance to supply chain management, executed with transparency and trust [57].
- **Inter Planetary File System (IPFS):** IPFS is a decentralized storage network that allows users to store and share data in a secure and distributed manner. Unlike traditional centralized storage solutions, IPFS eliminates the need for a single point of failure and censorship [102]. This makes it a crucial technology for Web 3.0, enabling users to control their data and ensuring permanent access to information stored on the web. Additionally, IPFS can be used with blockchains to store content referenced by smart contracts, guaranteeing long-term accessibility and immutability of data [103].

B. DECENTRALIZED APPLICATIONS(DAPPS)

Decentralized applications (dApps) are the driving forces behind the transformative potential of Web 3.0. Ethereum-based applications, exemplified by Uniswap [104]–[106] for decentralized exchanges and AAVE [91] for decentralized lending, showcase the versatility and innovation facilitated by dApps in reshaping the digital landscape [107]. These platforms underscore the power of blockchain technology to redefine traditional financial processes and establish a new era of decentralized and trustless financial services [105]. The success of Ethereum-based dApps is a testament to the adaptability and disruptive potential of Web 3.0 in finance and beyond [108]. Fig. 5 represents the basic architecture of an Ethereum dApp.

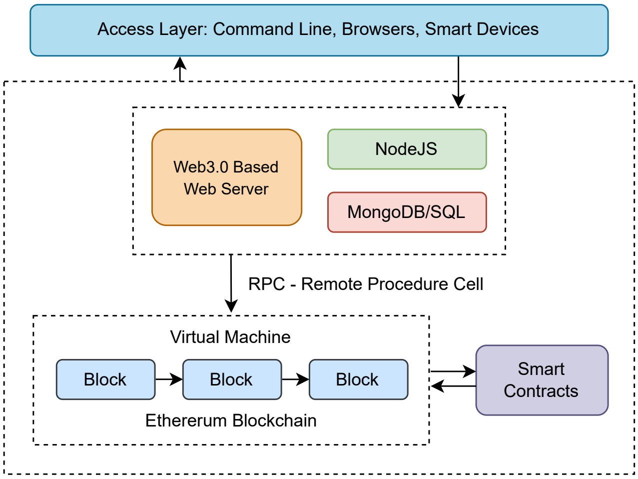

FIGURE 5: Ethereum Based dApp [109].

C. SELF-SOVEREIGN IDENTITY

Web 3.0 introduces decentralized identity systems, such as self-sovereign identity solutions. The Sovrin Network is an example, providing a decentralized identity infrastructure allowing individuals to control their personal information securely. Users can selectively disclose information without compromising their privacy [110].

D. DATA INTEGRITY AND TRACEABILITY

In the era of Web 3.0, data integrity thrives through blockchain solutions

- **Blockchain-Based Data Storage:** Web 3.0 incorporates blockchain-based data storage, enhancing data integrity and traceability. Filecoin, a leading decentralized storage network, empowers users to store and retrieve data in a decentralized manner securely. This ensures the integrity of information and provides a verifiable and tamper-resistant storage solution [110].
- **Distributed File Storage:** Complementing blockchain-based solutions, the rise of distributed file storage systems in Web 3.0 further contributes to data integrity. Platforms like IPFS (Inter Planetary File System) enable content addressing and distribution in a peer-to-peer network, fostering a more resilient and censorship-resistant approach to file storage. This distributed model enhances data traceability and reduces reliance on centralized servers [64].

The integration of blockchain and Web 3.0 technologies signifies a fundamental shift towards a more decentralized, secure, and user-centric internet. As decentralized applications, smart contracts, and self-sovereign identity systems become integral, the digital landscape is evolving to meet the demands of a more transparent and trustworthy online experience.

VI. DECENTRALIZED GOVERNANCE IN THE METAVERSE

As the metaverse evolves into a dynamic intersection of digital landscapes and real-world implications, the governance models orchestrating its development stand as linchpins in shaping its trajectory. This section delves into the intricate fabric of decentralized governance within the metaverse. We explore the transformative role of Decentralized Autonomous Organizations (DAOs) and navigate the challenges, considerations, and ethical dimensions that underscore this innovative paradigm.

A. GOVERNANCE MODELS IN DECENTRALIZED METAVERSE

Decentralized Autonomous Organizations (DAOs) act as critically essential entities within the governance framework of the metaverse [111]. Fueled by smart contracts, DAOs empower users with the capacity to shape decisions that guide the metaverse's evolution collectively [57]. Fig 6 describes the architecture of Aragon DAO. This transformative model encourages heightened user engagement and cultivates a novel paradigm of democratic decision-making, where stakeholders' voices hold significant weight. A few DAOs with their characteristics, governance, and use cases are provided in Table 5.

Recent developments highlight the increasing adoption of DAOs in projects such as the "Decentraland," where users collectively govern virtual land ownership and development decisions. This collaborative approach has resulted in a burgeoning virtual real estate market, underscoring the potential of DAOs to revolutionize digital asset ownership [63].

- **Empowerment through Collective Decision-making:** DAOs represent a radical shift from conventional centralized governance. Users actively participate in deliberations and decisions, transcending geographical boundaries and traditional hierarchies [111], [112]. This approach fosters a sense of ownership among participants, encouraging engagement and creating a dynamic ecosystem.
- **Smart Contracts as Architectural Pillars:** At the heart of DAOs' functionality, smart contracts stand as unwavering architectural pillars. These intricate self-executing codes impeccably encode governance rules and decision-making procedures [113]. By executing with precision and transparency, smart contracts eliminate intermediaries, instill trust, and ensure that the tenets of governance are upheld in an automated and tamper-proof manner [14]. Their deterministic nature streamlines decision implementation and mitigates potential conflicts, reaffirming their foundational role in shaping the decentralized metaverse's governance landscape [114].

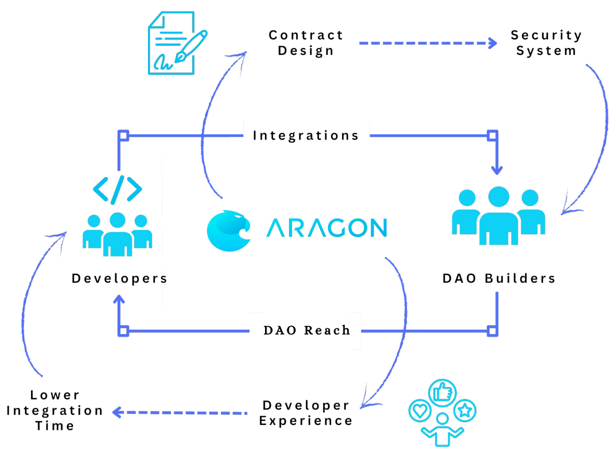

FIGURE 6: Aragon's DAO Architecture [115].

B. CHALLENGES AND CONSIDERATIONS IN DECENTRALIZED GOVERNANCE

While DAOs offer a compelling vision for decentralized governance within the metaverse, translating this potential into reality presents a unique set of challenges, particularly when considering large-scale, diverse user environments. Here, we delve into the practical difficulties that necessitate further exploration and refinement:

- **Scalability and Voter Apathy:** DAOs often rely on voting mechanisms to guide decision-making. However, achieving a quorum (the minimum number of participants required for a vote to be valid) can be complex in large-scale environments with many users. This can lead to voter apathy, where users feel their vote holds little sway, further hindering participation [117]. Research by Hermstruwer *et al.* [118] explores potential solutions, such as exploring alternative voting mechanisms like delegated proof-of-stake or quadratic voting, which can mitigate the influence of voter fatigue and apathy.
- **Complexity of Participation:** The inherently decentralized nature of metaverse governance can potentially lead to conflicts. Navigating DAO structures and protocols can be challenging for users with varying technical backgrounds. Understanding governance proposals, participating in discussions, and casting votes can become hurdles, particularly for users unfamiliar with blockchain technology or cryptocurrencies. Initiatives to enhance user experience have become crucial. For instance, developing user-friendly interfaces and educational resources can empower users to engage in DAO governance actively, providing a more inclusive environment.
- **Sybil Attacks and Tokenomics:** Large-scale environments can be vulnerable to Sybil attacks, where malicious actors attempt to manipulate voting outcomes by creating multiple fake identities. DAO structures need to be fortified with robust Sybil resistance mechanisms to ensure the integrity of the voting process. Furthermore, careful consideration needs to be given to tokenomics (the design and distribution of voting tokens within a DAO) [119]. Concentrated ownership of governance tokens can lead to plutocracy, where a small group wields disproportionate influence. Exploring alternative token distribution models and voting rights structures can help mitigate this risk.
- **Addressing Heterogeneous Motivations:** A diverse user base within a metaverse project can lead to a clash of motivations. While some users prioritize long-term value creation, others focus on short-term gains. DAO governance must find ways to bridge these divides, fostering mechanisms that encourage collaborative decision-making considering the metaverse project's long-term health.
- **Conflict Resolution and Protocol Transparency:** The inherently decentralized nature of metaverse governance can potentially lead to conflicts. Transparent protocols and predefined conflict resolution mechanisms are imperative to ensure fair and equitable solutions, preserving the collaborative spirit of the metaverse

TABLE 5: Comparison of DAO Implementations in the Metaverse

DAO	Characteristics	Governance	Use Cases
Decentraland [63]	Transparent, community-driven rules	Decentralized voting	Virtual land management, asset exchange
Aragon [115]	Decentralized governance, token-based voting	Proposal submission	Digital identity, content creation
The Graph [111]	Community-driven rules, distributed decision-making	Liquid democracy	Data indexing, social interaction
MakerDAO [116]	Token-based governance, dynamic voting weights	Proof of stake (PoS)	Decentralized finance (DeFi), stablecoin creation

[120]. Research from the Ethereum blockchain network shows that transparent dispute resolution mechanisms, such as those employed by Decentralized Autonomous Organizations (DAOs), have successfully mitigated conflicts by providing a platform for open discussions and consensus-building among stakeholders [98].

- **Inclusivity and Community Representation:** Safeguarding inclusivity requires proactive efforts to dismantle barriers that inhibit participation. Establishing channels for community representation, bridging linguistic and cultural divides, and promoting diversity contribute to holistic decision-making reflective of the metaverse's multifaceted user base. Decentralized metaverse projects like "Cryptovoxels" [121] have implemented features like language-localized forums and events to foster inclusivity. This approach has led to a diverse user base with active participation from various cultural backgrounds.
- **Integrating Real-World Legal Frameworks:** Harmonizing decentralized governance with existing legal frameworks remains a complex endeavor [112]. A framework that respects the metaverse's autonomy while adhering to real-world legal obligations demands a delicate balance involving legal experts, technologists, and policymakers [122]. Many alliances have been established to bridge the gap between virtual-world governance and real-world legalities. This collaborative initiative brings legal experts, scholars, and technology developers together to address the legal challenges arising from the intersection of metaverse activities and traditional legal systems. The MSF (The Metaverse Standards Forum) is an important example of such an alliance working to harmonize decentralized governance with existing legal frameworks [94], [123]. The MSF's work is helping to ensure that the metaverse is developed in a way consistent with the rule of law and that protects the rights of users [124].
- **Characteristics and Potential impacts of different blockchain-based voting mechanisms:** Blockchain technology has emerged as a potential solution for enhancing the security, transparency, and efficiency of traditional voting systems. By leveraging distributed ledger technology, blockchain-based voting mechanisms offer a tamper-proof and auditable record of votes, mitigating the risks of fraud and manipulation. Additionally, blockchain can automate voter registration and identity verification, streamlining the voting process and potentially increasing voter turnout. However, alongside these potential benefits, it is crucial to acknowledge the inherent characteristics and potential drawbacks of blockchain-based voting systems. One key characteristic, as highlighted by Buterin (2021) [125], is the concept of coin voting, where token holders wield voting power proportional to their stake in the system. While this can incentivize participation, it also raises concerns about plutocracy, where wealthy individuals or groups can disproportionately influence the outcome of votes. Drawing from "Decentralized E-Voting Systems Based on the Blockchain Technology" [126], the concept revolves around integrating blockchain technology with secret sharing schemes and homomorphic encryption. This fusion aims to establish a decentralized e-voting application without relying on a trusted third party. The system ensures a transparent voting process accessible to the public while safeguarding voter anonymity, data transmission privacy, and ballot verifiability throughout the billing phase.
Additionally, there may be drawbacks to the anonymity that blockchain-based voting systems offer. We have delved into implementing the Ethereum blockchain to address the essential security properties required for a fair and transparent voting system. Recognizing the significant cost concern, we aimed to minimize computational and storage expenses while upholding crucial security measures. Our implementation utilizes Ganache, a local blockchain platform within Truffle, to elucidate the process and evaluate associated costs in conducting generic elections. Furthermore, we conduct a comparative analysis of our proposal's performance against previous approaches [127]. While it protects voter privacy, it can also hinder accountability and make tracing and prosecuting malicious actors difficult. Scalability remains another challenge, as blockchain networks can become congested during high-volume elections, potentially compromising transaction speeds and overall system efficiency. Further research is necessary to ad-

dress these challenges and ensure the responsible implementation of blockchain voting. Exploring alternative voting mechanisms beyond simple coin voting, such as quadratic voting or delegated proof-of-stake, could help mitigate the influence of wealth concentration. Additionally, developing mechanisms to prevent voter coercion and ensure the anonymity of votes while maintaining accountability for malicious actors are critical areas for future exploration. By carefully considering these characteristics and potential impacts, policymakers and developers can work towards harnessing the potential of blockchain technology to create more secure, transparent, and inclusive voting systems.

C. ETHICAL DIMENSIONS OF DECENTRALIZED GOVERNANCE

The contours of metaverse governance intersect with profound ethical considerations, necessitating a conscientious exploration of the ethical terrain:

- **Equity, Privacy, and Consent:** As the metaverse's digital interactions transcend into the real world, safeguarding equity, privacy, and consent becomes paramount. Policies must be forged to preserve users' rights, mitigating the risk of exploitation within the virtual realm [128].
- **Ethical Frameworks for Collective Decisions:** Incorporating ethical frameworks into metaverse governance aids in steering decisions toward universally accepted moral standards. Striking a delicate equilibrium between cultural nuances and ethical universals can pave the path for harmonious coexistence within the metaverse [129].
- **Trust and Responsible Evolution:** Upholding ethical standards in governance cultivates user trust. An ecosystem built on trust is more likely to evolve responsibly, navigating technological advancements and societal shifts with accountability and sensitivity [130].

