GRAND CHALLENGES 2025

World Wide Metaverse: Open, Free, and Secure

GESELLSCHAFT FÜR INFORMATIK

The vision of the metaverse promises a new stage of digital society. However, for it to reach more than just a small segment of the population, several challenges must be addressed, and numerous requirements must be met.

Initially dismissed, the internet has evolved into an integral part of our lives since its inception. While today's internet is ubiquitous and accessible through various devices, the metaverse goes far beyond that. It represents nothing less than the promise of merging virtual space with physical reality. By leveraging technologies such as Virtual Reality and Augmented Reality, multimodal digital content is seamlessly integrated into our lives. The vision of the metaverse holds the potential to fundamentally improve our lives: climate-friendly remote, mobile, and home-based work, more conscious consumption, and new leisure activities are just a few of the benefits. However, to make these advantages accessible to a broad population, three key challenges must be overcome: First, like the internet, the metaverse must be interoperable and scalable while ensuring consistency and persistence of content. Establishing open interfaces, protocols, and standards is essential for this purpose. Second, access must be multimodal, multisensory, and low-barrier. Simply transferring existing 2D content into immersive environments is insufficient. It requires novel user interfaces that not only engage all senses but are at least as easy to use as today's internet technologies. Third, information security must be integrated from the outset. The architecture of the metaverse should be designed from the ground up to ensure that both security and privacy are fundamental components.

As a responsible research and application discipline, computer science can and must play an active role in addressing all three challenges. Only then can we harness the potential of the metaverse for society and usher in the next stage of our digital world.

The Challenge

The metaverse, as we understand it, represents a comprehensive and flexible fusion of reality and virtuality, encompassing mixed forms such as Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) itself. Reality can exist as a digital twin within the metaverse and be enhanced by digital elements. At the same time, the metaverse also contains unique virtual content. Within this space, all types of activities can take place—work, leisure, services, shopping, travel, and much more. These activities can occur in reality, virtually, or within a blended environment. Such a hybrid space will fundamentally transform our daily lives by serving as an omnipresent computing, governance, commerce, and social media platform. Like all technologies, the metaverse offers numerous opportunities but also presents risks. These challenges can be summarized as follows and are addressed by the Grand Challenge:

Cross-Platform Interoperability, Scalability, and Persistence

To fully unlock the metaverse's potential, it must meet fundamental requirements similar to those of the internet. This includes the ability to interact with various devices such as smartphones and head-mounted displays. Additionally, different platforms and services

providing access to the metaverse must be interoperable, enabling cross-platform interactions and seamless transitions between environments. These platforms must efficiently scale with user numbers, store data in a standardized and persistent format, and ensure secure data exchange across different metaverse services.

Multimodal, Multisensory, and Inclusive Access
Today's internet and current AR/VR applications primarily rely on audiovisual content. Research is actively exploring the integration of other modalities (e.g., haptics and olfaction) to expand interaction possibilities between humans and digital systems. In the metaverse, multimodal and multisensory user interfaces will play a crucial role, as only they can enable a seamless and immersive fusion of virtuality and reality. These interfaces must also be designed with inclusivity and accessibility in mind from the outset to ensure that as many people as possible can participate.

Security and Privacy by Design
In today’s internet, data—especially credentials, personal information, and payment details—serve as the foundation for many business models but also present opportunities for surveillance and cybercrime. The same concerns will likely apply to the metaverse. Therefore, protocols, standards, exchange formats, and platforms must be designed to ensure data sovereignty and prevent misuse from the outset. Collaboration with other disciplines, particularly legal sciences, is necessary to advise lawmakers and enable proactive regulatory measures.

On these foundations, the metaverse can unlock new possibilities for communication, creativity, collaboration, and immersive experiences. It has the potential to extend reality, allowing people to explore their imagination and develop innovative ideas. By integrating commercial and non-commercial entities as well as governmental institutions, the metaverse can evolve into a diverse and dynamic ecosystem that is accessible to all and enriches human life in comprehensive ways. However, for this vision to become reality, the challenges outlined in this Grand Challenge must be addressed.

