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Research Article

MetaverseBench: Instantiating and benchmarking metaverse challenges

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ABSTRACT

The rapid evolution of the metaverse has led to the emergence of numerous metaverse technologies and productions. From a computer systems perspective, the metaverse system is a complex, large-scale system that integrates various state-of-the-art technologies, including AI, blockchain, big data, and AR/VR. It also includes multiple platforms, such as IoTs, edges, data centers, and diverse devices, including CPUs, GPUs, NPUs, and 3D glasses. Integrating these technologies and components to build a holistic system poses a significant challenge for system designers. The first step towards building the metaverse is to instantiate and evaluate the challenges and provide a comprehensive benchmark suite. However, to the best of our knowledge, no existing benchmark defines the metaverse challenges and evaluates state-of-the-art solutions from a holistic perspective. In this paper, we instantiate metaverse challenges from a system perspective and propose MetaverseBench, a holistic and comprehensive metaverse benchmark suite. Our preliminary experiments indicate that the existing system performance needs to catch up to the requirements of the metaverse by two orders of magnitude on average.

1. Introduction

In recent years, there has been increasing commercial interest in the metaverse. While the metaverse is still a developing concept, the term was first coined in Neal Stephenson's novel "Snow Crash" [1] published in 1992, referring to a shared virtual reality inhabited by millions of users with its economy, laws, and social interactions. For a long time, the metaverse was seen more as science fiction than something achievable until recently.

On the one hand, technologies enabling the metaverse have made considerable progress, including but not limited to artificial intelligence, blockchain, and extended reality. Specifically, artificial intelligence, especially deep learning and reinforcement learning, which have advanced significantly since the 2010s, has been crucial for developing the metaverse and is expected to be fundamental for realizing it. With the rise of blockchain technology, decentralization has become a vital feature of the metaverse. Improvements in devices and wearable technologies have also spurred growing interest in virtual and augmented reality among the general public. On the other hand, since 2020 and the global COVID-19 pandemic, online industries like online education have grown explosively. Analysts estimated the global online education market size at $210.1 billion in 2021 and predicted it would reach $848.12 billion by 2030 [2]. Online offices, gaming, and other industries have also seen similar growth. The rapid growth of these industries not only drives the development of relevant technologies but also promotes the evolution of the metaverse.

The metaverse is a complex interdisciplinary concept encompassing extensive technological domains and presenting challenges surpassing the capabilities of existing computing, storage, network, and other infrastructure. For example, Raja Koduri [3] has pointed out that providing real-time access to immersive computing for billions of people would require an increase in computing power of at least one thousand times from the current state-of-the-art, with real-time response latency of fewer than ten milliseconds. Therefore, the first step in designing a system that can meet the metaverse requires building a quantitative benchmark for metaverse systems.

However, existing benchmarks typically focus on specific technological domains. For example, MLPerf [4] and AIBench [5] aim to benchmark deep learning systems, while BigDataBench [6] aims to benchmark big data systems. The interdisciplinary nature of the metaverse means that existing benchmarks can only cover certain aspects of its related technological domains. Furthermore, the entanglement of various technologies significantly complicates the metaverse system. Therefore, Zhan [7] claimed that it is critical to propose a benchmark suite that quantitatively defines the challenges of the metaverse system and explores and evaluates state-of-the-art and state-of-practice solutions. Such a benchmark suite is necessary to systematically assess the metaverse system and address how far different technologies are from realizing the metaverse within the current computing, storage, and network capabilities.

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In this study, firstly, we summarize various definitions and concepts of metaverse by investigating existing literature, and we propose a comprehensive and sophisticated conceptual system of the metaverse from the perspective of computer systems. Secondly, we present a methodology based on the aforementioned conceptual system for benchmarking the metaverse system. Finally, we introduce an implementation of a benchmark suite based on this methodology, named MetaverseBench. Our contributions are as follows.

(1) We propose the metaverse conceptual system from the computer systems perspective, including three key aspects: components, technological domains, and specifications. The fundamental components include the access system, avatar, environment, and activity. We have summarized nine relevant technological domains: artificial intelligence, big data, extended reality, blockchain, cloud computing, edge computing, and networking. Furthermore, we distill five specifications to which the metaverse should adhere: automatic computing, immersive experience, decentralized architecture, ubiquitous access, and hyperspace interaction.

(2) We propose a benchmarking methodology for the metaverse system, which combines our conceptual system with the scenario-based approach proposed in [8]. Considering the complexity of the metaverse system, firstly, we build a typical metaverse application scenario and analyze its workflow, extracting critical paths, modules, and algorithms. Next, we select representative workloads based on nine technological domains to determine candidate workloads. Finally, we combine the results from the previous two steps to acquire the final workloads representing the designated scenario.

(3) We propose MetaverseBench, a benchmark suite for evaluating metaverse systems that conform to our conceptual system. Now, MetaverseBench comprises eight workloads corresponding to four components and nine domains. We also conduct experiments using MetaverseBench on a state-of-the-practice platform. The experimental results suggest that the existing platform requires an average of two orders of magnitude of performance improvements to support the metaverse.

This study is structured as follows: Section 2 reviews representative definitions of the metaverse. Section 3 introduces the metaverse conceptual system. Section 4 presents the methodology for benchmarking metaverse systems. MetaverseBench is presented in Section 5. Preliminary experiments under MetaverseBench are discussed in Section 6. Section 7 concludes related work, while Section 8 outlines the conclusions and plans for further research.

2. The metaverse definitions

A forward-looking research project that cannot be ignored, and the earliest systematic research project about the metaverse, is the "Metaverse Roadmap (MVR)" initiated by the Acceleration Studies Foundation (ASF) around 2006. In 2007, ASF published "Metaverse Roadmap: Pathways to the 3D Web", which provides a comprehensive overview of the potential of the metaverse and the pathways that may lead to its realization to report their research. In this study, we dig into ASF's report as a beginning. To explore and summarize up-to-date definitions and concepts of the metaverse, we investigate extensive literature, especially those published in recent years.