Recent studies indicate that implementing ethical guidelines in decentralized metaverse governance positively correlates with user satisfaction and long-term sustainability. Platforms prioritizing user rights and data protection are gaining traction, reflecting a growing awareness of the ethical underpinnings of metaverse development.

As we traverse the intricate landscape of decentralized governance within the metaverse, the intricate interplay of technology, community dynamics, and ethical considerations beckons for continuous exploration and refinement, anchoring the metaverse's evolution in responsible stewardship.

VII. USE CASES AND APPLICATIONS OF THE DECENTRALIZED METAVERSE

The implementation scenarios and utilizations of the decentralized metaverse encompass a diverse range of applications that transcend conventional boundaries. From virtual economies to transformative educational experiences, this dynamic landscape showcases the metaverse's potential to reshape industries and redefine human interactions. Delving into the multifaceted nature of these scenarios reveals the profound impact of this emerging paradigm on various aspects of our lives.

A. VIRTUAL LAND POSSESSION AND ECONOMIES

In the evolving landscape of the decentralized metaverse, the concept of virtual land ownership and the emergence of blockchain-backed tokenization have ushered in transformative possibilities. This subsection explores how blockchain technology and tokenomics reshape how we perceive, own, and trade virtual properties within this immersive realm.

- **Blockchain-Backed Tokenization:** The decentralized metaverse pioneers a novel approach to land ownership by leveraging blockchain-backed tokens, such as those on Ethereum [98] and Binance Smart Chain [99]. These tokens authenticate ownership and transactions, ensuring security and transparency in virtual property dealings [131].
- **Tokenomics as a Catalyst:** Tokenomics, the study of tokens' economic dynamics, plays a central role in the decentralized metaverse. It fuels virtual economies by establishing value, incentivizing participation, and generating opportunities for innovation and growth. For instance, Decentraland's MANA token drives its virtual real estate ecosystem [63].
- **NFTs Redefining Ownership:** Non-Fungible Tokens (NFTs) have disrupted conventional notions of ownership [132]. Each NFT is unique, representing digital assets like virtual land parcels or exclusive in-game items. NFTs have revolutionized provenance tracking and asset trading, fostering a thriving virtual asset marketplace [133]. Notably, Cryptovoxels has gained prominence for its NFT-powered virtual land [121].

The emerging virtual economies will play an essential role in defining the future landscape of economics. While the transformative potential of tokenization and virtual economies within the decentralized metaverse is undeniable, it is crucial to acknowledge the complexities and challenges associated with these nascent systems. Here, we delve deeper into the economic implications to provide a more comprehensive analysis.

- **Sustainability and Profitability:** The long-term sustainability of virtual economies hinges on user adoption, token utility, and a well-defined value proposition. A critical aspect is balancing in-game rewards and real-world economic integration. Over-reliance on speculation or unsustainable token inflation can lead to bubbles and crashes. Striking a balance between attracting new users and fostering a healthy in-game economy is paramount for long-term profitability [134].
- **Value Determination:** Establishing clear metrics for valuing virtual land parcels is crucial. Factors like location (proximity to high-traffic areas or social hubs),

resource availability (scarcity of resources or unique features), and development potential all influence value. Understanding these factors allows for informed investment decisions and prevents potential bubbles.
- **Utility and Functionality:** The functionalities associated with virtual land ownership significantly impact its economic viability. Can landowners generate revenue streams through rentals (leasing land for virtual events or experiences), hosting functionalities (providing in-world services or games), or resource extraction (harvesting virtual resources for crafting or trade)? The ability to monetize virtual land is essential for a healthy virtual economy [135].
- **Tokenomics Model Design:** The design of the tokenomic model underlying the virtual land ecosystem directly affects its economic stability. Careful consideration of token supply (avoiding excessive token creation to prevent inflation), distribution mechanisms (ensuring fair distribution and rewarding user participation), and potential inflationary or deflationary pressures are paramount. Sustainable tokenomics models are essential for long-term economic viability [136].
- **Regulatory Landscape:** The evolving regulatory landscape surrounding virtual land ownership presents challenges and opportunities. Clear regulations regarding ownership rights, taxation on virtual land transactions, and user protection are crucial for fostering trust and stability within the virtual economy. Establishing a framework for responsible development and preventing fraudulent practices is also essential [137].

B. GAMING AND AMUSEMENT

The convergence of blockchain technology and gaming has introduced a new dimension to entertainment, characterized by the integration of Non-Fungible Tokens (NFTs) and interconnected virtual worlds. This section delves into the world of gaming within the decentralized metaverse, highlighting how NFTs and interoperability are revolutionizing player experiences and economic models.
- **Unique In-Game Assets via NFTs:** The infusion of blockchain and NFTs into gaming introduces a paradigm shift. Players can now possess one-of-a-kind in-game assets as NFTs, granting a sense of exclusivity and personalization to their gaming experience. Examples include Axie Infinity's NFT-based creatures [138].
- **Interconnected Virtual Worlds:** The potential for interoperability across various metaverse gaming platforms marks an exciting advancement [139]. This interconnection allows users to traverse different virtual realms seamlessly, fostering a unified gaming experience across diverse environments. Decentral Games showcases this interoperability by connecting Ethereum-based virtual worlds [140].
- **Innovative Monetization Models:** The marriage of blockchain and gaming has given rise to new monetization strategies [141]. The play-to-earn model, where players earn tokens or NFTs for in-game achievements, adds a fresh layer of economic engagement to gameplay, blurring the lines between leisure and earnings. Blankos Block Party exemplifies this model [142].

C. SOCIAL AND COOPERATIVE ENVIRONMENTS

The dynamic potential of immersive shared spaces and global networking lies at the intersection of technology and human interaction. In this subsection, we delve into the social fabric of the decentralized metaverse, unveiling the way virtual spaces create cross-cultural connections and collaborative environments that transcend physical limitations.
- **Immersive Shared Spaces:** The decentralized metaverse serves as a canvas for constructing immersive shared spaces where users worldwide can connect, communicate, and collaborate in ways transcending geographical boundaries. Decentralized social platforms like Somnium Space exemplify this concept [143].
- **Global Networking Opportunities:** These shared spaces foster global connections, enabling cross-cultural interactions and collaborations [144]. Users can engage in virtual events, attend seminars, and participate in exhibitions regardless of location. VRChat facilitates such cross-cultural interactions [145].
- **Transforming Workspaces:** Collaborative workspaces within the metaverse offer a novel approach to remote teamwork and professional gatherings [146]. Enterprises can utilize these spaces for training sessions, virtual conferences, and interactive workshops, redefining how people collaborate and learn [147]. Spatial is a leading example of such virtual collaboration spaces [148].

D. UNIFYING ACTUAL AND VIRTUAL ECONOMIES

The impact of the decentralized metaverse extends beyond the confines of the virtual realm, influencing real-world economies and regulatory frameworks. This section explores the intricate relationship between virtual and physical markets, shedding light on the transformative power of decentralized technologies in bridging these previously distinct economic landscapes.
- **Influence on Physical Markets:** The integration of virtual real estate purchases with real-world property markets highlights the tangible impact of the decentralized metaverse [131]. Decisions made within virtual spaces can reverberate into the physical realm, creating a fascinating interplay between digital and corporeal economies [149]. Decentraland's LAND token interactions demonstrate this connection [63].
- **Legal and Regulatory Challenges and Solutions:** As real and virtual economies intertwine, challenges emerge around legal frameworks, taxation, and regulatory compliance [150]. The decentralized nature of the metaverse can solve this issue by implementing adaptive frameworks, blockchain-backed identity verification, smart contracts, and more. The Sandbox Game's

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approach to managing virtual land sales provides insight into this challenge [67].

E. HEALTHCARE, EDUCATION, AND BEYOND

Beyond its role in entertainment, the decentralized metaverse finds applications in fields as diverse as healthcare and education. This subsection uncovers the potential for medical training simulations, innovative educational approaches, and cross-sector integration, showcasing how this immersive paradigm revolutionizes learning, interacting, and conducting professional activities.

- **Medical Simulations and Training:** In healthcare, the decentralized metaverse's immersive simulations aid medical professionals in training and therapeutic interventions. Virtual environments provide a safe space for practicing complex procedures and refining medical skills. Surgical training platforms like Osso VR leverage this potential [151], [152].
- **Educational Innovation:** The convergence of metaverse technologies and blockchain can revolutionize education by creating immersive, interactive learning experiences. Blockchain ensures secure and transparent verification of educational credentials, reducing fraud. Virtual classrooms and campuses in the metaverse provide engaging environments that transcend geographical barriers like Blockchain-based academic library systems as portrayed by Ponnusamy *et al.* in their paper [153]. Teachers can enhance lessons using augmented and virtual reality, making complex subjects more accessible. Blockchain can also support decentralized learning platforms, enabling direct interaction, resource sharing, and assessments. Smart contracts can automate administrative tasks like enrollment, grading, and certification, increasing efficiency. This integration democratizes access to quality education, fosters innovation in teaching methods, and prepares students for the digital future. Interactive educational platforms like Engage VR are working towards providing such educational experiences [154], [155].
- **Cross-Sector Integration:** The metaverse transcends industry boundaries. Enterprises utilize virtual spaces for employee collaboration, customer engagement, and product demonstrations, underlining the versatile applications of the decentralized metaverse. Examples include Microsoft Mesh for collaborative meetings and virtual product showcases [156].
- **Smart Cities:** Integrating metaverse technologies with blockchain can enhance smart cities by providing a secure, transparent framework for managing city services and infrastructure. Blockchain ensures data integrity, promotes citizen engagement, and streamlines processes. The metaverse offers immersive environments for urban planning, enabling real-time visualization and interaction with city layouts and projects. Additionally, blockchain improves IoT security, decentralized identity management, and secure transactions for city services. For instance, blockchain-based energy grids optimize power distribution, and decentralized transportation networks enhance traffic management [157]. A recent example is Seoul's "Metaverse Seoul" project, which aims to create a virtual communication ecosystem for administrative services, urban planning, and citizen interaction, showcasing the potential of these technologies to drive innovation and efficiency in smart city ecosystems.

In summary, the decentralized metaverse is a dynamic realm beyond entertainment. It redefines traditional sectors, reshaping societal norms while blurring the lines between the digital and the tangible. Its multifaceted nature invites exploration and innovation across various dimensions of human experience. This exploration of diverse utilization scenarios showcases the far-reaching implications of the decentralized metaverse.

VIII. CASE STUDY

In this section, we delve into two compelling case studies—Decentraland and Vault Hill—that vividly exemplify the practical application of the decentralized metaverse concept. With a solid foundation in blockchain and Web 3.0 technologies, each case study presents a unique facet of the decentralized metaverse landscape, redefining ownership, interactions, and virtual experiences.

A. DECENTRALAND: A DECENTRALIZED VIRTUAL WORLD

Decentraland is a pioneering blockchain-based virtual reality platform that empowers users to construct, explore, and engage within an immersive decentralized digital realm. Launched in 2017, it harnesses the capabilities of the Ethereum blockchain and revolves around the concept of non-fungible tokens (NFTs), which symbolize ownership of virtual land and in-world assets [63].

– **Land Ownership and Parcels:** Central to Decentraland's architecture is the notion of virtual land ownership through NFTs. The expansive virtual landscape is meticulously divided into distinct land parcels, each represented by a unique NFT. These NFTs confer ownership rights, enabling users to acquire, sell, and develop their parcels. Possessing a parcel empowers users to sculpt their digital domains, creating an array of experiences, from interactive art installations and virtual museums to bustling marketplaces and multiplayer games [158].

– **Monetization and Economy:** Decentraland pioneers an innovative economic framework where users can monetize their creativity and endeavors. This is achieved through the use of its native cryptocurrency, MANA. Participants can employ MANA to engage in various activities within the metaverse, including purchasing virtual land, trading virtual goods, and provisioning virtual services. The demand and utility of virtual assets

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TABLE 6: Comparison of Decentralized Metaverse Platforms

Feature	Decentraland	Vault Hill	The Sandbox
Focus	• Decentralized platform • User-driven world ownership • Content creation	• Human-centric approach • Enhancing real-world experiences • Health and well-being integration	• User-centric platform • Emphasis on gaming • Community engagement
Virtual Land	• ERC-20 tokens (MANA) • Freely divisible land parcels • User-created content	• ERC-721 NFTs (VLAND) • Varying parcel functionalities • Real-world asset integration	• ERC-20 tokens (SAND) • Land parcels as ERC-721 tokens • User-created games and assets
Monetization	• Selling or leasing land • Participation in events • Marketplace for virtual goods	• Monetization through VLAND • Virtual wellness services • Virtual real estate opportunities	• Play-to-earn model • Marketplace for trading assets • Partnerships with gaming companies
User Engagement	• Community events • Collaborative projects • Social spaces	• Focus on user well-being • Health-related activities • Personalized environments	• Regular updates • Engaging events • Social interaction
Technology	• Ethereum blockchain • Smart contracts for transactions • Decentralized governance via DAO	• Blockchain integration • Smart contracts for services • Oracles for real-world data	• Ethereum with layer 2 scaling • Smart contracts for game mechanics • Integration with other blockchain projects
Challenges	• Scalability issues • High transaction costs • Interoperability with other platforms	• Balancing regulations • User privacy and data security • Adoption of health technologies	• Scalability and transaction speed • Stable in-game economy • Long-term user engagement
Future Directions	• Layer 2 scalability solutions • Interoperability with other platforms • Improved user governance models	• Advanced health technologies • Expanding virtual real estate • User personalization and immersive experiences	• Enhancing scalability with Polygon • New play-to-earn mechanisms • Partnerships with gaming companies

wield influence over their value, potentially resulting in economic gains for their creators and users alike [158].

– **Creation and Development:** Decentraland empowers users with tools and capabilities for creating and evolving their virtual spaces. From coding and scripting to intuitive drag-and-drop interfaces, users can fabricate intricate scenes, structures, interactive experiences, and games. This open-ended creative process has catalyzed a dynamic user-generated content ecosystem, continually redefining the metaverse's landscapes [63].