Why It Is Important to Address This Challenge Now

The solution of the Grand Challenge—a cross-platform, interoperable, scalable, and persistent environment; multimodal, multisensory, and accessible user interfaces; and security and privacy by design—requires coordinated efforts across various fields of computer science and beyond.

Ensuring that virtual content in the metaverse remains persistent, coherent, and simultaneously expandable, modifiable, and scalable demands platform-independent and interoperable solutions in software and database design. These solutions go beyond the current state of research. While similar systems exist in video games, they often rely on proprietary data exchange formats and communication protocols that lack interoperability. Furthermore, they do not scale to the number of users seen on online live platforms such as Twitch or YouTube. The challenge, therefore, is to develop and establish a future-proof technological foundation and standards for networking and integrating different instances. Considering sustainability and energy efficiency adds another layer of complexity, as resources cannot be consumed indefinitely.

The metaverse holds significant potential for science, industry, and society. Its benefits include training and simulation applications, reduced travel through realistic virtual meetings, and easier access to multimodal knowledge. However, these benefits can only be realized if the metaverse is widely accessible and provides an intuitive and seamless user experience. Just as with the internet, the challenge lies in making access inclusive and ensuring a high-quality user experience. XR technologies, with their multimodal and immersive characteristics, promise intuitive and inclusive interaction. However, their user interfaces still require further development to achieve widespread adoption, prevent risks to users, and maximize their potential advantages. In addition to continued research, fostering digital literacy is crucial. The rapid development and heterogeneity of input and output hardware further complicate the design of inclusive, intuitive, and simultaneously platform-independent and interoperable user interfaces.

The metaverse should, on one hand, be fair, decentralized, and open—ideally, it should operate without central entities. On the other hand, ensuring security without such entities is difficult. This conflict has not been satisfactorily resolved even for the internet: while individual actors provide the necessary infrastructure, theoretically allowing them to restrict or shut down parts of the network at any time, they are simultaneously unable to create a legally compliant space. Despite criticism of such actors, they remain necessary in many cases. If the metaverse is to handle sensitive personal, corporate, or research data, controlled and secure access will be essential. Guaranteeing such access without installing trusted entities is an ongoing research challenge in cryptography. Resolving these apparent contradictions technologically is a complex interdisciplinary problem for a free metaverse.

The metaverse can only reach its full potential if these individual challenges are addressed in parallel, in a coordinated manner, and to a sufficiently high standard.

A solution can be expected within this timeframe

The Metaverse is currently emerging, as evidenced by numerous commercial and non-commercial activities. For example, the Metaverse Standards Forum already has over 2,400 members. However, it will likely take another ten years for existing isolated solutions to evolve into a globally integrated Metaverse.

Efforts Already Invested in the Solution

Public perception is currently focused on the increasing number of commercial providers, who primarily promote proprietary solutions. While these approaches partially contradict the previously outlined requirements, there are also numerous overarching efforts to establish unified and open standards. The following list of initiatives and organizations provides an overview of the activities of key stakeholders:

1. Standards
Various actors at national, European, and international levels are working to standardize the Metaverse and its technical foundations (Metaverse Standards Forum, Khronos Group, DIN, VDE, CENELEC) to ensure, among other things, interoperability, scalability, and persistence.

2. Awareness, Research, and Governance

NGOs, networks, and associations highlight the societal and economic challenges and opportunities (EFF, Bitkom, XR4All, XR4EU, EuroXR). Government organizations discuss the topic to proactively engage with developments and anticipate and regulate changes (Committee on Digital Affairs of the German Bundestag, European Union).