The definition of metaverse originates from a single 3D virtual world, gradually deriving into multiple interconnected virtual worlds and the fusion of reality and virtuality. In the ASF's report, John et al. [9] adopted the definition of the metaverse as "the convergence of virtually enhanced physical reality and physically persistent virtual space". Dionisio et al. [10] viewed the metaverse as "an integrated network of 3D virtual worlds". Lee et al. [11] considered the metaverse "a virtual environment blending physical and digital spaces". Ning et al. [12] defined the metaverse as "a new type of Internet application and social form that integrates a variety of new technologies" existing as a hyperspatiotemporal virtual world. PARK and KIM [13] summarized and compared the definitions of fifty-four papers published from 1992 to 2021 that specifically described the metaverse. Moreover, following the idea that the social value of Generation Z constructed the core of the contemporary metaverse, they proposed a new definition referring to the metaverse as "a three-dimensional virtual world where avatars engage in political, economic, social, and cultural activities". From the digital economy perspective, YANG et al. [14] viewed the metaverse as "a complete and self-consistent economic system, a complete chain of the production and consumption of digital items". Wang et al. [15] defined the metaverse as "a computer-generated world with a consistent value system and an independent economic system linked to the physical world". Dwivedi et al. [16] agreed with describing the metaverse as "the layer between you and reality". More specifically, the metaverse is viewed as "a 3D virtual shared world where all activities can be carried out with the help of augmented and virtual reality services". The summary is in Table 1.

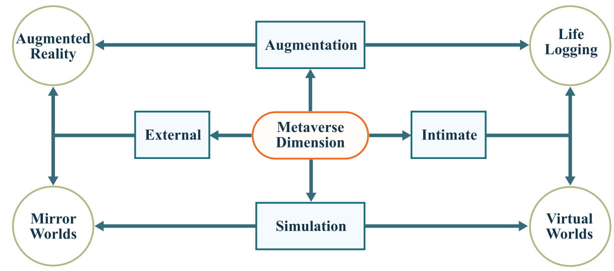

Fig. 1. Metaverse dimensions and categories.

Reviewing the definitions described above, we find that the metaverse involves virtuality and relies heavily on reality, constructing a bridge between the virtual and physical worlds. From this point of view, the version adopted by ASF [9] (i.e., "the convergence of virtually enhanced physical reality and physically persistent virtual space") elaborates the metaverse concisely and precisely. In the rest of this article, we use this definition.

3. Metaverse systems: Components, domains, and specifications

Researchers who engage in the metaverse debates are interested in identifying the essential concepts necessary for its construction. We propose a conceptual system encompassing three aspects: the components that make up the metaverse, the technological domains that enable the realization of the metaverse, and the specifications to which the metaverse should adhere. Despite numerous proposals for metaverse concepts in recent years, a comprehensive conceptual system that covers all three aspects has yet to be put forward. In this section, we will review the state-of-the-art concepts of the metaverse and present our conceptual system for the metaverse.

3.1. State-of-the-art concepts of metaverse

The ASF's report [9] published in 2007 is the first effort to provide a systematic viewpoint for analyzing the metaverse. As shown in Fig. 1, according to different dimensions determining how the metaverse evolves, John et al. [9] categorized the metaverse into the following four scenarios: "virtual worlds, mirror worlds, augmented reality, and lifelogging".

Dionisio et al. [10] argued that realism, ubiquity, interoperability, and scalability were decisive areas enabling the metaverse. Among the four areas, realism allows users to feel fully immersed; ubiquity facilitates users to access via various devices and maintains the identities of users; interoperability enables interaction across multiple virtual worlds; and scalability allows the metaverse to accommodate a massive number of users. Lee et al. [11] proposed a metaverse

Table 1
Representative metaverse definitions.

Definition	Year	Refs.
"The convergence of virtually enhanced physical reality and physically persistent virtual space."	2007	[9]
"An integrated network of 3D virtual worlds."	2013	[10]
"A virtual environment with duality blending physical and digital spaces."	2021	[11]
"A new type of Internet application and social form exists as a hyper spatiotemporal virtual world."	2021	[12]
"A three-dimensional virtual world where avatars engage in political, economic, social, and cultural activities."	2022	[13]
"A complete and self-consistent economic system, a complete chain of the production and consumption ofdigital items."	2022	[14]
"A computer-generated world with a consistent value system and an independent economic system linked tothe physical world."	2022	[15]
"A 3D virtual shared world where all activities can be carried out with the help of augmented and virtualreality services."	2022	[16]

Table 2
Key concepts of the metaverse.

Concept	Corresponding to the concept system	Refs.
Virtual world, mirror world, augmented reality, lifelogging. Avatar, environment.	N/A Component	[9]
Realism, ubiquity, interoperability, scalability.	Specification	[10]
Avatar, content creation, virtual economy. Social acceptability, security, privacy, trust, and accountability.	Component N/A	[11]
Multi-technology, sociality, hyper spatiotemporality.	Specification	[12]
Hardware, software, content.	Component	[13]
Economy, digital creation, digital asset, digital market, digital currency.	Component	[14]
Digital avatar, virtual environment, virtual goods/services. Immersiveness, hyper spatiotemporality, sustainability, interoperability, scalability,heterogeneity.	Component Specification	[15]
Immersive, boundless, connected.	Specification	[16]

ecosystem composed of "six user-centric factors: avatar, content creation, virtual economy, social acceptability, security, and privacy, and trust and accountability" to enable a self-sustaining, persistent, and shared realm. While an avatar is a vital element representing physical users, content creation and virtual economy are, respectively, activities and derivatives. Moreover, social acceptability, security, privacy, trust, and accountability correspond to social norms and regulations in the physical world. According to Ning et al. [12], the metaverse was characterized by multi-technology (as an internet application), sociality (as a social form), and hyper spatiotemporality (as a virtual world). PARK and KIM [13] also considered avatars as one of the core concepts of the metaverse. In addition, they divided the metaverse into hardware, software, and contents from the component perspective. Hardware refers to physical devices and sensors, software refers to recognition and rendering, and contents refer to scenarios and stories. YANG et al. [14] paid the most attention to the economy, claiming it to be the fundamental component of the metaverse. Furthermore, they stated that digital creation, digital assets, digital markets, and digital currency were the four components of the metaverse economy system. Wang et al. [15] proposed an architecture of metaverse integrating the human, physical, and digital worlds, in which digital avatars, virtual environments, and virtual goods/services supported the interconnected virtual worlds. They further refined six critical characteristics of the metaverse: immersiveness, hyper spatiotemporality, sustainability, interoperability, scalability, and heterogeneity. Dwivedi et al. [16] conceptualized metaverse building on contributions from twenty individual researchers. According to the conceptualization, the metaverse holds immersive, boundless, and connected features. Additionally, they aligned with the categories of metaverse scenarios presented in the ASF's report [9].