– **Interactivity and Socialization:** At the heart of Decentraland lies the emphasis on social interaction and collaboration. Represented by avatars, users can navigate the virtual world, engage in conversations, and collaborate with peers. These avatars foster a sense of presence, enabling real-time interactions, discussions, and cooperative efforts within the metaverse. This immersive engagement fosters a shared understanding of community and participation [159].
– **Blockchain and Ownership:** Blockchain technology underpins Decentraland's foundation, ensuring secure, transparent, and verifiable ownership of virtual land and assets. Each transaction, interaction, and modification is recorded immutably on the Ethereum blockchain. This guarantees authenticity, traceability, and tamper-resistance, instilling trust in the ownership and provenance of digital assets [159].
– **Architecture:** Decentraland's architecture is characterized by a multi-layered integration of blockchain, NFTs, smart contracts, and peer-to-peer networking. It comprises three core layers: the Content Layer, the Settlement Layer, and the Consensus Layer [63]. Fig 7 portrays the architecture of Decentraland.
  - **Content Layer:** This layer encompasses the creative aspects of the metaverse. Users utilize a range of tools and development environments to design, build, and furnish their virtual parcels. The Content Layer is where user-generated experiences come to life, from art installations to interactive games.
  - **Settlement Layer:** The Settlement Layer handles property ownership and economic transactions. NFTs represent individual parcels, and users can securely buy, sell, and trade these parcels using MANA. Smart contracts facilitate the secure exchange of assets, ensuring trust and transparency throughout transactions.
  - **Consensus Layer:** At the heart of Decentraland's architecture lies its consensus mechanism, which ensures the security and integrity of the platform. Decentraland employs the Ethereum blockchain, utilizing its Proof of Stake (PoS) protocol to validate and record transactions. This consensus layer guarantees that ownership records and transactions are tamper-proof and verifiable.
– **Challenges and Considerations:** Decentraland encounters challenges that impact its growth and user experience while offering numerous benefits. These include:
  - **Scalability Issues:** Decentraland faces challenges in scaling its virtual environment and infrastructure

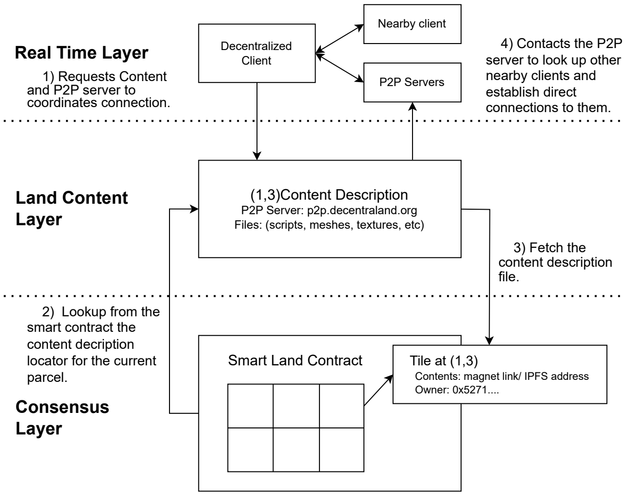

FIGURE 7: Architecture of Decentraland [63].

  to accommodate a growing number of users and activities without compromising performance.
  - **Governance and Decision-Making:** The platform's decentralized governance model can lead to slower decision-making processes and potential conflicts among stakeholders, impacting the efficiency of platform development.
  - **User Retention and Engagement:** Decentraland struggles with keeping users engaged and attracting new participants due to the challenge of creating a compelling and constantly evolving virtual experience.
  - **Economic Sustainability:** Ensuring long-term economic sustainability is challenging as the platform must balance virtual land value, user incentives, and revenue generation while avoiding market volatility.
  - **Appeal Beyond Cryptocurrency Enthusiasts:** Extending Decentraland's appeal to a broader audience beyond cryptocurrency enthusiasts is essential for mainstream adoption and growth.
  - **User Experience for Non-Tech Savvy Users:** Refining the user experience to accommodate individuals unfamiliar with blockchain technology is crucial for attracting and retaining a diverse user base.

B. VAULT HILL: BLURRING REAL AND VIRTUAL BOUNDARIES

Vault Hill emerges as a pioneering amalgamation of real-world assets and the decentralized metaverse underpinned by the transformative technologies of blockchain and Web 3.0. Launched in 2022, it redefines the contours of ownership and investment by tokenizing tangible assets, primarily real estate properties, into the digital realm, engendering hybrid experiences where physical and virtual dimensions coalesce seamlessly [160].

– **Tokenization of Real Estate:** The cornerstone of Vault Hill's innovation rests on transforming real estate properties into non-fungible tokens (NFTs). Each NFT encapsulates the essence of the physical property while creating a digital bridge to the metaverse. This symbiotic relationship empowers users with ownership of both the tangible asset and its virtual representation [160].
– **Hybrid Experiences and Ownership:** Vault Hill engenders a groundbreaking fusion where users traverse between the tactile and the digital. Possessing an NFT not only represents ownership of the underlying property but extends to the digital metaverse, enabling users to interact, transact, and even develop within the virtual realm. This duality of ownership diversifies investment avenues and redefines traditional interactions with real estate [160].

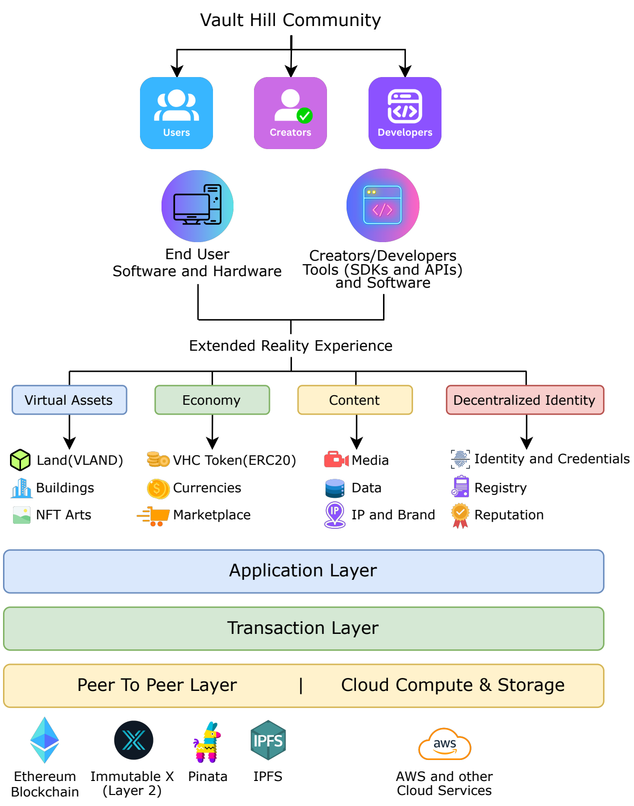

FIGURE 8: Architecture of Vault Hill [160].

– **Architecture:** At the core of Vault Hill's architecture lies a multi-layered integration of blockchain, smart contracts, and digital representations of real-world assets. The process begins with tokenizing real estate properties into unique NFTs, where each token is minted as a digital representation of the property's ownership. These NFTs are then registered on a blockchain, ensuring transparency, security, and immutability.
Underpinning this architecture is a set of smart contracts that define the rules governing ownership, transactions, and interactions within the metaverse. These smart contracts facilitate fractional ownership, allowing users to invest in portions of real estate properties. Fig. 8 portrays the architecture of Vault Hill. Moreover, they enable seamless transfers of ownership, ensuring the authenticity and provenance of each transaction.
The architecture also incorporates oracle systems that bridge the gap between the physical and digital worlds. These oracles provide real-time data feeds, validating property ownership, market values, and legal compliance. This ensures that the virtual representation accurately mirrors the status of the tangible asset, fostering trust and transparency [160].
– **Economic Paradigms and Accessibility:** By tokenizing real estate, Vault Hill democratizes access to investments historically confined to a select few. Fractional ownership becomes a reality, as users can invest in fractions of high-value properties, decentralizing investment landscapes and fostering inclusivity. This opens doors for a broader spectrum of individuals to engage in real estate investment, altering the dynamics of traditional asset ownership [160].
– **Challenges and Opportunities:** While Vault Hill offers groundbreaking opportunities in the metaverse space, it faces several distinct challenges. Addressing these challenges is essential for the platform's long-term success and adoption [161].
To address these challenges, Vault Hill has adopted several strategies:
  - **Regulatory Compliance:** Vault Hill collaborates with legal experts to ensure adherence to evolving regulations, creating a secure user environment.
  - **Integration with Legal Systems:** The platform works on aligning virtual property rights with real-world legal frameworks to support digital ownership and transactions.
  - **User Experience:** Vault Hill prioritizes user experience by providing intuitive interfaces and educational resources to simplify onboarding for all users.
  - **Security Measures:** The platform uses encryption, decentralized identity systems, and regular audits to safeguard user data and assets.
  - **Content Diversity:** Vault Hill promotes a diverse content ecosystem, offering tools for varied and culturally rich experiences to attract a broad user base.

– **Future Outlook:** Vault Hill embodies the profound impact of integrating blockchain and real-world assets, illuminating a path toward a future where the virtual and the physical coexist harmoniously. As the blockchain and Web 3.0 ecosystem evolves, Vault Hill's model could catalyze new forms of investment, redefine how we perceive ownership,p and revolutionize real estate markets globally [160].

C. THE SANDBOX: A USER-CENTRIC METAVERSE

The Sandbox represents a user-centric virtual world where players can create, own, and monetize their gaming experiences using NFTs and blockchain technology. Launched in 2012 as a mobile game and transitioning to a blockchain-powered metaverse in 2018, The Sandbox has positioned itself as a leading platform for user-generated content, fostering a decentralized ecosystem of creativity and economic opportunity [11], [162].

– **Land Ownership and Parcels:** In The Sandbox, virtual land ownership is a cornerstone of the platform, facilitated through NFTs. The virtual world is divided into land parcels, each represented by an NFT on the Ethereum blockchain. Owners can develop their parcels, creating unique gaming experiences and interactive spaces. These parcels can be bought, sold, and traded on the marketplace, allowing users to monetize their digital real estate [162].
– **Monetization and Economy:** The Sandbox introduces an innovative economic model centered around its native cryptocurrency, SAND. Users can earn SAND by participating in various activities, such as creating and selling assets, participating in games, and staking. The platform also supports the creation of in-game assets and experiences that can be monetized through the sale of NFTs. This economic structure incentivizes creativity and engagement, providing users with multiple revenue streams [162].
– **Creation and Development:** The Sandbox provides an extensive suite of tools for content creation, including the Game Maker and the VoxEdit. The Game Maker allows users to create and publish their 3D games without any coding knowledge, utilizing a simple drag-and-drop interface. VoxEdit enables the creation of voxel-based assets that can be used in the game or sold as NFTs. This focus on user-generated content has led to a thriving ecosystem of creators and developers who continually contribute to the platform's growth [162].
– **Interactivity and Socialization:** The Sandbox emphasizes social interaction and community building. Users, represented by customizable avatars, can explore the virtual world, interact with others, and participate in collaborative projects. The platform supports multiplayer experiences, enabling users to play games together, attend virtual events, and engage in social activities. This social aspect fosters community and belonging within the metaverse [162].
– **Blockchain and Ownership:** The Ethereum blockchain underpins The Sandbox's infrastructure, ensuring secure and transparent ownership of virtual assets. An NFT represents each land parcel, asset, and in-game item, providing verifiable proof of ownership. Smart contracts facilitate transactions, ensuring that trades and exchanges are secure and tamper-proof. This blockchain foundation enhances trust and authenticity within the platform [162].

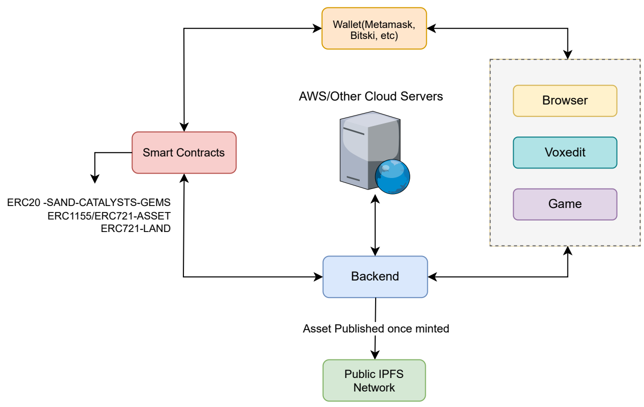

FIGURE 9: Working of The Sandbox [162].

Recent Developments and Features:

- **Sandbox Game Maker:** Sandbox has introduced the Sandbox Game Maker, a tool that allows users to create complex games and interactive experiences without any coding knowledge. This feature democratizes game development, enabling more users to contribute to the ecosystem.
- **Voxel Editor (VoxEdit):** The platform includes VoxEdit, a powerful and user-friendly 3D voxel modeling and NFT creation package. Users can design, rig, and animate their voxel-based NFTs, which can be traded on the Sandbox marketplace.
- **Metaverse Events and Social Hubs:** Sandbox has recently hosted several high-profile virtual events, including concerts, art exhibitions, and brand collaborations. These events have helped attract a broader audience and increase user engagement. Social hubs within Sandbox serve as community gathering points, fostering user interaction and collaboration.
- **Play-to-Earn (P2E) Mechanics:** Sandbox's play-to-earn model rewards users with SAND tokens for participating in various activities, such as playing games, completing quests, and creating content. This model has been a significant driver of user growth and retention.
- **Partnerships and Collaborations:** Sandbox has formed strategic partnerships with major brands, celebrities, and other blockchain projects. Notable collaborations include partnerships with Atari, The Smurfs, and Deadmau5, which bring exclusive content and experiences to the platform.
- **Land Sales and Virtual Real Estate:** Sandbox conducts periodic land sales, allowing users to purchase virtual land parcels using cryptocurrency. These land parcels can be developed, rented, or

sold, contributing to a thriving virtual real estate market.

– **Architecture:** The Sandbox's architecture integrates blockchain technology, NFTs, smart contracts, and a user-friendly interface. It comprises three primary layers: the User Layer, the Content Layer, and the Blockchain Layer [162]. Fig 9 illustrates the barebone workings of The Sandbox.
  - **User Layer:** This layer encompasses the user-facing components, including the Game Maker, VoxEdit, and the marketplace. It provides the tools and interfaces necessary for users to create, manage, and trade their digital assets and experiences.
  - **Content Layer:** The Content Layer is where user-generated content is created and stored. It includes the games, assets, and experiences developed by users. This layer ensures that the creative potential of the community is fully harnessed and showcased.
  - **Blockchain Layer:** The Blockchain Layer underpins the entire ecosystem, ensuring the security and integrity of transactions and ownership. It uses the Ethereum blockchain to record ownership of land parcels, assets, and in-game items, leveraging smart contracts to facilitate secure exchanges.
  - **Technologies used include:**
    - **Ethereum Blockchain:** Ensures transparency, security, and immutability of all transactions.
    - **IPFS (InterPlanetary File System):** For decentralized storage of assets.
    - **AWS (Amazon Web Services):** For hosting and cloud computing services.
    - **WebRTC (Web Real-Time Communication):** For real-time communication and interactions.
    - **Chainlink Oracles:** For secure and reliable data exchange between blockchain and off-chain systems.
    - **Polygon (previously Matic Network):** For layer 2 scaling solutions to ensure faster and cheaper transactions.
    - **zk-SNARKs (Zero-Knowledge Succinct Non-Interactive Argument of Knowledge):** For enhanced privacy and security.
    - **Aragon:** For DAO governance and management.
    - **OpenSea:** For NFT marketplace integration.
    - **ERC-20 and ERC-721:**For token standards to manage fungible and non-fungible tokens, respectively.