Disciplines Collaborating on this Challenge

Different fields of computer science and other scientific disciplines contribute to addressing various aspects of the Metaverse, aiming to solve the Grand Challenge. Within computer science, these include:

- VR/AR, Human-Computer Interaction, Media Informatics
- Distributed Systems, Green Computing
- Databases, Knowledge Management, Big Data
- Geographic Information Systems
- Information Security
- AI/Machine Learning
- Hardware Design

Other involved disciplines include:

- Law (Computer Science & Society, Data Protection, ELSI/ELSA)
- Communication Science
- Psychology
- Architecture
- Sociology

To tackle the previously mentioned challenges effectively, coordinated efforts are required—both in terms of content and geographic collaboration.

A Vision for 2035

It is a Friday morning in the year 2035. Wade is preparing breakfast for his daughters when a holographic reminder from his personal metaverse server notifies him that his older daughter has a school field trip today. Meanwhile, the children excitedly discuss their upcoming visit to a dinosaur park, where they will experience lifelike virtual dinosaurs either in a mixed-reality outdoor setting or as a fully virtual experience, depending on the weather. The park, like many similar offerings, is hosted on third-party metaverse servers, which operators lease rather than own.

After dropping off his younger daughter at kindergarten, Wade rushes back home for a meeting. As he arrives, his colleagues are already seated virtually at his table. His real-life surroundings are irrelevant—each participant sees the others seamlessly integrated into their personal environments, ensuring privacy and immersion.

Wade rarely commutes to the office anymore—saving time, costs, and reducing his carbon footprint. His company provides secure metaverse workspaces through its own corporate servers. Looking at his window, he enjoys a garden view—but it is actually a digital overlay, hiding the view of the neighboring wall.

Later that day, Wade is scheduled to speak at a hybrid academic conference an hour away. Just as he is about to leave, he receives a holographic call from his child's kindergarten—his daughter is sick. Since he cannot attend in person, his AI-driven avatar will deliver his presentation. Authentication and participation are handled automatically through biometric verification, and a green certification badge clearly indicates that his avatar is AI-controlled rather than human-operated.

After picking up his daughter and putting her to bed, Wade rejoins the conference remotely. His avatar's badge switches to blue, signaling that he is now participating in person. Conversations feel natural, despite half the attendees being present only in virtual form. At one point, a colleague spills coffee on his white shirt, and Wade is relieved to be in a fully digital space, unaffected by real-world mishaps. Meanwhile, a colleague physically attending the conference can instantly mask the stain, ensuring that her appearance remains professional—thanks to real-time augmented reality overlays.

Later, Wade's wife returns from work, exhausted. She relaxes virtually at the beach—an experience offered by her audiobook provider. In the evening, the couple explores a digital twin of a potential new apartment, a standard feature for modern real estate listings. For dinner, Wade's parents join them from Florida—virtually. The experience feels as natural as a real family gathering, reinforcing relationships despite physical distance. The day ends with Wade and his wife immersing themselves in the latest interactive VR movie, an evolution of traditional entertainment.

Addressing Social, Societal, and Economic Challenges

A free and open metaverse can help tackle critical global challenges across multiple domains:

1. **Social Integration**
   - The metaverse enables inclusive virtual interactions, allowing people with mobility limitations or geographically distant communities to engage, connect, and form relationships.
   - Cross-cultural exchange is promoted, reducing social isolation and fostering understanding between diverse populations.
2. **Access to Education**
   - The metaverse expands immersive educational opportunities, democratizing access to high-quality learning experiences.
   - Virtual classrooms, interactive simulations, and real-time knowledge hubs transform how people learn.
3. **Economic Transformation**
   - New job markets emerge in virtual design, digital commerce, and metaverse-based services.
   - Businesses operate globally without traditional overhead, boosting economic inclusivity.
4. **Preservation of Culture and Creativity**
   - The metaverse supports collaborative digital art, performances, and exhibitions.
   - Creators can monetize virtual experiences, enhancing artistic and cultural engagement.
5. **Sustainability and Environmental Benefits**

- Reduced travel and virtual alternatives to physical infrastructure lower CO_2 emissions.
- Businesses and individuals rely less on resource-intensive physical spaces.

A coordinated, interdisciplinary approach is essential to ensuring the metaverse remains open, ethical, and sustainable, maximizing its potential for all of society.

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