Based on the above discussions, we have summarized the keywords of state-of-the-art concepts in Table 2, categorized according to components, domains, and specifications. Despite the numerous studies on metaverse concepts, it is clear that a comprehensive and sophisticated conceptual system still needs to be improved.

3.2. Metaverse conceptual systems

We propose a comprehensive and sophisticated conceptual system of the metaverse, covering the three aspects of system components, technological domains, and specifications. Components are the essential elements of the conceptual system; the technological domains are the implemented technological, and specifications are the implemented standards. There is no real metaverse conceptual system, and the science fiction movie "Ready Player One" [17] explores the concept of a metaverse system, as the film takes place in a highly advanced virtual space called the "OASIS". So, in this section, we take OASIS as an example to elaborate on the conceptual system.

3.2.1. Components

According to the metaverse concepts and considering the aspect of system components, we divide a metaverse system into four critical components: access systems, avatars, environments, and activities (see Fig. 2).

Access Systems. An access system serves as a bridge between real users and the objective environment of the metaverse. While similar in functionality to the user login system of a game scenario, the metaverse access system is far more complicated in terms of access approaches and user experience. The access system of OASIS plays a crucial role in allowing users to enter and interact within the virtual world determining who can access the OASIS, how they can access it, and what permissions and privileges they have within the virtual environment. In its initial stage, the access system is expected to include two subsystems: core access and auxiliary access, each composed of corresponding hardware and software parts. Specifically, the core access subsystem is derived from wearable devices, with VR/AR/MR glasses serving as its most essential component, providing visual perception in the metaverse; the auxiliary access subsystem is necessary to meet the vast computing power need of the metaverse, with various end devices such as smartphones, tablets, laptops, and desktops providing auxiliary storage and computation capabilities, turning out to maximizes user convenience.

Avatars. An avatar is a digital representation of a real user in the metaverse, carrying their character role and identity. While the term avatar gained popularity after the movie "Avatar" was released, it has been widely used in account-based platforms for a long time. In recent years, various companies, led by Apple, have introduced capabilities for building avatars that are much more sophisticated, vivid,

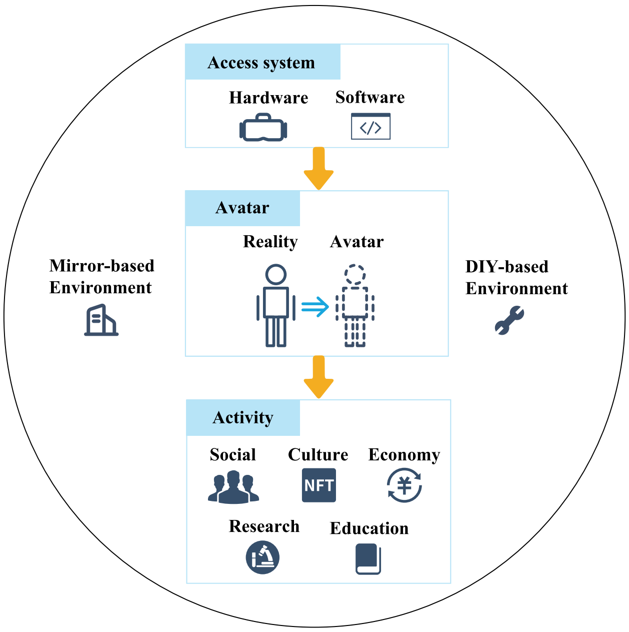

Fig. 2. Metaverse components.

and immersive than those created before. The concept of avatars in OASIS demonstrates their powerful role in enhancing user experiences within a metaverse. Avatars in the OASIS offer users a means of self-expression, enabling them to take on virtual personas and participate in diverse activities within the virtual reality universe. Considering the implementation approaches, theoretically, an avatar can mirror a real user, generally called a digital twin, or be a virtual character based on creation, called a digital native. Avatars in the metaverse should support digital twins and digital natives to satisfy different requirements from various application scenarios. In scenarios requiring accurate identity recognition, digital twins are suitable. In contrast, in entertainment scenarios like virtual games, digital natives and the fusion of digital twins and natives suggest broader application prospects.

Environments. Similar to the physical environment in the real world, the metaverse also requires a corresponding setting to carry out all the activities of the avatars. The metaverse environment is a 3D digital space designed to look and feel like a real-world environment. For example, OASIS is depicted as an expansive, interconnected virtual world featuring countless planets, zones, and domains. Each area within OASIS offers unique themes, landscapes, and challenges for users to explore. Considering the implementation approaches, the metaverse environment can mirror the real-world environment or be a completely DIY (Do-It-Yourslef) virtual environment. Similar to the implementation of avatars, the fusion of mirror-based and DIY-based approaches is also reasonable. And the need for these different types of metaverse environments is also to satisfy various application scenarios. Specifically, a DIY-based process is essential for building sufficiently immersive environments in gaming, learning, and work scenarios. In contrast, a mirror-based climate allows users to achieve almost the same experience as in the real world in systems such as sightseeing.

Activities. Just like humans conduct different kinds of activities in the real world, in the metaverse, interactions between other avatars and between avatars and the environment yield activities too. Activities within OASIS (the metaverse) are central to the plot and serve as the primary focus of the movie's narrative. These diverse and engaging activities reflect the vast possibilities that a fully realized metaverse system can offer. This study classifies the metaverse activities into four categories: sociality, economy, culture and entertainment, and education and research. Social activities are the most basic everyday activities in the metaverse, eliminating spatial constraints and language barriers. Economic activities involve concepts such as digital currency, digital assets, and digital market [15], with high reliance on decentralization and interoperability. Typical cultural and entertaining activities include literary and artistic creation, cultural tourism, and playing electronic games. For education and research, the metaverse provides platforms enabling immersive learning and teaching and interoperable experimental environments by applying extended reality and various sensors.

3.2.2. Domains

From the perspective of technological domains, we summarize the following nine elements as fundamental infrastructure that enable the realization of the metaverse and discuss several examples of how each element is applied in different components of the metaverse.