– **Challenges and Considerations:** While The Sandbox offers numerous opportunities, it faces challenges such as ensuring scalability to accommodate a growing user base, enhancing the user experience for those unfamiliar with blockchain technology, and maintaining security against potential threats. Overcoming these challenges is crucial for the platform's sustained success and adoption [162]. To address these challenges, The Sandbox has adopted several strategies:
  - **Scalability:** The Sandbox ensures faster and more cost-effective transactions by adopting layer 2 scaling solutions, such as Polygon. This reduces congestion on the Ethereum mainnet and enhances the user experience.
  - **User Engagement:** The platform continuously introduces new features, content, and events. The play-to-earn model, which rewards users with SAND tokens for their activities, has been instrumental in keeping users engaged and incentivized to contribute.
  - **Economic Management:** To maintain a stable in-game economy, The Sandbox implements economic balancing measures. This includes adjusting token rewards, monitoring market activity, and introducing new utilities for SAND tokens.

The collective exploration of Decentraland, Vault Hill, and The Sandbox unveils the dynamic interplay between blockchain technology, real-world assets, and the decentralized metaverse. These case studies underscore the transformative power of blockchain and Web 3.0, illuminating how they redefine traditional paradigms of ownership, engagement, and economic models.

Decentraland is a pioneering beacon, exemplifying the fusion of blockchain and virtual reality to cultivate an immersive metaverse. Through tokenization and NFTs, it redefines ownership, enabling users to curate virtual landscapes that transcend artistic expression into economic opportunities. Intricately layered with content creation, secure settlements, and robust consensus, its architecture demonstrates the coordination required to sustain a vibrant and secure virtual world. Challenges in scalability and accessibility beckon for innovative solutions, yet Decentraland's influence reverberates as a testament to the democratization of virtual experiences.

In contrast, Vault Hill illuminates the integration of tangible assets within the decentralized metaverse, showcasing the transformation of real estate into tokenized representations. This pioneering convergence of the physical and digital realms reshapes investment paradigms, affording fractional ownership and economic participation to a broader audience. Vault Hill's architecture ingeniously harnesses smart contracts, oracles, and blockchain to bridge real and virtual worlds while grappling with regulatory considerations and user experience optimization.

The Sandbox represents a user-centric approach to the metaverse, emphasizing creativity, ownership, and monetization of gaming experiences. It provides an extensive suite of tools for content creation, allowing users to build and share their own 3D games and assets. The Sandbox's economic model revolves around its native cryptocurrency, SAND, which users can earn and spend within the platform. Integrating user-generated content with blockchain technology, The Sandbox creates a thriving ecosystem where users can monetize their creativity and engage in social interactions. Its architecture combines user-friendly interfaces with secure blockchain infrastructure, promoting an inclusive and participatory metaverse.

Table 6 represents the comparative analysis of the case study between Decentraland, Vault Hill, and The Sandbox.

Collectively, these case studies embody the metamorphosis of the metaverse. They demonstrate how blockchain and Web 3.0 technologies transcend the boundaries of traditional domains, fostering inclusivity, redefining ownership structures, and catalyzing innovation. Decentraland, Vault Hill, and The Sandbox symbolize the possibilities ahead, heralding an era where the virtual and physical dimensions harmonize to shape a future defined by collaborative creation, economic fluidity, and interconnected experiences. As the metaverse narrative evolves, these case studies stand as guides, inviting exploration, adaptation, and revolution across industries, economies, and societies.

IX. CHALLENGES, THREATS, AND FUTURE RESEARCH DIRECTIONS

At the intersection of blockchain, Web 3.0, and immersive technologies, realizing a decentralized metaverse presents a promising picture of a dynamic and linked digital world. However, this innovative environment presents a range of difficulties, including technical complexities, security flaws, and the need for forward-thinking innovations. This section delves into these issues, examines new dangers, and opens the way for a creative future by outlining potential paths for developing the decentralized metaverse ecosystem. Table 7 briefly summarizes the technical and privacy challenges with their potential solutions.

A. TECHNICAL CHALLENGES AND POTENTIAL SOLUTIONS

Many complex technical obstacles exist to overcome a fully functional decentralized metaverse. These issues highlight the need for creative solutions that protect decentralization while boosting user experience, from scaling issues in addressing escalating user demands to assuring seamless interoperability across varied platforms. A few such obstacles are as follows:

- **Scalability:** Imagine millions of users inhabiting a virtual world, interacting and generating data. How do we ensure smooth operations without compromising performance? Traditional blockchain networks often struggle with scalability, leading to slow transactions and high fees [163]. Here is where innovation comes in: sharding (partitioning data across multiple ledgers) and layer-two scaling solutions (handling transactions off the main chain) offer promising avenues for increased capacity. Additionally, efficient consensus mechanisms like Proof of Stake (PoS) can improve transaction speed and reduce costs. Continued research and development in these areas are crucial for building a scalable decentralized metaverse that can accommodate massive user bases and diverse activities [25].
- **Interoperability:** The decentralized metaverse will not be a monolithic entity but a constellation of diverse platforms, each with its own protocols and data structures. This heterogeneity creates challenges in data exchange and user experience. Imagine struggling to move one's prized virtual sword or avatar between different metaverse platforms. Collaboration and standardization efforts across the metaverse ecosystem are essential [164]. Developers, industry owners, and regulatory bodies must work hand-in-hand to establish standard protocols for data exchange, communication, and asset ownership. Open-source development and interoperable standards will be vital in fostering a genuinely interconnected metaverse where users can move freely between platforms without friction. By achieving interoperability, the metaverse can evolve into a unified and cohesive experience for all participants [42], [165].
- **User Experience:** Although decentralization is fundamental, user experience cannot be compromised. It is imperative to balance robust security features and user-friendly interfaces [166]. However, how do we balance the core principles of decentralization (security, user control) with an intuitive interface? Complex cryptographic concepts and cumbersome wallet management can be daunting for newcomers. User-centric design is essential to solve this issue [167], [168]. Developing intuitive interfaces for managing digital assets and interacting with the metaverse is vital. Educational initiatives can empower users with a deeper understanding of decentralized technologies, fostering trust and confidence in the system. Maintaining the right balance between security and user-friendliness will be crucial for widespread adoption and a seamless user experience in the decentralized metaverse [14], [169].
- **Network Bandwidth:** The decentralized metaverse demands significant and consistent bandwidth to handle the high volume of data transfer for real-time communication (voice, video), streaming high-fidelity environments with complex textures and lighting, and user-generated content like avatars and creations [45]. Fortunately, advancements in infrastructure like fiber optic networks and next-generation wireless technologies (5G/6G) are increasing global internet speeds and accessibility [170]. Additionally, data compression techniques and strategically placed Content Delivery Networks (CDNs) can further optimize data transfer and reduce bandwidth requirements without sacrificing user experience [171].
- **Hardware Requirements:** Rendering complex virtual environments and interacting with them in real-time will demand powerful hardware from users, including high-performance graphics cards (GPUs) and central processing units (CPUs) and potentially specialized VR/AR peripherals like headsets and gloves [172]. The cost and

accessibility of such hardware could limit participation, creating an entry barrier. Cloud-based rendering offers a promising solution, shifting processing power to remote servers and allowing users to access the metaverse through less powerful devices and developing metaverse applications that can run efficiently on a broader range of hardware capabilities and continued advancements in VR/AR technology towards more powerful and affordable devices can significantly improve accessibility for a broader audience [168].

– **Latency:** Low latency, or minimal delay in data transfer over networks, is crucial for a smooth and immersive metaverse experience. Lag or delays can cause disorientation, hinder real-time interactions like conversations or collaborative tasks, and make the experience feel unresponsive. Network infrastructure improvements and advancements in communication protocols will be necessary to ensure low latency for a global user base [173]. Edge computing, which distributes processing power closer to users through strategically placed servers at network endpoints, can significantly reduce the distance data needs to travel and minimize latency [40], [174]. Additionally, research into new and improved network protocols designed explicitly for the metaverse can further reduce latency and improve data transfer efficiency [25], [40].

– **Storage:** The metaverse generates vast amounts of data, from user avatars and virtual assets to complex world simulations. Decentralized storage solutions are needed to distribute this data securely and efficiently across the network. Scalable and cost-effective storage solutions are essential for the long-term viability of the decentralized metaverse. Distributed ledger technologies (DLTs) like blockchain technology can provide secure and transparent storage solutions for metaverse data [42], [175]. However, the scalability and cost efficiency of these solutions need further development. The InterPlanetary File System (IPFS), a peer-to-peer storage network, offers a decentralized and potentially more scalable alternative to traditional storage solutions [103], [176]. Further integration and development of IPFS for metaverse applications alongside data sharding (splitting data across multiple storage nodes) and replication (creating copies of critical data sets) can improve storage efficiency and redundancy within the decentralized network [103].

B. SECURITY AND PRIVACY IN THE DECENTRALIZED METAVERSE

While brimming with potential, the decentralized metaverse introduces a unique set of security and privacy challenges due to its distributed nature. Unlike traditional, centralized systems, control and data are spread across a peer-to-peer network in decentralized environments. While ensuring transparency and immutability, this very distribution also opens doors to novel security and privacy concerns that demand careful consideration and robust mitigation strategies.

Here, we delve into specific vulnerabilities within decentralized metaverse systems and blockchain technologies, along with potential countermeasures:

1) **Decentralized Network Attacks:** The distributed nature of decentralized metaverse systems makes them susceptible to attacks targeting the underlying blockchain network. These attacks can disrupt operations, steal user assets, or manipulate data. Here are some common threats:
   - **Distributed Denial-of-Service (DDoS) Attacks:** The likelihood of Distributed Denial-of-Service (DDoS) assaults has dramatically increased with the growth of metaverse adoption. Malicious actors can flood the network with traffic, hindering user access and degrading service quality [177].
   - **Sybil Attacks:** In case of a Sybil attack, the attacker gains control of a significant portion of the network nodes, allowing them to manipulate the consensus mechanism and potentially steal assets [178].
   - **51% Attacks:** If an attacker controls more than half of the computing power on a Proof-of-Work (PoW) blockchain, they can disrupt transactions or reverse them altogether [179].

   Example: In 2022, a popular play-to-earn metaverse game, Axie Infinity, suffered a devastating DDoS attack that damaged its network for days. This attack highlighted the vulnerability of decentralized networks to such disruptions, impacting the user experience and potentially causing financial losses [180].
   Countermeasures: Network Security Fortification: To combat these network attacks, several advancements are crucial:
   - **Scalable Consensus Mechanisms:** Shifting towards scalable consensus mechanisms like Proof-of-Stake (PoS) or Delegated Proof-of-Stake (DPoS) can alleviate the computational burden on the network, making DDoS attacks less effective [181].
   - **Byzantine Fault Tolerance (BFT) Algorithms:** Implementing BFT protocols can ensure data consistency even in the presence of malicious nodes [182].
   - **Decentralized Traffic Routing and Load Balancing:** Distributing network traffic across various nodes can mitigate the impact of DDoS attacks [183].
2) **Smart Contract Vulnerabilities:** Smart contracts are self-executing code deployed on the blockchain that govern interactions within the metaverse. However, attackers may use smart contract flaws and vulnerabilities to their advantage to steal money, alter in-game items, or interfere with operations.
   Example: In 2017, a vulnerability in the Parity Multisig Wallet contract, used to store and manage funds on

TABLE 7: Challenges and their Potential Solutions in the Decentralized Metaverse

Challenge/Threat	Description	Potential Solutions
Scalability	Difficulty in handling millions of users, leading to slow transactions and high fees.	Implementing sharding, layer-two scaling solutions, and efficient consensus mechanisms like Proof of Stake (PoS).
Interoperability	Challenges in data exchange and user experience across diverse platforms.	Collaboration and standardization efforts, open-source development, and establishment of common protocols.
Hardware Requirements	High-performance hardware needed for rendering complex virtual environments and real-time interaction.	Cloud-based rendering, development of efficient metaverse applications, and advancements in affordable VR/AR technology.
Latency	Need for minimal delay in data transfer to ensure a smooth and immersive experience.	Network infrastructure improvements, edge computing, and research into new network protocols.
Storage	Vast amounts of data generation require secure and efficient network distribution.	Decentralized storage solutions like IPFS, data sharding, and replication.
Decentralized Network Attacks	Vulnerability to attacks like Distributed Denial-of-Service (DDoS) which can disrupt operations and steal assets.	Robust network security measures, frequent security audits, and development of resilient consensus protocols.
Privacy and Data Security	Ensuring user privacy and data security in a decentralized environment with no central authority.	Advanced encryption techniques, zero-knowledge proofs, and decentralized identity management systems.
Regulatory and Legal Challenges	Navigating the complex legal landscape and ensuring compliance with diverse regulations.	Collaborative efforts between developers and regulators, proactive legal frameworks, and global standards.
Economic Model and Incentives	Creating sustainable economic models and incentives for user participation.	Designing fair tokenomics, implementing reward systems, and ensuring transparency in economic transactions.
Content Moderation and Governance	Managing user-generated content and maintaining a fair governance system.	Decentralized Autonomous Organizations (DAOs), community-driven moderation, and transparent decision-making processes.

the Ethereum blockchain, resulted in the loss of over $150 million worth of Ether. The vulnerability allowed attackers to lock a portion of the funds within the contract, irretrievable by the intended owners. This incident highlights the critical need for secure smart contract development practices and thorough audits before deployment [184].

Countermeasures: Secure Smart Contract Development and Auditing: Several measures can be adopted to minimize smart contract vulnerabilities:

- **Formal Verification Techniques:** Employing formal verification methods can mathematically prove the correctness and security of smart contracts before deployment [185].
- **Secure Coding Practices:** Adherence to secure coding practices and standardized best practices can significantly reduce the likelihood of vulnerabilities [186].
- **Rigorous Smart Contract Audits:** Third-party audits by security experts can identify potential weaknesses before deployment.