Artificial Intelligence. Relevant technologies based on deep neural networks have experienced tremendous progress in the last decade to become powerful driving forces for the development of the metaverse. For access systems, AI-based biometric identification technology can be applied to verify the identity of users as they attempt to log into the metaverse. For avatars in the metaverse, AI-based personalization algorithms can be used to create avatars that are more personalized to the individual user based on factors such as their preferences, interests, and behavior within the metaverse. This can make interactions with avatars more engaging and meaningful. For the metaverse environment, AI-based generation and reconstruction techniques can automatically create and populate vast and diverse backgrounds within the metaverse. For activities in the metaverse, AI-based natural language processing technology can enable users to interact with others and the metaverse environment, which helps create a more intuitive and user-friendly experience. It would allow users to quickly and easily access the necessary functions and features.

Big Data. The realization of the metaverse poses daunting challenges for the storage, transmission, and processing of big data, due to which big data is a necessary element. For access systems, big data can be used to monitor and analyze user access patterns and identify potential security threats, such as unauthorized access attempts or suspicious behavior. This can help to identify and prevent security breaches and enable the implementation of more effective access control mechanisms. For avatars in the metaverse, by collecting and analyzing data on user preferences, behaviors, and interests within the metaverse, it is possible to build detailed user profiles that can be used to personalize the avatar experience. This can include avatar appearance, behavior, interaction style, and the content and activities presented to the user. For environment and activities in the metaverse, it is possible to gain insights into how users interact with the environment and what features and activities are most popular by analyzing large datasets on user behavior and preferences. This can inform the development of new social features and activities and enable the creation of more engaging and interactive user experiences.

Data Security And Privacy. Data security and privacy are critical considerations in the metaverse, as users interact and engage within virtual environments that collect and process vast amounts of personal and sensitive information. For the metaverse access systems, robust access control mechanisms need to be implemented to restrict data access to authorized personnel only, and role-based access controls should be utilized to ensure that individuals can only access the data necessary for their specific roles. Data encryption must be adopted for other metaverse components to protect data during transmission and storage. Moreover, by utilizing anonymization and pseudonymization, we can minimize the use of personally identifiable information whenever possible, further protecting user identities and reducing the risk of data breaches.

Extended Reality. Extended reality refers to a family of technologies, including augmented reality (AR), virtual reality (VR), and mixed reality (MR). These relevant technologies generally function as wearable devices. However, it limits human perception mainly to vision and hearing. The metaverse will gradually expand users' perception boundaries and bring more interactive possibilities. For the access system and environment of the metaverse system, users can access the metaverse and interact with the metaverse environment more intuitively and naturally without the need for traditional input devices such as keyboards or controllers. Furthermore, users can immerse themselves in the metaverse as if they were physically present in that environment. For avatars users can design and try on virtual clothing and accessories for their avatars, allowing for greater personalization and self-expression. For activities in the metaverse, extended reality can be applied to various activities within the metaverse, enhancing the user experience and making it more immersive, intuitive, and engaging. For example, users can access immersive educational or training content, allowing for more effective learning and skill development in a safe and controlled environment.

Brain–Computer Interface. While extended reality relies on additional external devices to function, the brain–computer interface (BCI) allows users to interact with the metaverse through neural signals. BCI can be applied in the metaverse in various ways, enhancing the user experience and interaction within the virtual world. BCI provides an alternative access method for the metaverse access systems that is more convenient and direct than the XR-based method. For avatars, BCI enables users to control their avatars within the metaverse using their neural signals directly. Instead of relying on traditional input devices like keyboards or controllers or XR-based devices, users can move, interact, and perform actions within the virtual world using their thoughts or intentions. For environment and activities in the metaverse, BCI can provide a more immersive and natural way of interacting with the metaverse environment. Users can perform actions in the metaverse, such as picking up objects or navigating through the virtual space, by simply thinking about those actions, creating a more intuitive and embodied experience.

Blockchain. Blockchain is expected to be used to establish the decentralized network in the metaverse. For access system by leveraging blockchain's ability to create a decentralized and secure identity system, users can have greater control over their digital identity and access to the metaverse environment without relying on a central authority or platform. For avatars, blockchain can be applied to manage the ownership and control of avatars, enabling users to have complete control over their avatars. For the metaverse environment, creating decentralized marketplaces with blockchain is possible. This can allow users to trade virtual assets directly with each other without the need for intermediaries or third-party platforms. For activities in the metaverse, blockchain can be applied to create non-fungible tokens (NFTs), representing unique and valuable digital assets such as virtual real estate, digital art, and collectibles. NFTs can be traded on blockchain-based marketplaces, providing users with a new way to engage in economic activities in the metaverse.

Cloud Computing. Cloud computing provides on-demand availability of computer system resources, especially data storage and computing power, without direct active management by users themselves. Scalable application scenarios and massive amounts of data in the metaverse require extremely huge computing and storage capacities, making cloud computing necessary. As fundamental infrastructure, cloud computing can be applied to the metaverse in specific ways. Firstly, cloud computing provides the scalability needed to accommodate the increasing number of users and their interactions within the metaverse, allowing for seamless user experiences even during peak usage times. Secondly, cloud-based data processing services can process and analyze large volumes of data generated within the metaverse, including user interactions, social behaviors, and market trends. Lastly, cloud-based content distribution services can distribute content, including 3D models, textures, and other digital assets, to users within the metaverse, improving the user experience and reducing latency.

Edge Computing. Edge computing is a distributed computing paradigm that brings computation and data storage closer to the data sources. This is expected to improve response latency and save bandwidth. Since the metaverse poses daunting challenges to computing and response delays, entirely using edge and end devices to provide auxiliary storage and computing capabilities is a promising solution. To be specific, on the one hand, edge computing can reduce the latency in the metaverse by placing computing resources closer to the end-user, thus reducing the round-trip time between the user's device and the central server. This can lead to a more responsive experience in the metaverse. On the other hand, edge computing can reduce the bandwidth requirements for the metaverse by processing data locally at the edge instead of sending it back to the central server. This can lead to cost savings for both end-users and service providers.

Network. Networks play a crucial role in enabling connection and communication within the metaverse. First, the metaverse relies on high-speed connectivity to help seamless communication and interaction between users. Therefore, networks must be designed to support high-bandwidth applications and low-latency connections. Moreover, the metaverse is expected to accommodate a large number of users, and as such, networks must be designed to be highly scalable to handle high traffic and data volumes. Last, deploying wireless networks is significant to enable users to access the metaverse anytime and anywhere.

3.2.3. Specifications

Although the exact specifications to which the metaverse should conform may evolve, we must summarize existing key elements that would be valuable for designing and evaluating metaverse systems. In this study, the following five aspects are considered.

Autonomic Computing. The metaverse is a persistent virtual world that remains available and accessible to users at all times, even when they are not logged in. In other words, the metaverse should be a self-running system parallel to the real world.

Immersive Experience. The metaverse offers a high level of immersion, allowing users to feel fully present in the digital space through the use of advanced graphics, haptic feedback, and other sensory experiences. Immersive experiences heavily rely on wearable devices such as AR/VR glasses, but the metaverse should expand its boundaries to include touch, smell, taste, and other perception approaches.

Decentralized Architecture. The metaverse is designed to operate distributed and decentralized without being controlled by any single entity or organization. In a decentralized metaverse, no single company or organization has complete control over the platform, the digital assets, or the user data.

Ubiquitous Access. The metaverse is designed to be accessible and available to users from anywhere, at any time, and through any device. In a ubiquitous metaverse, users can seamlessly transition between the physical and virtual worlds and between devices such as smartphones, computers, and VR headsets.

Hyperspace Interaction. The metaverse enables seamless communication and interaction between applications, platforms, and digital spaces, even between the metaverse and the physical world. In an interoperable metaverse, users can transfer and use digital assets, identities, and experiences across different environments and contexts. In a hyperspace-enabled metaverse, users can move from one virtual environment to another without noticeable lag or disruption, creating a seamless and immersive experience.

We summarize our metaverse conceptual system in Fig. 3.

4. Benchmarking the metaverse

According to Zhan [7], definition, instantiation, and measurement are three essential processes of a benchmark (see Fig. 4). In this section, we propose the problem definition of the metaverse benchmark and introduce our methodology for benchmarking the metaverse. First, we define the problem of benchmarking the metaverse as: **Quantifying design/tune challenges for the metaverse conceptual system.** Then, we introduce our metaverse benchmark methodology.

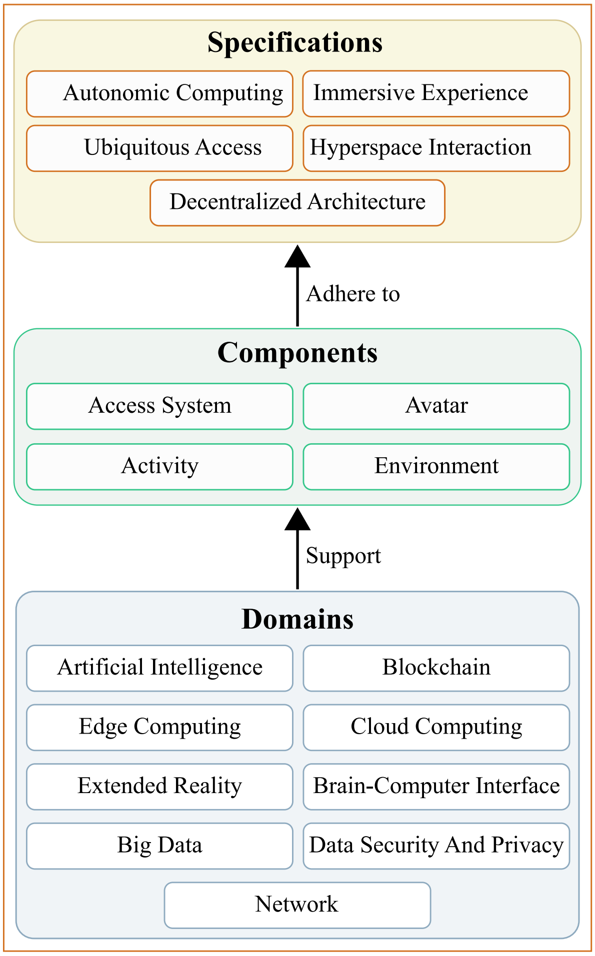

Fig. 3. Metaverse conceptual system.

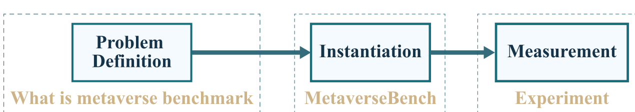

Fig. 4. Metaverse benchmark roadmap.

4.1. The metaverse benchmark methodology

We combine the metaverse conceptual system with the scenario-based approach proposed by Gao et al. [8] to build our methodology for the metaverse benchmark. As depicted in Fig. 5, firstly, we select three representative application scenarios of the metaverse. Secondly, we determine the common critical path by analyzing how each metaverse component functions in these scenarios and summarize several vital elements. Thirdly, viewing the essential elements from the perspective of underlying technologies, we determine candidate workloads by extracting representative ones corresponding to the metaverse domains. Finally, for the benchmark implementation, we further build a reduced set from the set of candidate workloads for the critical path of corresponding scenarios. Moreover, we refer to the specifications part of the metaverse concept system to determine the final workloads and related metrics.

4.2. The metaverse scenarios

Office, education, and entertainment are three primary activities in human society. The Internet era has accelerated the forms of these

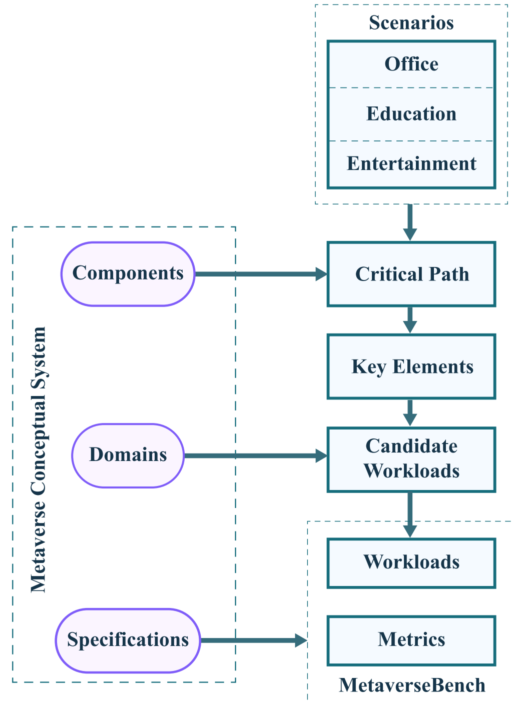

Fig. 5. Metaverse benchmark methodology.

activities to shift from offline to online. What is certain is that they will still constitute the most basic application scenarios in the metaverse.