3) **User Identity and Data Management:** The metaverse thrives on user-generated content and interactions. However, managing user identities and data securely in a decentralized environment poses challenges:

- **Privacy Concerns:** User data, including avatars, financial information, and social interactions, needs to be protected from unauthorized access.
- **Pseudonymous Identity Management:** Balancing anonymity for user privacy with accountability to prevent malicious activities can be tricky [187].
- **Data Ownership and Control:** Users should have clear ownership of their data and the ability to control how it is used within the metaverse [188].

Example: Decentraland, a popular metaverse platform, is exploring the use of Self-Sovereign Identity (SSI) solutions to empower users with control over their data and digital identities. This approach allows users to choose what information they share [72].

Countermeasures: Decentralized Identity Solutions and Privacy-Preserving Techniques To address these concerns, fostering user trust requires:

- **Self-Sovereign Identity (SSI):** SSI empowers users to control their identities and decide what data

to share with different entities within the metaverse [10], [73].
- **Zero-Knowledge Proofs (ZKPs):** ZKPs allow users to prove they possess specific attributes without revealing the underlying data, enhancing privacy. For instance, users could prove they are above a certain age limit to access age-restricted content without disclosing their exact birthdate [189].
- **Differential Privacy Techniques:** These techniques can be used to aggregate user data for analytics purposes without compromising individual privacy. Differential privacy adds noise to the data in a controlled way, making it statistically impossible to identify specific individuals within the dataset [190].

By implementing these solutions and fostering a culture of security awareness, developers and researchers can create a more secure and privacy-preserving foundation for the decentralized metaverse. Building upon these solutions and promoting user education on security best practices will be crucial for ensuring user trust and a thriving decentralized metaverse ecosystem.

C. FUTURE RESEARCH DIRECTIONS AND POTENTIAL INNOVATIONS

The investigation of prospective future research topics and inventions becomes increasingly essential as the decentralized metaverse continues its dynamic evolution. This section explores the growing landscape of possibilities, highlighting areas that have the potential to push the metaverse's technological boundaries and alter its course toward a more open, secure, and linked digital space. Table 8 summarizes the findings of this subsection.

– **Sustainable Consensus Mechanisms: Addressing Scalability and Security** The environmental impact of Proof of Work (PoW) remains a significant hurdle for widespread metaverse adoption. While shifting toward Proof of Stake (PoS) is a positive step, current research must delve deeper. Here is how:
  - **Optimizing PoS Variants:** We need to explore the intricacies of existing PoS variations like Delegated Proof of Stake (DPoS) [83] and their scalability limitations within the metaverse context.
  - **Hybrid Consensus Systems:** Research into hybrid consensus models that leverage the strengths of PoS and emerging mechanisms like Proof of Space-Time (PoST) is crucial for achieving optimal scalability and security [86].
  - **Security Analysis of Novel Consensus Models:** As new consensus models emerge, rigorous security analysis is essential to ensure they can withstand potential attacks and maintain the integrity of the metaverse.

– **Bridging the User Experience Gap: Towards Seamless Metaverse Interaction** A seamless and immersive user experience is paramount for metaverse adoption. Here is where research can bridge the gap:
  - **AR/VR Integration and AI-powered Avatars:** Research should focus on developing seamless integration between Augmented Reality (AR) and Virtual Reality (VR) technologies. Additionally, exploring AI-powered avatars that enhance user expression and interaction within the metaverse is crucial [191].
  - **Haptic Feedback and Multisensory Experiences:** Research into advanced haptic feedback systems can further heighten the immersive experience and improve user engagement in the metaverse.
  - **Open Metaverse Interoperability Standards (OMIs):** Continued research and development around OMI standards will ensure smooth cross-platform interactions, allowing users to navigate different metaverse environments seamlessly [33].

– **Evolving Governance: Building Inclusive and Equitable Systems** Decentralized Autonomous Organizations (DAOs) are the vehicles through which the participatory governance models of the metaverse are taking shape. Recent disagreements about governance on platforms like The Graph (GRT) have brought attention to the necessity for reliable systems [111]. These challenges highlight the need for robust systems. Here is where future research can help:
  - **Enhancing DAO Effectiveness:** Research should explore methods to improve the efficiency and effectiveness of DAOs, including streamlining voting processes and decision-making mechanisms.
  - **Open and Transparent Governance:** Ensuring open communication channels and fostering transparency within DAOs will be crucial for building trust and user confidence.
  - **Inclusive Decision-Making Models:** Exploring innovative models like stakeholder token-weighted decision-making and quadratic voting can promote a more inclusive and equitable governance structure within the metaverse.

  Additionally, investigating creative strategies like stakeholder token-weighted decision-making and quadratic voting can promote more inclusive and equitable metaverse governance [192].

– **Converging Infrastructure: Powering the Decentralized Metaverse** Building a robust and scalable infrastructure is vital for the metaverse to thrive. Here is where research can play a crucial role:
  - **Decentralized Storage Solutions:** Research into efficient and secure decentralized storage solutions like Filecoin and Arweave is crucial for storing vast amounts of metaverse data in a distributed and censorship-resistant manner.
  - **Scalable Networking Protocols:** Exploring novel networking protocols specifically designed for the

TABLE 8: Future Research Directions in the Decentralized Metaverse

Field of Improvement	Research Scope
Open Metaverse Interoperability Standards (OMIs)	• Continued research and development around OMI standards to ensure smooth cross-platform interactions. • Enabling users to navigate different metaverse environments seamlessly.
Enhancing DAO Effectiveness	• Researching methods to improve the efficiency and effectiveness of DAOs. • Streamlining voting processes and decision-making mechanisms. • Ensuring open communication channels and fostering transparency within DAOs. • Exploring innovative models like stakeholder token-weighted decision-making and quadratic voting.
Decentralized Storage Solutions	• Researching efficient and secure decentralized storage solutions like Filecoin and Arweave. • Ensuring secure and censorship-resistant storage of vast amounts of metaverse data.
Scalable Networking Protocols	• Exploring novel networking protocols designed for the metaverse. • Addressing scalability challenges and ensuring smooth user experiences.
Edge Computing for Decentralized Processing	• Researching integration of edge computing technologies. • Distributing processing power at the network's edge to reduce latency and improve performance.
Quantum-Safe Encryption for Metaverse Security	• Researching quantum-safe encryption techniques. • Safeguarding the decentralized metaverse against potential threats from advancements in quantum computing.
Quantum-Enhanced Simulations for Complex Systems	• Exploring the application of quantum-enhanced simulations. • Opening doors for complex simulations in scientific research and engineering fields.

metaverse can address scalability challenges and ensure smooth user experiences.

- **Edge Computing for Decentralized Processing:** Research into integrating edge computing technologies can distribute processing power at the network's edge, reducing latency and improving metaverse performance.

Information on research directions in infrastructure for decentralized metaverses is also mentioned previously in the first subsection.

– **Convergence with Cutting-Edge Technologies: Unlocking New Possibilities** The metaverse has the potential to be transformed by emerging technologies like quantum computing. Recent innovations, such as quantum computing successes by businesses like IBM and Google, present chances to reimagine the computational capability and security of the metaverse [80], [193]. Here is how research can further improve these innovations:

- **Quantum-Safe Encryption for Metaverse Security:** Research into quantum-safe encryption techniques is essential to safeguard the decentralized metaverse against potential threats posed by advancements in quantum computing [194].
- **Quantum-Enhanced Simulations for Complex Systems:** Exploring the application of quantum-enhanced simulations within the metaverse can open doors for complex simulations in various fields like scientific research and engineering [194].

By addressing these research gaps, we can pave the way for a more secure, scalable, and user-centric decentralized metaverse. This structured roadmap, aligned with the identified research limitations, presents a focused approach toward shaping a future where the metaverse becomes an integral part of our digital lives.

X. RESULTS & DISCUSSION

In this survey, we delved into the emerging landscape of decentralized metaverse ecosystems fueled by blockchain and Web 3.0 technologies. Once a mere speculative concept, the metaverse has materialized into a vibrant reality characterized by decentralization and immersive experiences. The integration of blockchain and Web 3.0 has elevated the metaverse to unprecedented levels of security, transparency, and user empowerment.

A. KEY FINDINGS

The key findings of our survey paper are briefly summarized below:

1) **Ownership and Interoperability:** Decentralized metaverse platforms redefine digital ownership through the use of non-fungible tokens (NFTs), which represent unique virtual assets, including land and in-game items. For instance, Decentraland and Sandbox use NFTs to enable users to own, develop, and trade virtual land. This approach grants users actual ownership and promotes interoperability across different platforms, enhancing the user experience by enabling seamless asset transfers.
2) **Economic Frameworks and Monetization:** The decentralized metaverse introduces innovative economic models, empowering users to monetize their activities. Platforms like Decentraland and Axie Infinity incorporate native cryptocurrencies (e.g., MANA and SLP) to facilitate transactions and incentivize user participation. These economic frameworks allow users to earn real-world income through virtual land sales, in-game item trading, and participation in virtual events, thereby blurring the lines between virtual and physical economies.
3) **Governance and Community Participation:** Decentralized Autonomous Organizations (DAOs) play a crucial role in metaverse governance, providing a framework for user-driven decision-making. Vault Hill exemplifies the potential of DAOs in managing virtual spaces, allowing users to vote on platform policies and development directions. This decentralized governance model fosters a sense of community ownership and ensures the platform evolves in line with the users' collective interests.
4) **Technological Integration, Scalability, and Web 3.0 Impact:** Blockchain technology and Web 3.0 collectively underpin the security, transparency, and user autonomy within the metaverse. The integration of scalable consensus mechanisms, such as proof-of-stake and sharding, significantly enhances the performance and sustainability of these platforms. Web 3.0 further contributes by decentralizing control, allowing users to interact directly without intermediaries. The case study on The Sandbox highlights the importance of these technologies in supporting large-scale user interactions and transactions, ensuring efficiency and security. Web 3.0 technologies also facilitate the seamless integration of various decentralized applications (dApps), creating a more interconnected and responsive virtual ecosystem.
5) **Applications Across Various Sectors:** The decentralized metaverse extends beyond gaming and entertainment, finding applications in education, healthcare, and enterprise collaboration. For example, virtual simulations in healthcare can aid in medical training, while educational platforms can offer immersive learning experiences. Enterprises can leverage the metaverse for virtual meetings, product demonstrations, and customer engagement, showcasing the versatility and far-reaching impact of these technologies.
6) **Challenges and Future Directions:** While the potential of the decentralized metaverse is immense, several challenges must be addressed to realize its full potential. Scalability becomes a critical issue as user participation and transaction volumes increase, necessitating the implementation of layer 2 solutions and optimized blockchain protocols to handle higher loads and ensure smooth user experiences. Interoperability is essential for creating a unified virtual ecosystem, requiring standardized protocols and collaborative frameworks to facilitate cross-platform interactions. Security remains paramount, with the need for advanced encryption methods, secure smart contract coding practices, and robust governance mechanisms to mitigate risks and build user trust. Enhancing user experience and accessibility is also crucial for broader adoption, involving improvements in user interfaces and providing educational resources to help users navigate the metaverse's complexities. Lastly, navigating regulatory landscapes is increasingly crucial as the metaverse integrates more with real-world assets and economies, requiring clear guidelines and compliance frameworks to protect users and ensure platform legitimacy.

B. DISCUSSION

The findings from the case studies of Decentraland, Vault Hill, and The Sandbox reveal a multi-faceted view of how blockchain technology and Web 3.0 are shaping the decentralized metaverse. Each platform demonstrates unique approaches to ownership, user engagement, economic management, and the integration of real-world assets within virtual spaces.

Decentralized governance, facilitated by DAOs, emerges as a critical component in ensuring community-driven decision-making and enhancing inclusivity. This aligns with the metaverse's ethos of user empowerment, where participants have a say in developing and managing their virtual environments.

Despite these advancements, several challenges persist. Scalability remains a critical issue, necessitating innovative solutions to handle the increasing volume of transactions and interactions within the metaverse. Interoperability between different platforms is essential to create a seamless user experience and enable cross-platform interactions. Additionally, security concerns related to data ownership and privacy require ongoing attention to safeguard users' digital assets and identities.

The integration of real-world assets into the metaverse, as demonstrated by Vault Hill, introduces regulatory considerations that must be addressed to ensure compliance and protect user interests. Furthermore, the balance between virtual and real-world interactions must be carefully managed to create a cohesive and immersive experience.

XI. CONCLUSION

At the confluence of blockchain and Web 3.0 technologies, the decentralized metaverse is poised to revolutionize digital interactions and economies. Our survey underscores its transformative potential, demonstrating how these technologies enhance security, transparency, and user empowerment within virtual environments.

The case studies of Decentraland, Vault Hill, and The Sandbox illustrate diverse approaches to integrating blockchain within the metaverse, each showcasing unique benefits and challenges. Decentraland exemplifies the fusion of blockchain with virtual reality, fostering a robust virtual economy. Vault Hill bridges the gap between real-world assets and the metaverse, promoting broader economic participation through tokenization. The Sandbox empowers users with tools to create, own, and monetize content, thus democratizing digital creation and engagement.

Despite these advancements, significant challenges remain. Scalability, interoperability, and security are critical areas that require continuous innovation and research. Addressing these challenges is vital for the sustainable growth and widespread adoption of decentralized metaverse platforms.

Looking ahead, the role of researchers, developers, and visionaries will be crucial in shaping the future of the decentralized metaverse. Ethical and responsible development practices are essential to ensure these virtual environments are inclusive, secure, and beneficial for all users. By embracing the principles of decentralization, we can create immersive, community-owned digital spaces that redefine our digital existence.

In conclusion, the decentralized metaverse represents a bold frontier in the evolution of digital technologies. As we continue to explore and innovate, we are paving the way for a future where virtual and physical realities seamlessly integrate, fostering new forms of collaboration, creativity, and economic activity. The journey of the decentralized metaverse is just beginning, and its potential to transform how we interact with digital worlds is boundless.

REFERENCES

[1] Y. Zhao and L. Wu, "Second life: A new window for e-learning," in 2009 Ninth International Conference on Hybrid Intelligent Systems, vol. 3, 2009, pp. 191–194.

[2] V. T. Truong, L. Le, and D. Niyato, "Blockchain meets metaverse and digital asset management: A comprehensive survey," IEEE Access, vol. 11, pp. 26 258–26 288, 2023.

[3] L. Cao, "Decentralized ai: Edge intelligence and smart blockchain, metaverse, web3, and desci," IEEE Intelligent Systems, vol. 37, no. 3, pp. 6–19, 2022.

[4] G. V. Research, "Virtual reality market size, share trends analysis report by technology (semi fully immersive, non-immersive), by device (hmd, gtd, pdw), by component (hardware, software), by application, by region, and segment forecasts, 2022 - 2030," 2023.

[5] R. Di Pietro and S. Cresci, "Metaverse: Security and privacy issues," in 2021 Third IEEE International Conference on Trust, Privacy and Security in Intelligent Systems and Applications (TPS-ISA), 2021, pp. 281–288.

[6] OECD, "Data portability, interoperability, and digital platform competition," OECD Competition Committee Discussion Paper, 2021. [Online]. Available: http://oe.cd/dpic

[7] C. Chen, L. Zhang, Y. Li, T. Liao, S. Zhao, Z. Zheng, H. Huang, and J. Wu, "When digital economy meets web3.0: Applications and challenges," IEEE Open Journal of the Computer Society, vol. 3, no. 01, pp. 233–245, jan 2022.

[8] M. Goldberg and F. Schär, "Metaverse governance: An empirical analysis of voting within decentralized autonomous organizations," Journal of Business Research, vol. 160, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0148296323001224

[9] Y. K. Dwivedi, L. Hughes, A. M. Baabdullah, S. Ribeiro-Navarrete, M. Giannakis, M. M. Al-Debei, D. Dennehy, B. Metri, D. Buhalis, C. M. Cheung, K. Conboy, R. Doyle, R. Dubey, V. Dutot, R. Felix, D. Goyal, A. Gustafsson, C. Hinsch, I. Jebabli, M. Janssen, Y.-G. Kim, J. Kim, S. Koos, D. Kreps, N. Kshetri, V. Kumar, K.-B. Ooi, S. Papagiannidis, I. O. Pappas, A. Polyviou, S.-M. Park, N. Pandey, M. M. Queiroz, R. Raman, P. A. Rauschnabel, A. Shirish, M. Sigala, K. Spanaki, G. Wei-Han Tan, M. K. Tiwari, G. Viglia, and S. F. Wamba, "Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy," International Journal of Information Management, vol. 66, p. 102542, 2022.

[10] G. V. Research, "Blockchain technology market size, share trends analysis report by type (private cloud, public cloud), by application (digital identity, payments), by enterprise size, by component, by end use, and segment forecasts, 2023 - 2030," 2023.

[11] T. Huynh-The, T. R. Gadekallu, W. Wang, G. Yenduri, P. Ranaweera, Q.-V. Pham, D. B. da Costa, and M. Liyanage, "Blockchain for the metaverse: A review," Future Generation Computer Systems, vol. 143, pp. 401–419, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167739X23000493

[12] H. Sami, A. Hammoud, M. Arafeh, M. Wazzeh, S. Arisdakessian, M. Chahoud, O. Wehbi, M. Ajaj, A. Mourad, H. Otrok, O. A. Wahab, R. Mizouni, J. Bentahar, C. Talhi, Z. Dziong, E. Damiani, and M. Guizani, "The metaverse: Survey, trends, novel pipeline ecosystem future directions," 2023.

[13] D. M. Doe, J. Li, N. Dusit, Z. Gao, J. Li, and Z. Han, "Promoting the sustainability of blockchain in web 3.0 and the metaverse through diversified incentive mechanism design," IEEE Open Journal of the Computer Society, vol. 4, pp. 171–184, 2023.

[14] T. Maksymyuk, J. Gazda, G. Bugár, V. Gazda, M. Liyanage, and M. Dohler, "Blockchain-empowered service management for the decentralized metaverse of things," IEEE Access, vol. 10, pp. 99 025–99 037, 2022.

[15] Y. Fu, C. Li, F. R. Yu, T. H. Luan, P. Zhao, and S. Liu, "A survey of blockchain and intelligent networking for the metaverse," IEEE Internet of Things Journal, vol. 10, no. 4, pp. 3587–3610, 2023.

[16] R. Qin, W. Ding, J. Li, S. Guan, G. Wang, Y. Ren, and Z. Qu, "Web3-based decentralized autonomous organizations and operations: Architectures, models, and mechanisms," IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 53, no. 4, pp. 2073–2082, 2023.

[17] Y. Wang, Z. Su, N. Zhang, R. Xing, D. Liu, T. H. Luan, and X. Shen, "A survey on metaverse: Fundamentals, security, and privacy," IEEE Communications Surveys Tutorials, vol. 25, no. 1, pp. 319–352, 2023.

[18] B. Tao, H.-N. Dai, H. Xie, and F. L. Wang, "Structural identity representation learning for blockchain-enabled metaverse based on complex

network analysis," IEEE Transactions on Computational Social Systems, pp. 1–12, 2023.

[19] A. Abilkaiyrkyzy, A. Elhagry, F. Laamarti, and A. E. Saddik, "Metaverse key requirements and platforms survey," IEEE Access, vol. 11, pp. 117 765–117 787, 2023.

[20] J. Ramírez Masferrer, J. Herrera Herbert, and R. Arranz Revenga, "Evolution of teaching in the metaverse from 2011 to 2024," in INTED2024 Proceedings, ser. 18th International Technology, Education and Development Conference. IATED, 4-6 March, 2024 2024, pp. 516–525. [Online]. Available: https://doi.org/10.21125/inted.2024.0192

[21] Decentraland, "What makes a virtual world more than a game?" unknown. [Online]. Available: https://decentraland.org/blog/technology/virtual-worlds

[22] P. Z. L. W. D. X. Z. L. A. K. C. B. P. H. Lik-Hang Lee, Tristan Braud, "All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystems, and research agenda." [Online]. Available: https://doi.org/10.48550/arXiv.2110.05352,https://arxiv.org/abs/2110.05352

[23] H. Chen, H. Duan, M. Abdallah, Y. Zhu, Y. Wen, A. E. Saddik, and W. Cai, "Web3 metaverse: State-of-the-art and vision," ACM Trans. Multimedia Comput. Commun. Appl., vol. 20, no. 4, dec 2023. [Online]. Available: https://doi.org/10.1145/3630258

[24] D. Wang, X. Yan, and Y. Zhou, "Research on metaverse: Concept, development and standard system," in 2021 2nd International Conference on Electronics, Communications and Information Technology (CECIT), 2021, pp. 983–991.

[25] M. Xu, W. C. Ng, W. Y. B. Lim, J. Kang, Z. Xiong, D. Niyato, Q. Yang, X. Shen, and C. Miao, "A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges," IEEE Communications Surveys Tutorials, vol. 25, no. 1, pp. 656–700, 2023.

[26] Q. Yang, Y. Zhao, H. Huang, Z. Xiong, J. Kang, and Z. Zheng, "Fusing blockchain and ai with metaverse: A survey," IEEE Open Journal of the Computer Society, vol. 3, pp. 122–136, 2022.

[27] L.-H. Lee, Z. Lin, R. Hu, Z. Gong, A. Kumar, T. Li, S. Li, and P. Hui, "When creators meet the metaverse: A survey on computational arts," arXiv preprint arXiv:2111.13486, 2021.

[28] G. Makamara and M. Adolph, "A survey of extended reality (xr) standards," in 2022 ITU Kaleidoscope- Extended reality – How to boost quality of experience and interoperability, 2022, pp. 1–11.

[29] D. Owens, A. Mitchell, D. Khazanchi, and I. Zigurs, "An empirical investigation of virtual world projects and metaverse technology capabilities," DATA BASE, vol. 42, pp. 74–101, 02 2011.

[30] M. Uddin, S. Manickam, H. Ullah, M. Obaidat, and A. Dandoush, "Unveiling the metaverse: Exploring emerging trends, multifaceted perspectives, and future challenges," IEEE Access, pp. 1–1, 2023.

[31] I. Nikolaidis, "Networking the metaverses [editor's note]," IEEE Network, vol. 21, no. 5, pp. 2–4, 2007.

[32] L. Rosenberg, C. Wallace, K. Pearlman, and B. Choudhary, "The metaverse and standards," 05 2023.

[33] "Open Metaverse Interoperability Group," https://omigroup.org.

[34] "Decentralized Identifiers (DIDs) v1.0," https://www.w3.org, accessed: Aug. 12, 2023.

[35] "Interledger Protocol(ILP)-Overview," https://interledger.org, accessed: Aug. 12, 2023.

[36] "VRM Consortium," https://www.vrm-consortium.org, accessed: Aug. 12, 2023.

[37] L. Daly and D. Brutzman, "X3d: Extensible 3d graphics standard [standards in a nutshell]," IEEE Signal Processing Magazine, vol. 24, no. 6, pp. 130–135, 2007.

[38] A. M. Al-Ghaili, H. Kasim, N. M. Al-Hada, Z. B. Hassan, M. Othman, J. H. Tharik, R. M. Kasmani, and I. Shayea, "A review of metaverse's definitions, architecture, applications, challenges, issues, solutions, and future trends," IEEE Access, vol. 10, pp. 125 835–125 866, 2022.

[39] S. H. Jung and I.-o. Jeon, "A study on the components of the metaverse ecosystem." Journal of Digital Convergence, vol. 20, no. 2, 2022.

[40] D. Van Huynh, S. R. Khosravirad, A. Masaracchia, O. A. Dobre, and T. Q. Duong, "Edge intelligence-based ultra-reliable and low-latency communications for digital twin-enabled metaverse," IEEE Wireless Communications Letters, vol. 11, no. 8, pp. 1733–1737, 2022.

[41] X. Huang, W. Zhong, J. Nie, Q. Hu, Z. Xiong, J. Kang, and T. Q. S. Quek, "Joint user association and resource pricing for metaverse: Distributed and centralized approaches," in 2022 IEEE 19th International Conference on Mobile Ad Hoc and Smart Systems (MASS), 2022, pp. 505–513.

[42] A. J. Bokolo, "Exploring interoperability of distributed ledger and decentralized technology adoption in virtual enterprises," Information Systems and e-Business Management, vol. 20, no. 4, pp. 685–718, 2022.

[43] J. Han, J. Heo, and E. You, "Analysis of metaverse platform as a new play culture: Focusing on roblox and zepeto," in International Conference on Human-centered Artificial Intelligence, 2021, pp. 1–10.

[44] M. Lacity and S. Lupien, Blockchain Fundamentals for Web 3.0: -. Epic Books, 2022. [Online]. Available: https://books.google.co.in/books?id=ctmPEAAAQBAJ

[45] J. Ryu, S. Son, J. Lee, Y. Park, and Y. Park, "Design of secure mutual authentication scheme for metaverse environments using blockchain," IEEE Access, vol. 10, pp. 98 944–98 958, 2022.

[46] I. Yaqoob, K. Salah, R. Jayaraman, and Y. Al-Hammadi, "Blockchain for healthcare data management: opportunities, challenges, and future recommendations," Neural Computing and Applications, pp. 1–16, 2021.

[47] T. M. Tan and S. Saraniemi, "Trust in blockchain-enabled exchanges: Future directions in blockchain marketing," Journal of the Academy of Marketing Science, vol. 51, 07 2022.

[48] J. Sun, W. Gan, Z. Chen, J. Li, and P. S. Yu, "Big data meets metaverse: A survey," 2022.

[49] Y. Wang, Z. Su, and M. Yan, "Social metaverse: Challenges and solutions," arXiv preprint arXiv:2301.10221, 2023.

[50] Y. Pan and A. Steed, "The impact of self-avatars on trust and collaboration in shared virtual environments," PloS one, vol. 12, no. 12, p. e0189078, 2017.

[51] M. I. Khalid, I. Ehsan, A. K. Al-Ani, J. Iqbal, S. Hussain, S. S. Ullah, and Nayab, "A comprehensive survey on blockchain-based decentralized storage networks," IEEE Access, vol. 11, pp. 10 995–11 015, 2023.

[52] A. S. Rajawat, S. Goyal, A. Goyal, K. Rajawat, M. S. Raboaca, C. Verma, and T. C. Mihaltan, "Enhancing security and scalability of metaverse with blockchain-based consensus mechanisms," in 2023 15th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), 2023, pp. 01–06.

[53] F. A. Alabdulwahhab, "Web 3.0: The decentralized web blockchain networks and protocol innovation," in 2018 1st International Conference on Computer Applications Information Security (ICCAIS), 2018, pp. 1–4.

[54] T. Huynh-The, T. R. Gadekallu, W. Wang, G. Yenduri, P. Ranaweera, Q.-V. Pham, D. B. da Costa, and M. Liyanage, "Blockchain for the metaverse: A review," Future Generation Computer Systems, vol. 143, pp. 401–419, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167739X23000493

[55] S. Ghirmai, D. Mebrahtom, M. Aloqaily, M. Guizani, and M. Debbah, "Self-sovereign identity for trust and interoperability in the metaverse," in 2022 IEEE Smartworld, Ubiquitous Intelligence Computing, Scalable Computing Communications, Digital Twin, Privacy Computing, Metaverse, Autonomous Trusted Vehicles (SmartWorld/UIC/ScalCom/DigitalTwin/PriComp/Meta), 2022, pp. 2468–2475.

[56] E. L. Katarína Válišková, Veronika Machová, "Virtual marketplace dynamics data, spatial analytics, and customer engagement tools in a real-time interoperable decentralized metaverse," Linguistic and Philosophical Investigations, vol. 21, pp. 105–120, 2022.

[57] M. Muneeb, Z. Raza, I. U. Haq, and O. Shafiq, "Smartcon: A blockchain-based framework for smart contracts and transaction management," IEEE Access, vol. 10, pp. 23 687–23 699, 2022.

[58] T. Q. Duong, D. Van Huynh, S. R. Khosravirad, V. Sharma, O. A. Dobre, and H. Shin, "From digital twin to metaverse: The role of 6g ultra-reliable and low-latency communications with multi-tier computing," IEEE Wireless Communications, vol. 30, no. 3, pp. 140–146, 2023.

[59] J. Schulz, C. Dubslaff, P. Seeling, S.-C. Li, S. Speidel, and F. H. Fitzek, "Negative latency in the tactile internet as enabler for global metaverse immersion," IEEE Network, 2024.

[60] "Filecoin," https://filecoin.io/, accessed: May. 13, 2024.

[61] "Arweave," https://www.arweave.org/, accessed: May. 13, 2024.

[62] L.-H. Lee, T. Braud, P. Zhou, L. Wang, D. Xu, Z. Lin, A. Kumar, C. Bermejo, and P. Hui, "All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda," CoRR, 10 2021.