Office. Metaverse offers a more immersive experience for online offices than traditional internet applications, allowing individuals to work remotely through extended reality while interacting with colleagues in the shared online space as avatars. Various companies have developed related products and services, such as Microsoft's virtual collaboration platform Mesh [18] and Meta's Horizon Workrooms [19]. By utilizing VR devices, Horizon Workrooms enables users to bring their desks, computers, and keyboards into the virtual world for work.

Education. Generally, the education industry involves three elements: teachers, students, and learning environments. In the metaverse education scenario, students could interact with their environment, collaborate with classmates, and engage in experiential learning activities. For example, they could explore historical landmarks, visit foreign countries, or participate in simulated experiments that might not be possible in the physical world.

Entertainment. The entertainment industry is anticipated to play a significant role in the metaverse. For instance, the movie "Ready Player One" showcases a game experience that shatters traditional geographical restrictions, facilitates instant scene switching, accommodates unlimited user capacity, and provides a low-cost immersive experience. Another example is Faye Wong's Fantastic Music concert in 2016, which utilized VR to give a three-dimensional online experience that went viral online.

4.3. The critical path and key elements

Upon examining the three primary application scenarios of office, education, and entertainment in the metaverse, we summarize the critical path of these scenarios as follows: users are granted access to the metaverse environment through the access system; following successful authority, users then operate within the metaverse environment in the form of avatars; interactions between avatars and the overall environment precipitate a range of activities encompassing various social, economic, and cultural fields. Considering how the

Table 3
Candidate workloads for MetaverseBench.

Key elements	Workloads
User authentication	Fingerprint recognition Face recognition Voice recognition
Creation and rendering of models	3D reconstruction Graphics rendering
Technologies facilitating interactions	Semantic segmentation Image classification Object detection Image generation Text classification Question answering Machine translation Speech recognition
Decentralized networks	Proof of Work Proof Of Stake Proof of Space
Big data processing	Read, write Sort, grep Data caching Media streaming

metaverse components function in the critical path, we can get the key elements of each component. The part that most affects the user experience in the access system is **user authentication**. For avatars and environments, sophisticated models enable users to feel immersive, so we focus on the **creation and rendering of models**. Activities are the results of interactions between different avatars and between avatars with environments. We focus on not only **technologies that can help facilitate those interactions** but also the **performance of decentralized networks** based on blockchain to ensure a consistent experience. Moreover, as the essential part, **the capabilities for storage, computing, and transmission of big data** are also considered.

5. MetaverseBench

We present MetaverseBench as our solution instantiation for the metaverse benchmark. For most benchmark suites, workloads, datasets, and metrics are the three fundamental elements that apply to MetaverseBench. Moreover, selecting datasets and metrics depends on specific workloads; the paramount step is determining the workloads.

We adopt a three-step process to determine the workloads. Firstly, we follow the critical path and key elements of general scenarios. We select representative workloads from the nine technological domains described in the conceptual system to form a set of candidate workloads. Secondly, we conduct an in-depth analysis of general scenarios and build the mapping from specific workloads to them by reviewing the workflow of metaverse components. Finally, we extract and refine workloads that cover the critical path and the components from candidates to reflect general metaverse scenarios as realistically as possible.

5.1. Candidate workloads

We utilize the critical elements concluded in Section 4.3 and refer to the metaverse technological domains to obtain the candidate workloads. In particular, we refer to typical benchmarks in these domains for selection. Table 3 lists our candidate workloads according to the essential elements.

Various methods have been applied for user authentication, such as username/password authentication, token-based authentication, and multi-factor authentication. Biometric authentication is being adopted widely since it offers a more secure, convenient, and reliable experience than traditional methods. We take different types of biometric identification, such as fingerprint recognition, face recognition, and voice recognition, as part of our candidate workloads. Creation and rendering of models comprise various processes within which 3D modeling using specialized software like Blender [20], real-time streaming for loading models, and real-time rendering with GPUs are fundamental. We respectively include 3D reconstruction, media streaming, and rendering performance across multiple graphics APIs (OpenGL, Vulkan, DirectX, etc.) into the candidate workloads. As for technologies facilitating interactions, we focus on underlying AI-based algorithms. Specifically, we select representative algorithms in computer vision: semantic segmentation, image classification, object detection, and image generation, and in natural language processing, text classification, question answering, machine translation, and speech recognition as candidate workloads. Decentralized networks based on blockchain involve various aspects such as consensus protocols, smart contracts, governance mechanisms, security management, etc. Mainly, consensus algorithms are what we are concerned about the most. Therefore, relevant tasks like "Proof of Work" (PoW) and "Proof of Stake" (PoS) are included in our candidate workloads. Moreover, we include representative workloads: read, write, sort, grep, and data caching, for evaluating capabilities of storage, computing, and transmission provided by the overall hardware and software infrastructure for handling big data.