[63] A. M. Esteban Ordano and J. Araoz, "Decentraland: A blockchain-based virtual world - white paper," Decentralnd.org, 2017. [Online]. Available: https://decentraland.org/whitepaper.pdf

[64] R. Belk, M. Humayun, and M. Brouard, "Money, possessions, and ownership in the metaverse: Nfts, cryptocurrencies, web3 and wild

markets," Journal of Business Research, vol. 153, pp. 198–205, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0148296322007147

[65] S. N. Khan, F. Loukil, C. Ghedira-Guegan, E. Benkhelifa, and A. Bani-Hani, "Blockchain smart contracts: Applications, challenges, and future trends," Peer-to-peer Networking and Applications, vol. 14, pp. 2901–2925, 2021.

[66] K. Christodoulou, L. Katelaris, M. Themistocleous, P. Christodoulou, and E. Iosif, "Nfts and the metaverse revolution: research perspectives and open challenges," Blockchains and the Token Economy: Theory and Practice, pp. 139–178, 2022.

[67] "The Sandbox Game." https://www.sandbox.game/en/, accessed: Oct. 28, 2023.

[68] J. Proelss, S. Sévigny, and D. Schweizer, "Gamefi: The perfect symbiosis of blockchain, tokens, defi, and nfts?" International Review of Financial Analysis, vol. 90, p. 102916, 2023.

[69] O. Alam, "Understanding the economies of blockchain games: An empirical analysis of axie infinity," Distributed Computing Group Computer Engineering and Networks Laboratory ETH Zürich.—2022.—URL: https://pub. tik. ee. ethz. ch/students/2, 2022.

[70] A. J. Delic and P. H. Delfabbro, "Profiling the potential risks and benefits of emerging "play to earn" games: a qualitative analysis of players' experiences with axie infinity," International Journal of Mental Health and Addiction, vol. 22, no. 1, pp. 634–647, 2024.

[71] D. A. Aguila, J. M. Bartolata, and J. G. Estrañero, "Axeing the axie infinity (ai): The ai of modern gaming, business model strategem, and global economy towards cryptocurrency era," College of Liberal Arts and Sciences Dasmariñas, 2022.

[72] M. Kuperberg, "Blockchain-based identity management: A survey from the enterprise and ecosystem perspective," IEEE Transactions on Engineering Management, vol. 67, no. 4, pp. 1008–1027, 2019.

[73] A. M. Thomas, R. Ramaguru, and M. Sethumadhavan, "Distributed identity and verifiable claims using ethereum standards," in Inventive Communication and Computational Technologies: Proceedings of ICICCT 2021. Springer, 2022, pp. 621–636.

[74] M. S. Ferdous, F. Chowdhury, and M. O. Alassafi, "In search of self-sovereign identity leveraging blockchain technology," IEEE access, vol. 7, pp. 103 059–103 079, 2019.

[75] A. Tan, "Metaverse realities: A journey through governance, legal complexities, and the promise of virtual worlds," Legal Complexities, and the Promise of Virtual Worlds (December 9, 2021), 2021.

[76] B. Lashkari and P. Musilek, "A comprehensive review of blockchain consensus mechanisms," IEEE Access, vol. 9, pp. 43 620–43 652, 2021.

[77] Y. Wang, C. Tang, F. Lin, Z. Zheng, and Z. Chen, "Pool strategies selection in pow-based blockchain networks: Game-theoretic analysis," IEEE Access, vol. 7, pp. 8427–8436, 2019.

[78] S. Misra, A. Mukherjee, A. Roy, N. Saurabh, Y. Rahulamathavan, and M. Rajarajan, "Blockchain at the edge: Performance of resource-constrained iot networks," IEEE Transactions on Parallel and Distributed Systems, vol. 32, no. 1, pp. 174–183, 2020.

[79] C. T. Nguyen, D. T. Hoang, D. N. Nguyen, D. Niyato, H. T. Nguyen, and E. Dutkiewicz, "Proof-of-stake consensus mechanisms for future blockchain networks: fundamentals, applications and opportunities," IEEE access, vol. 7, pp. 85 727–85 745, 2019.

[80] M. Kaiiali, S. Sezer, and A. Khalid, "Cloud computing in the quantum era," in 2019 IEEE Conference on Communications and Network Security (CNS). IEEE, 2019, pp. 1–4.

[81] O. Nnamonu, M. Hammoudeh, and T. Dargahi, "Digital forensic investigation of web-based virtual reality worlds: decentraland as a case study," IEEE Communications Magazine, vol. 61, no. 9, pp. 72–78, 2023.

[82] V. Sagar and P. Kaushik, "Ethereum 2.0 blockchain in healthcare and healthcare based internet-of-things devices," in Proceedings of the International Conference on Paradigms of Computing, Communication and Data Sciences, M. Dave, R. Garg, M. Dua, and J. Hussien, Eds. Singapore: Springer Singapore, 2021, pp. 225–233.

[83] D. Rhodes, "What is delegated proof of stake? an overview of dpos blockchains," Komodo Academy, 2022.

[84] W. Song, W. Zhang, L. Zhai, L. Liu, J. Wang, S. Huang, and B. Li, "Eos. io blockchain data analysis," The Journal of Supercomputing, pp. 1–32, 2022.

[85] D. Mikhaylov, A. Kutin, J. Anderson, and M. Faleev, "Analysis of the" dandruff attack" on the tron network: risks, damage assessment, and solutions," Journal of Information Security and Cybercrimes Research, vol. 6, no. 1, pp. 01–11, 2023.

[86] T. Moran and I. Orlov, "Simple proofs of space-time and rational proofs of storage," in Advances in Cryptology–CRYPTO 2019: 39th Annual International Cryptology Conference, Santa Barbara, CA, USA, August 18–22, 2019, Proceedings, Part I 39. Springer, 2019, pp. 381–409.

[87] S. de Figueiredo, A. Madhusudan, V. Reniers, S. Nikova, and B. Preneel, "Exploring the storj network: A security analysis," in Proceedings of the 36th Annual ACM Symposium on Applied Computing, 2021, pp. 257–264.

[88] A. Cong An, P. Thi Xuan Diem, L. Thi Thu Lan, T. Van Toi, and L. Duong Quoc Binh, "Building a product origins tracking system based on blockchain and poa consensus protocol," in 2019 International Conference on Advanced Computing and Applications (ACOMP), 2019, pp. 27–33.

[89] M. Mazzoni, A. Corradi, and V. Di Nicola, "Performance evaluation of permissioned blockchains for financial applications: The consensys quorum case study," Blockchain: Research and applications, vol. 3, no. 1, p. 100026, 2022.

[90] L. Gudgeon, S. Werner, D. Perez, and W. J. Knottenbelt, "Defi protocols for loanable funds: Interest rates, liquidity and market efficiency," in Proceedings of the 2nd ACM Conference on Advances in Financial Technologies, 2020, pp. 92–112.

[91] H. Chen and W. Cai, "A comparative analysis of centralized and decentralized developer autonomous organizations managing conflicts in discussing external crises," IEEE Transactions on Computational Social Systems, 2023.

[92] G. A. Pierro and R. Tonelli, "Can solana be the solution to the blockchain scalability problem?" in 2022 IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER), 2022, pp. 1219–1226.

[93] M. Kaur and B. Gupta, "Metaverse technology and the current market," National Institute of Technology Kurukshetra, 2021.

[94] T. A. Hemphill, "The 'metaverse'and the challenge of responsible standards development," Journal of Responsible Innovation, vol. 10, no. 1, p. 2243121, 2023.

[95] D. Tanana, "Avalanche blockchain protocol for distributed computing security," in 2019 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom). IEEE, 2019, pp. 1–3.

[96] Y. Wang, S. Cai, C. Lin, Z. Chen, T. Wang, Z. Gao, and C. Zhou, "Study of blockchains's consensus mechanism based on credit," IEEE Access, vol. 7, pp. 10 224–10 231, 2019.

[97] K. Nath, S. Dhar, and S. Basishtha, "Web 1.0 to web 3.0 - evolution of the web and its various challenges," in 2014 International Conference on Reliability Optimization and Information Technology (ICROIT), 2014, pp. 86–89.

[98] H. Chen, M. Pendleton, L. Njilla, and S. Xu, "A survey on ethereum systems security: Vulnerabilities, attacks, and defenses," ACM Comput. Surv., vol. 53, no. 3, jun 2020. [Online]. Available: https://doi.org/10.1145/3391195

[99] Y. Patashkova, S. Niyazbekova, S. Kerimkhulle, M. Serikova, and M. Troyanskaya, "Dynamics of bitcoin trading on the binance cryptocurrency exchange." Economic Annals-XXI, vol. 187, 2021.

[100] S. Banaeian Far, A. Imani Rad, and M. Rajabzadeh Asaar, "Blockchain and its derived technologies shape the future generation of digital businesses: a focus on decentralized finance and the metaverse," Data Science and Management, vol. 6, no. 3, pp. 183–197, 2023.

[101] L. Breidenbach, C. Cachin, B. Chan, A. Coventry, S. Ellis, A. Juels, F. Koushanfar, A. Miller, B. Magauran, D. Moroz et al., "Chainlink 2.0: Next steps in the evolution of decentralized oracle networks," Chainlink Labs, vol. 1, pp. 1–136, 2021.

[102] H. Huang, J. Lin, B. Zheng, Z. Zheng, and J. Bian, "When blockchain meets distributed file systems: An overview, challenges, and open issues," IEEE Access, vol. 8, pp. 50 574–50 586, 2020.

[103] N. Sangeeta and S. Y. Nam, "Blockchain and interplanetary file system (ipfs)-based data storage system for vehicular networks with keyword search capability," Electronics, vol. 12, no. 7, p. 1545, 2023.

[104] H. Adams, N. Zinsmeister, M. Salem, R. Keefer, and D. Robinson, "Uniswap v3 core," Tech. rep., Uniswap, Tech. Rep., 2021.

[105] L. Zhou, K. Qin, C. F. Torres, D. V. Le, and A. Gervais, "High-frequency trading on decentralized on-chain exchanges," in 2021 IEEE Symposium on Security and Privacy (SP). IEEE, 2021, pp. 428–445.

[106] J. A. Berg, R. Fritsch, L. Heimbach, and R. Wattenhofer, "An empirical study of market inefficiencies in uniswap and sushiswap," in International Conference on Financial Cryptography and Data Security. Springer, 2022, pp. 238–249.

[107] J. Xu, S. Wang, A. Zhou, and F. Yang, "Edgence: A blockchain-enabled edge-computing platform for intelligent iot-based dapps," China Communications, vol. 17, no. 4, pp. 78–87, 2020.
[108] X. Liu, Z. Tang, P. Li, S. Guo, X. Fan, and J. Zhang, "A graph learning based approach for identity inference in dapp platform blockchain," IEEE Transactions on Emerging Topics in Computing, vol. 10, no. 1, pp. 438–449, 2020.
[109] M. Rimsan and A. K. Mahmood, "Application of blockchain and smart contract to ensure temper-proof data availability for energy supply chain," Hunan Daxue Xuebao/Journal of Hunan University Natural Sciences, vol. 47, pp. 154–164, 12 2020.
[110] A. Grech, I. Sood, and L. Ariño, "Blockchain, self-sovereign identity and digital credentials: Promise versus praxis in education," Frontiers in Blockchain, vol. 4, p. 616779, 2021. [Online]. Available: https://app.dimensions.ai/details/publication/pub.1136782813
[111] M. Goldberg and F. Schär, "Metaverse governance: An empirical analysis of voting within decentralized autonomous organizations," Journal of Business Research, vol. 160, p. 113764, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0148296323001224
[112] X. Liu, S. X. Sun, and G. Huang, "Decentralized services computing paradigm for blockchain-based data governance: Programmability, interoperability, and intelligence," IEEE Transactions on Services Computing, vol. 13, no. 2, pp. 343–355, 2020.
[113] S. Badruddoja, R. Dantu, Y. He, M. Thompson, A. Salau, and K. Upadhyay, "Trusted ai with blockchain to empower metaverse," in 2022 Fourth International Conference on Blockchain Computing and Applications (BCCA). IEEE, 2022, pp. 237–244.
[114] S. Wang, Y. Yuan, X. Wang, J. Li, R. Qin, and F.-Y. Wang, "An overview of smart contract: Architecture, applications, and future trends," in 2018 IEEE Intelligent Vehicles Symposium (IV), 2018, pp. 108–113.
[115] "Aragon Decentralized Networks." https://aragon.org/about-aragon, accessed: Oct. 31, 2023.
[116] "Maker Decentralized Systems." https://makerdao.com/en/, accessed: Nov. 1, 2023.
[117] G. Kao, J. Hong, M. Perusse, W. Sheng, G. Kao, J. Hong, M. Perusse, and W. Sheng, "Election meddling: How one man changed an election," Turning Silicon into Gold: The Strategies, Failures, and Evolution of the Tech Industry, pp. 9–13, 2020.
[118] Y. Hermstruwer, "The limits of blockchain democracy," NYUJL & Liberty, vol. 14, p. 402, 2020.
[119] A. S. Berthelsen and E. Bjellerås, "Best practices in decentralized autonomous organization (dao) venture capital: A bibliometric analysis and systematic review," Master's thesis, University of Agder, 2023.
[120] O. Rikken, M. Janssen, and Z. Kwee, "Governance challenges of blockchain and decentralized autonomous organizations," Journal Name, pp. 397–417, January 1 2019.
[121] "Voxels: Cryptovoxels." https://www.voxels.com/, accessed: Oct. 28, 2023.
[122] C. Jentzsch, "Decentralized autonomous organization to automate governance," White paper, Tech. Rep., November 2016.
[123] L. Yang, "Recommendations for metaverse governance based on technical standards," Humanities and Social Sciences Communications, vol. 10, no. 1, pp. 1–10, 2023.
[124] W. Hyun, "Study on standardization for interoperable metaverse," in 2023 25th International Conference on Advanced Communication Technology (ICACT). IEEE, 2023, pp. 319–322.
[125] V. Buterin, "Moving beyond coin voting governance." [Online]. Available: https://vitalik.eth.limo/general/2021/08/16/voting3.html
[126] J.-H. Hsiao, R. Tso, C.-M. Chen, and M.-E. Wu, "Decentralized e-voting systems based on the blockchain technology," in Advances in Computer Science and Ubiquitous Computing, J. J. Park, V. Loia, G. Yi, and Y. Sung, Eds. Singapore: Springer Singapore, 2018, pp. 305–309.
[127] S. T. Alvi, M. N. Uddin, L. Islam, and S. Ahamed, "Dvtchain: A blockchain-based decentralized mechanism to ensure the security of digital voting system voting system," Journal of King Saud University - Computer and Information Sciences, vol. 34, no. 9, pp. 6855–6871, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1319157822002221
[128] U. W. Chohan, "The decentralized autonomous organization and governance issues," December 4 2017. [Online]. Available: https://ssrn.com/abstract=3082055
[129] A. J. Sulkowski, "The tao of dao: Hardcoding business ethics on blockchain," Business & Finance Law Review, vol. 3, no. 2, pp. 146–169, April 2020. [Online]. Available: https://heinonline.org/HOL/P?h=hein.journals/busfnclr3&i=184
[130] B. Schneider, R. Ballesteros, P. Moriggl, and P. M. Asprion, "Decentralized autonomous organizations–evolution, challenges, and opportunities," 2020.
[131] B.-A. Deaky and L. Parv, "Virtual reality for real estate: Its evolution in bluemind software," in 2017 4th Experiment@International Conference (exp.at'17), 2017, pp. 83–86.
[132] A. Wang, Z. Gao, L. H. Lee, T. Braud, and P. Hui, "Decentralized, not dehumanized in the metaverse: Bringing utility to nfts through multimodal interaction," in Proceedings of the 2022 International Conference on Multimodal Interaction, 2022, pp. 662–667.
[133] L. J. Trautman, "Virtual art and non-fungible tokens," Hofstra L. Rev., vol. 50, p. 361, 2021.
[134] J. Bi, H. Yuan, W. Tan, M. Zhou, Y. Fan, J. Zhang, and J. Li, "Application-aware dynamic fine-grained resource provisioning in a virtualized cloud data center," IEEE Transactions on Automation Science and Engineering, vol. 14, no. 2, pp. 1172–1184, 2015.
[135] J. Yan, Y. Yang, and F. Xia, "Subjective land ownership and the endowment effect in land markets: A case study of the farmland "three rights separation" reform in china," Land Use Policy, vol. 101, p. 105137, 2021.
[136] O. Letychevsky, V. Peschanenko, V. Radchenko, M. Poltoratzkyi, P. Kovalenko, and S. Mogylko, "Formal verification of token economy models," in 2019 IEEE International Conference on Blockchain and Cryptocurrency (ICBC). IEEE, 2019, pp. 201–204.
[137] O. Marian, "Are cryptocurrencies super tax havens?" Mich. L. Rev. First Impressions, vol. 112, p. 38, 2013.
[138] Y. Lai, S. Fan, and W. Cai, "Quantitative analysis of play-to-earn blockchain games: A case study of axie infinity," in 2023 IEEE International Conference on Metaverse Computing, Networking and Applications (MetaCom). IEEE, 2023, pp. 250–257.
[139] B. S. Rawal, A. Mentges, and S. Ahmad, "The rise of metaverse and interoperability with split-protocol," in 2022 IEEE 23rd International Conference on Information Reuse and Integration for Data Science (IRI). IEEE, 2022, pp. 192–199.
[140] "Decentral Games." https://decentral.games/, accessed: Oct. 28, 2023.
[141] F. Nissan, J. Hamade, J. Xiao, J. Ragle, J. Price, J. Fares, and M. Mahmoud, "Blockchain as a reliable security framework," in 2021 International Conference on Computational Science and Computational Intelligence (CSCI). IEEE, 2021, pp. 625–632.
[142] "Blankos." https://blankos.com/, accessed: Oct. 28, 2023.
[143] T. J. Chaffer and J. Goldston, "On the existential basis of self-sovereign identity and soulbound tokens: An examination of the" self" in the age of web3," Journal of Strategic Innovation and Sustainability, vol. 17, no. 3, pp. 1–9, 2022.
[144] D. Wu, Z. Yang, P. Zhang, R. Wang, B. Yang, and X. Ma, "Virtual-reality inter-promotion technology for metaverse: A survey," IEEE Internet of Things Journal, 2023.
[145] M. Rzeszewski and L. Evans, "Virtual place during quarantine–a curious case of vrchat," Rozwój Regionalny i Polityka Regionalna, no. 51, pp. 57–75, 2020.
[146] P. Galambos, P. Baranyi, and I. J. Rudas, "Merged physical and virtual reality in collaborative virtual workspaces: The virca approach," in IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society. IEEE, 2014, pp. 2585–2590.
[147] W. Liang, J. Liu, Y. Lang, B. Ning, and L.-F. Yu, "Functional workspace optimization via learning personal preferences from virtual experiences," IEEE transactions on visualization and computer graphics, vol. 25, no. 5, pp. 1836–1845, 2019.
[148] H. Kuzuoka, "Spatial workspace collaboration: a sharedview video support system for remote collaboration capability," in Proceedings of the SIGCHI conference on Human factors in computing systems, 1992, pp. 533–540.
[149] F. Palmas, J. Cichor, D. A. Plecher, and G. Klinker, "Acceptance and effectiveness of a virtual reality public speaking training," in 2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2019, pp. 363–371.
[150] A. Hendaoui, M. Limayem, and C. W. Thompson, "3d social virtual worlds: Research issues and challenges," IEEE Internet Computing, vol. 12, no. 1, pp. 88–92, 2008.
[151] M. Keller, S. Zuffi, M. J. Black, and S. Pujades, "Osso: Obtaining skeletal shape from outside," in Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, 2022, pp. 20 492–20 501.

[152] H. Ullah, S. Manickam, M. Obaidat, S. U. A. Laghari, and M. Uddin, "Exploring the potential of metaverse technology in healthcare: applications, challenges, and future directions," IEEE Access, 2023.
[153] C. Ponnusamy, A. Elumalai, R. K. Ayyasamy, S. Kavya, S. Dhanasekaran, and A. Kiran, "Bookchain: A secure library book storing and sharing in academic institutions using blockchain technology," 01 2023, pp. 1–5.
[154] "Engage VR." https://engagevr.io/, accessed: Oct. 28, 2023.
[155] P. Chinnasamy, D. R. Ramani, R. K. Ayyasamy, B. J. A. Jebamani, S. Dhanasekaran, and V. Praveena, "Applications of blockchain technology in modern education system – systematic review," in 2023 International Conference on Computer Communication and Informatics (ICCCI), 2023, pp. 1–4.
[156] "Microsoft Mesh Overview." https://learn.microsoft.com/en-us/mesh/overview, accessed: Oct. 28, 2023.
[157] P. Chinnasamy, C. Vinothini, S. Arun Kumar, A. Allwyn Sundarraj, S. V. Annlin Jeba, and V. Praveena, Blockchain Technology in Smart-Cities. Cham: Springer International Publishing, 2021, pp. 179–200. [Online]. Available: https://doi.org/10.1007/978-3-030-69395-4_11
[158] C. Goanta, "Selling land in decentraland: The regime of non-fungible tokens on the ethereum blockchain under the digital content directive," Disruptive technology, legal innovation, and the future of real estate, pp. 139–154, 2020.
[159] B. Guidi and A. Michienzi, "Social games and blockchain: exploring the metaverse of decentraland," in 2022 IEEE 42nd International Conference on Distributed Computing Systems Workshops (ICDCSW). IEEE, 2022, pp. 199–204.
[160] "Vault Hill - White Paper." https://vhc-website-files.s3.eu-west-2.amazonaws.com/VHWhitePaper.pdf, accessed: Oct. 29, 2023.
[161] "Kevin Rose's NFT Wallet With 40 High-Value Collectibles Hacked." https://www.coindesk.com/web3/2023/01/25/kevin-rose-says-nft-wallet-with-dozens-of-high-value-collectibles-hacked/, accessed: Oct. 30, 2023.
[162] "The Sandbox Game - White Paper." https://installers.sandbox.game/The_Sandbox_Whitepaper_2020.pdf, accessed: July. 17, 2024.
[163] R. Cheng, N. Wu, M. Varvello, S. Chen, and B. Han, "Are we ready for metaverse? a measurement study of social virtual reality platforms," in Proceedings of the 22nd ACM Internet Measurement Conference, 2022, pp. 504–518.
[164] A. Havele, N. Polys, W. Benman, and D. Brutzman, "The keys to an open, interoperable metaverse," in Proceedings of the 27th International Conference on 3D Web Technology, 2022, pp. 1–7.
[165] A. Park, M. Wilson, K. Robson, D. Demetis, and J. Kietzmann, "Interoperability: Our exciting and terrifying web3 future," Business Horizons, vol. 66, no. 4, pp. 529–541, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0007681322001318
[166] H. J. Lee and H. H. Gu, "Empirical research on the metaverse user experience of digital natives," Sustainability, vol. 14, no. 22, p. 14747, 2022.
[167] R. Cheng, N. Wu, M. Varvello, S. Chen, and B. Han, "Are we ready for metaverse? a measurement study of social virtual reality platforms," in Proceedings of the 22nd ACM internet measurement conference, 2022, pp. 504–518.
[168] K. Nabben, "Building the metaverse:'crypto states' and corporates compete, down to the hardware," Down to the Hardware (November 30, 2021), 2021.
[169] E. Karaarslan and S. Yazici Yilmaz, "Metaverse and decentralization," in Metaverse: Technologies, Opportunities and Threats. Springer, 2023, pp. 31–44.
[170] F. Zhou, L. Feng, P. Yu, W. Li, X. Que, and L. Meng, "Drl-based low-latency content delivery for 6g massive vehicular iot," IEEE Internet of Things Journal, vol. 9, no. 16, pp. 14 551–14 562, 2021.
[171] V. Ziegler, H. Viswanathan, H. Flinck, M. Hoffmann, V. Räisänen, and K. Hätönen, "6g architecture to connect the worlds," IEEE Access, vol. 8, pp. 173 508–173 520, 2020.
[172] S.-M. Park and Y.-G. Kim, "A metaverse: Taxonomy, components, applications, and open challenges," IEEE access, vol. 10, pp. 4209–4251, 2022.
[173] L. Qi, S. Dou, Z. Guo, C. Li, Y. Li, and T. Zhu, "Low control latency sd-wans for metaverse," in 2022 IEEE 42nd International Conference on Distributed Computing Systems Workshops (ICDCSW). IEEE, 2022, pp. 266–271.
[174] T. Anees, Q. Habib, A. S. Al-Shamayleh, W. Khalil, M. A. Obaidat, and A. Akhunzada, "The integration of wot and edge computing: Issues and challenges," Sustainability, vol. 15, no. 7, p. 5983, 2023.
[175] G. Fang, Y. Sun, M. Almutiq, W. Zhou, Y. Zhao, and Y. Ren, "Distributed medical data storage mechanism based on proof of retrievability and vector commitment for metaverse services," IEEE Journal of Biomedical and Health Informatics, 2023.
[176] S. Muralidharan and H. Ko, "An interplanetary file system (ipfs) based iot framework," in 2019 IEEE international conference on consumer electronics (ICCE). IEEE, 2019, pp. 1–2.
[177] "Latest DDoS News." https://portswigger.net/daily-swig/ddos, accessed: Oct. 30, 2023.
[178] S. T. Patel and N. H. Mistry, "A review: Sybil attack detection techniques in wsn," in 2017 4th International conference on electronics and communication systems (ICECS). IEEE, 2017, pp. 184–188.
[179] F. A. Aponte-Novoa, A. L. S. Orozco, R. Villanueva-Polanco, and P. Wightman, "The 51% attack on blockchains: A mining behavior study," IEEE access, vol. 9, pp. 140 549–140 564, 2021.
[180] Z. R. Mohima, S. Z. Bin Bashar, R. Muktadir, A. Hossain, and S. Mahmud, "Exploring attacks in the nft gaming industry: A study of risks and mitigation strategies," Ph.D. dissertation, Brac University, 2023.
[181] Z. Ouyang, J. Shao, and Y. Zeng, "Pow and pos and related applications," in 2021 International Conference on Electronic Information Engineering and Computer Science (EIECS), 2021, pp. 59–62.
[182] J. Yang, Z. Jia, R. Su, X. Wu, and J. Qin, "Improved fault-tolerant consensus based on the pbft algorithm," Ieee Access, vol. 10, pp. 30 274–30 283, 2022.
[183] A. H. Chow, R. Sha, and Y. Li, "Adaptive control strategies for urban network traffic via a decentralized approach with user-optimal routing," IEEE Transactions on Intelligent Transportation Systems, vol. 21, no. 4, pp. 1697–1704, 2019.
[184] P. Praitheeshan, L. Pan, J. Yu, J. Liu, and R. Doss, "Security analysis methods on ethereum smart contract vulnerabilities: a survey," arXiv preprint arXiv:1908.08605, 2019.
[185] H. Nowandish, A. Norta, and P. Normak, "Blockchain oracles for asset ownership verification and trust establishment in the metaverse," in International Congress on Blockchain and Applications. Springer, 2023, pp. 509–514.
[186] T. E. Gasiba, U. Lechner, M. Pinto-Albuquerque, and D. M. Fernandez, "Awareness of secure coding guidelines in the industry-a first data analysis," in 2020 IEEE 19th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom). IEEE, 2020, pp. 345–352.
[187] B. Friedberg and J. Donovan, "On the internet, nobody knows you're a bot: Pseudoanonymous influence operations and networked social movements," 2019.
[188] R. Belk, M. Humayun, and M. Brouard, "Money, possessions, and ownership in the metaverse: Nfts, cryptocurrencies, web3 and wild markets," Journal of Business Research, vol. 153, pp. 198–205, 2022.
[189] Y. Zhang, Y. Yin, X. Liu, Q. Zhang, and H. Jia, "Zero-knowledge proofs for improved lattice-based group signature scheme with verifier-local revocation," in International Conference on Frontiers in Cyber Security. Springer, 2019, pp. 107–127.
[190] Y. Zhao and J. Chen, "A survey on differential privacy for unstructured data content," ACM Computing Surveys (CSUR), vol. 54, no. 10s, pp. 1–28, 2022.
[191] E. Moriuchi, "Leveraging the science to understand factors influencing the use of ai-powered avatar in healthcare services," Journal of Technology in Behavioral Science, vol. 7, no. 4, pp. 588–602, 2022.
[192] B. Tang, "dao 2: Overcoming overall storage overflow in intermittently connected sensor networks," in IEEE INFOCOM 2018-IEEE Conference on Computer Communications. IEEE, 2018, pp. 135–143.
[193] M. Steffen, D. P. DiVincenzo, J. M. Chow, T. N. Theis, and M. B. Ketchen, "Quantum computing: An ibm perspective," IBM Journal of Research and Development, vol. 55, no. 5, pp. 13–1, 2011.
[194] M. Dyakonov, "When will useful quantum computers be constructed? not in the foreseeable future, this physicist argues. here's why: The case against: Quantum computing," Ieee Spectrum, vol. 56, no. 3, pp. 24–29, 2019.

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