5.2. Scenarios mapping and selected workloads

Corresponding to three scenarios (Office, Education, and Entertainment), we abstract the minimum set of workloads from candidate workloads. We consider mapping from the workloads to general metaverse scenarios. By building the mapping, we can ensure that our benchmark suite accurately reflects real-world scenarios and the performance requirements of the metaverse. We follow the critical path across different components to construct the mapping. Firstly, we choose the face recognition workload to inspect user authentication. According to a report from Frost&Sullivan [21], face recognition held over twenty percent of the global biometrics market in 2021. Therefore, face recognition suits three scenarios and is a representative workload for the access systems of the metaverse. Secondly, we choose the 3D reconstruction workload to inspect the creation and rendering of models. As mentioned in Section 3.2, the creation of avatars and environments in the metaverse both support the mirror-based approach, which heavily relies on the application of 3D reconstruction. Moreover, model creation consumes considerable resources in the components of avatars and environments. It is representative to choose 3D reconstruction to represent the model creation of avatars and environments. Thirdly, we use machine translation and speech recognition workloads to represent technologies facilitating interactions in the metaverse. The two technologies are state-of-the-art interaction technologies and can be utilized to break boundaries among users of different native languages and cultural backgrounds to maximize user experience. Fourthly, we use the Proof of Work (PoW) workload to represent decentralized networks. The choice of consensus algorithm depends on the goals of the blockchain network. The blockchain space has evolved to include various consensus algorithms that address different scalability, efficiency, and security considerations. Since PoW is historically significant due to its role in Bitcoin's creation [22], we include it to check the performance of decentralized networks. Lastly, we include sort, grep, and media streaming workloads for big data processing. The sort workload is indispensable in data organization, promoting searching efficiency, ensuring aggregation and analysis, and helping data deduplication. The grep workload is crucial for quick data retrieval, filtering, extraction, and cleansing. Both operations are essential for efficiently managing and processing big data. For media streaming workload, on the one hand, users need to utilize it to access the metaverse environment. On the other hand, users can conduct various activities like online meetings, attending classes, and watching videos in scenarios like office, education, and entertainment by media streaming.

Table 4
Workloads of MetaverseBench.

No.	Workloads	Key elements	Components	Metrics
1	Face recognition	User authentication	Access system	Accuracy; latency
2	3D reconstruction	Creation and rendering of models	Avatar; environment	IoU; latency
3	Machine translation	Technologies facilitating interactions	Activity	BLEU
4	Speech recognition	Technologies facilitating interactions	Activity	WER; F1-score
5	Proof of work	Decentralized net	Access system	Block confirmation time
6	Sort			
7	Grep	Big data processing	Environment; activity	Throughput
8	Media streaming			

We summarize the final selected eight workloads of MetaverseBench as shown in Table 4. We inspect different evaluation metrics for various workloads. For face recognition, we care about recognition accuracy and latency. The latency is necessary for Real-Time applications and user experience, and the recognition accuracy is essential for reliable identification. We also need to strike a balance between recognition accuracy and latency. For 3D reconstruction, except for latency, we check the intersection of union (IoU) for evaluating model quality. The latency is a critical performance metric for 3D reconstruction algorithms, especially when considering real-time or time-sensitive applications. The IoU is a widely used metric for measuring the accuracy of 3D reconstruction results, particularly in the context of comparing the reconstructed 3D model to a ground truth or reference model. For machine translation, bilingual evaluation understudy (BLEU) is adopted. The BLEU metric is an essential metric for evaluating the quality of machine translation systems. It is widely used in natural language processing and machine translation. We use word error rate (WER) and F1-score for speech recognition. Using WER and F1-score together allows a comprehensive assessment of speech recognition workload. While WER focuses on word-level errors and overall accuracy, the F1-score accounts for precision and recall, providing insights into how well the system handles correctly and incorrectly recognized words. For proof of work (PoW), block confirmation time is what we are concerned about. It refers to the time it takes for a new block to be added to the blockchain after being successfully mined by a miner, involving trade-offs between security, throughput, user experience, and the economics of the blockchain. For sort, grep, and media streaming, we inspect throughput to reflect the performance of storage, computing, and transmission. Throughput reflects the rate at which the workloads can process data and is often measured in terms of records per second or data size per unit of time.

6. Preliminary experiments

To illustrate the challenges of the metaverse to the point, we construct a concise metaverse scenario based on MetaverseBench and summarize the challenges based on evaluations. In the concise metaverse scenario, we only consider the minimum system requirement, which is constructed by four workloads corresponding to the metaverse components. Although the concise scenario cannot completely summarize the whole picture of the metaverse system, preliminary experiments on designated workloads can quickly clarify the gaps between the performance of state-of-the-art systems and that of metaverse systems.

6.1. The concise scenario

To construct the concise scenario, we choose four workloads from MetaverseBench: face recognition, 3D reconstruction, media streaming, and sort. As demonstrated in Fig. 6, face recognition is adopted to represent the metaverse access system; 3D reconstruction is adopted to describe the construction of both avatars and the metaverse environment; media streaming is adopted as a typical workload in all kinds of activities in the metaverse; sort is adopted to represent overall data processing of the metaverse system.

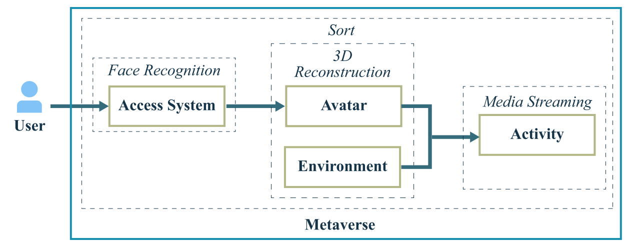

Fig. 6. Workloads in the concise scenario.

In the concise scenario, we assumed that a single server node serves a thousand users. The overall design target is to satisfy the concurrency, which is also the typical Internet service mode. We examined the latency or throughput for each workload to determine whether the system could meet the requirements. Specifically, we focus on latency for face recognition and 3D reconstruction, while for media streaming and sorting, we focus on throughput.

We further set the baseline performance for four workloads. For face recognition workload, we refer to smartphones' face recognition unlocking process and set its latency requirement to be no more than 3 s for a single user. For the 3D reconstruction workload, given that the latency of mainstream XR devices is generally under 50 ms and Apple Vision Pro makes it as low as 12 ms, it is reasonable that we set its latency requirement to be ten milliseconds. To enable an immersive experience, we take 4K videos as media sources for the media streaming workload. Specifically, the video parameters are resolution 3840*2160, frame rate 24 fps, video codec H.264, and bitrate 40 Mbps. Therefore, the throughput requirement of the media streaming workload is 5 MB per second per user. For the sort workload, the throughput requirement of the metaverse system is 1 GB per second. In our preliminary experiments, we only evaluated the performance of the state-of-the-practice system for each workload separately. All performance requirements are summarized in Table 5.

6.2. The preliminary results

We conducted preliminary experiments on a single server equipped with Intel(R) Xeon(R) CPU E5-2620 v3 @ 2.40 GHz CPU and NVIDIA Tesla V100 GPU. The testbed is a typical state-of-the-practice platform.

Face Recognition. We conducted offline inference on the LFW (Labeled Faces in the Wild) dataset [23]. At the same time, the pre-trained model used was a TensorFlow implementation of Google FaceNet [24] with the architecture of Inception ResNet v1, which was trained with VGGFace2 dataset [25] under the V100 GPU. The inference process took 9 min and 13 s on 13233 images and showed an accuracy of more than 0.99. This implied that the platform could deal with nearly 24 images per second. On the other hand, the latency requirement of the metaverse system for face recognition is 3 s. Therefore, it suggested that a state-of-the-practice solution is enough to meet the need.

Table 5
Preliminary results.

Workloads	Metrics	State-of-the-practice results	Requirements	Gaps
Face Recognition	Latency under Accuracy	0.05 s under 0.995 per user	3 s under 0.99 per user	No gap
3D Reconstruction	Latency under IoU	1800 s under 0.9 per scene	0.01 s under 0.8 per scene	180,000 times
Media Streaming	Throughput	0.15MB/s per user	5MB/s per user	33.3 times
Sort	Throughput	20.3MB/s per 1000 users	1GB/s per 1000 users	50.4 times

3D Reconstruction. Since scene reconstruction could be more challenging than object reconstruction due to the need to reconstruct multiple objects and their relationships within the scene, we focus on scene reconstruction for now. Specifically, we conducted an evaluation on SceneNet dataset [26] with the open source POCO pre-trained model [27], which was trained with ShapeNet dataset [28]. The inference results showed that the POCO model achieved a considerably fine reconstruction quality, while the average time consumed per scene was about 30 min. On the other hand, the latency requirement of the metaverse system for 3D reconstruction is ten milliseconds, and the gap is 180,000 times.

Media Streaming. We conducted this workload experiment with docker images released by CloudSuite [29]. During the running process, media streaming created four concurrent clients while each client held no more than 500 sessions (each session represented one user). The total throughput for all clients was about 292.4 MB per second. In other words, the throughput was 0.15 MB per second per user. On the other hand, the throughput requirement of the metaverse system for Media streaming is 5 MB per second per user, and the gap is about 33.3 times.

Sort. We adopted results in BigDataBench [6] as a reference to evaluate the state-of-the-practice performance of our big data workloads. BigDataBench conducted sort operations using a 32 GB unstructured Wikipedia data set of 4,300,000 English articles on a typical state-of-the-art processor, Intel Xeon E5645. The results showed the throughput was about 20.3 MB per second. On the other hand, the throughput requirement of the metaverse system for the sort workload is 1 GB per second, so the gap is about 50.4 times.

6.3. Summary

Table 5 summarizes the gaps between the performance requirements of the metaverse system and those of the state-of-the-practice system. Our evaluations show that to achieve the performance requirements of the metaverse system; the state-of-the-practice system performance needs to catch up by two orders of magnitude on average. The smallest gap is face recognition, whose state-of-the-art performance can meet the requirement, and the most significant gap is the one of 3D reconstruction, which is five orders of magnitude. So, state-of-the-art technology needs more revolutions to achieve the performance requirements of the metaverse system. Besides performance, we also conclude some requirements for metaverse system designs.

Fitting Various application scenarios. The metaverse involves a lot of application domains. Many real-life activities, such as business, social, education, finance, medicine, meetings, and games, can be mapped to the virtual world. These different application domains have other application characteristics and technical requirements. So, the metaverse system should define a set of standard interfaces and specifications to fit these different domains.

Providing Stronger interaction. In the metaverse, the ways of interaction will be more diverse. Users can issue instructions through handheld devices, head-mounted devices, etc.; the machine can also capture the user's actions and language through cameras and microphones. In addition, the user's brain turbulence, heart rate, blood pressure, breathing, and environmental information can also be obtained through sensors. Different types of precision sensors make the interaction between the user and the machine smoother. At the same time, through smart glasses, seats, projection equipment, and other output devices, technologies such as virtual reality and augmented reality can be used to make users immersive.

Using more edge or end devices to implement stronger interactions the metaverse collects user and environmental data through tremendous and heterogeneous sensors. These collected data have various formats, including images, videos, voices, etc. These data need to be quickly and accurately identified and processed accordingly. Traditional Internet applications often send user requests to servers, parse requests, and process data in servers. In the metaverse, some simple sensor data processing tasks can be performed in end and edge devices, while complex tasks are sent to the server for processing. Currently, task allocation and scheduling are not limited to servers in the data center but must be performed on ends or edges.

7. Related work

Although benchmark evaluations exist for the related technological domains involved in the metaverse, such as XRBench [30] for evaluating the performance of Machine-Learning hardware for future Extended Reality systems and BigDataBench [6] for evaluating big data systems and architectures, creating benchmarks for complete metaverse systems remains uncharted territory. The Hyperledger Foundation [31] introduced Hyperledger Caliper, a benchmark tool for blockchain. At the same time, in 2020, Dimitri et al. [32] developed BCTMark, a generic framework for benchmarking blockchain on an emulated network in a reproducible way. Additionally, there are benchmarks available for Artificial Intelligence, such as MLPerf [4] and AIBench [5]. However, building benchmarks against complete metaverse systems is still uncharted.

8. Conclusion and plan

Metaverse is a rapidly iterative interdisciplinary comprehensive concept, due to which building benchmarks for corresponding hardware and software systems is still an emerging subject. In this paper, firstly, we proposed a definition of the metaverse from the perspective of system composition: a metaverse system is composed of four subsystems, which are the access system, avatar, environment, and activity. Based on this definition, we investigated and analyzed nine specific related technological domains and explored the requirements and challenges of each component and the corresponding technological domains. Finally, combining system composition, technological domains, and requirements, we proposed our metaverse benchmark methodology. Furthermore, based on this methodology, we built a preliminary metaverse benchmark. We conducted experiments and evaluations on several relevant workloads, including face recognition, 3D reconstruction, big data sorting, and media streaming.

Regarding benchmark construction, this paper focuses on the workload abstraction of multiple individual real-world tasks. The challenges brought by the subsystems composed of multi-tasks and the entire system consisting of various subsystems greatly exceed that of a single task. We plan to build the respective metaverse subsystem based on different workload abstractions. Then, we will complete the complete metaverse system. Finally, we will construct the metaverse system-oriented metaverse benchmark suite.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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