https://doi.org/10.1038/s41562-023-01599-5

The promise and pitfalls of the metaverse for science

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The metaverse can improve the accessibility of scientific laboratories and meetings, aid in reproducibility efforts and provide new opportunities for experimental design. But researchers and research institutions must plan ahead and be ready to mitigate potential harms.

Fig. 1 | The promise and pitfalls of the metaverse for science. To understand how the metaverse might affect the global research enterprise, we build on existing applications of metaverse technologies in science to evaluate the different ways in which the metaverse might affect scientific research, collaboration and learning. We further discuss the various pitfalls that the metaverse may bring to science and scientists, which researchers and science policymakers should consider carefully.

Some technology companies and media have anointed the metaverse as the future of the internet[1]. Advances in virtual reality devices and high-speed connections, combined with the acceptance of remote work during the COVID-19 pandemic, have brought considerable attention to the metaverse as more than a mere curiosity for gaming. Despite substantial investments and ambitiously optimistic pronouncements, the future of the metaverse remains uncertain: its definitions and boundaries alternate among dystopian visions, a mixture of technologies (for example, Web3 and blockchain) and entertainment playgrounds.

As a better-defined and more-coherent realization of the metaverse continues to evolve, scientists have already started bringing their laboratories to 3D virtual spaces[2], running experiments with virtual reality[3] and augmenting knowledge by using immersive representations[4]. We consider how scientists can flexibly and responsibly leverage the metaverse, prepare for its uncertain future and avoid some of its pitfalls (Fig. 1).

Defining the metaverse

Here we define the metaverse as an immersive and persistent 3D environment in which people synchronously interact with others, with virtual agents and objects, and with representations of objects from the physical world. This definition has three components. First, the metaverse enables interactions with both digital environments and physical objects located in different places, all within an immersive environment that is persistent through time. Second, the metaverse enables individuals to interact with other people in remote locations. Third, by incorporating concepts such as the internet-of-things and digital twins[5], the metaverse enables objects manipulated in virtual reality to cause effects in the physical world and correspondingly enables remote physical phenomena to directly affect the immersive experience.

Opportunities for science

In anticipating various potential opportunities for science, here we build on existing early-stage applications to evaluate how the metaverse might help to address several current issues of concern for the research enterprise.

Accessibility. Scientific facilities and meetings are geographically dispersed across the globe, which poses a barrier to accessibility for researchers who are not co-located or who have mobility challenges. Moreover, hectic schedules, prohibitive travel expenses, travel restrictions, lack of access to childcare and increasing greenhouse gas emissions all limit access for many researchers. Video conferencing and online communication platforms, although immensely helpful, lack many of the benefits of meeting in person[6]. Screens narrow the attention and focus of scientists, by filtering out other stimuli that are essential in generating new ideas[7]. Holding meetings by video reduces opportunities for serendipitous discussions in the hallways, and hinder social connections and a sense of social presence. The 3D character of the metaverse could ameliorate some of these issues and further facilitate collaboration and communication. Furthermore, recorded 3D meetings in the metaverse can recreate the space, the attendees and their real-time reactions with fidelity, expanding access across the globe.

The metaverse can also enable personalized, immersive 3D environments to simulate and connect with remote laboratories. Scientists could visit them remotely, share them with other research groups and optimize their operations virtually before making physical changes. As such, distant scientists can be immersed together to collaborate and work with the same instruments and facilities. For instance, scientists at UCL School of Pharmacy have developed a digital replica of their laboratory that can be visited through virtual reality[2].

In both meeting and laboratory environments, artificial intelligence (AI) models could embody themselves within the metaverse as virtual agents or become part of the environment – all with the effect of enhancing collaborative scientific outcomes and human–AI teaming. For example, large language models can be implemented natively as virtual assistants to source information, provide recommendations or translate conversations to overcome language barriers.

Reproducibility. The reproducibility of experimental results is a critical issue for the credibility of science, which often hinges on precise record keeping. With the advent of the metaverse, instead of recording with handwritten or electronic laboratory notebooks, scientists could combine the use of cameras and sensors to record and then replicate laboratory conditions and procedures in immersive 3D simulations. Researchers can use headsets to record what they do, generating a first-person point-of-view in 3D. The resulting recordings – including the researchers, devices, room, materials and how the process evolves – could then be uploaded to the metaverse. Unlike video recordings, the metaverse can integrate the states of materials, objects and devices that are manipulated by the researchers, and automatically include data streams from instruments in the laboratories. Such immersive records would enable anyone to revisit what the scientists did. When questions arise, collaborators or reviewers can be present in the experiment in the metaverse along with the original researchers, either synchronously or asynchronously. Furthermore, implementing blockchain technologies for these recordings could make them immutable and trustworthy[8] – attributes that are especially important for expensive experiments or valuable equipment and samples. Owing to costs and logistical considerations, such solutions could not be universally implemented but they would make sense for studies of high impact for which replication might be challenging for a range of reasons.

Training and learning. One of the greatest challenges in maintaining a research programme is the appropriate training of new group members. The details of scientific processes can vary substantially between groups, and the time-honoured approach to training through one-on-one personal interactions is time-consuming, depends on co-location, is prone to disruptions due to personnel changes and often limits the sharing of techniques among groups.

The metaverse has the potential to enhance the process of such knowledge transfer. Research teams can design experiences using virtual reality technologies and share them at scale. Revisiting and experiencing what previous researchers did and being fully immersed in the metaverse – perhaps in the presence of a remote trainer – would naturally help trainees to replicate and learn laboratory procedures. Such training sessions conducted on the metaverse could also reduce research inequalities by allowing access to institutions across the globe. One example we can consider is the virtual laboratory training developed by the Centers for Disease Control and Prevention. Learners use a head-mounted display to immerse themselves in a virtual laboratory, where they need to identify the major parts of the laboratory, demonstrate how to keep the instrumentation working, apply safe work practices and conduct emergency procedures. As an added advantage, unlike traditional training, virtual simulation would enable learners to make costly mistakes without real-world consequences.

New experimental environments. One common challenge that faces researchers across fields is the visualization of data and experimental conditions, which are often essential for conducting research and for communicating findings. Although 3D objects can be visualized on screens, they are confined by the dimensions of the screen, which do not fully represent the materiality, depth or scale of objects. By contrast, virtual reality technology has (for example) enabled network scientists to design the VRNetzer platform[4] to explore large-scale networks in 3D. Similarly, modellers have interacted with molecular structures using Microsoft HoloLenses[9], and a medical team has visualized the brains of individuals as holograms. A networked metaverse implementation of this sort of technology would enable scientists from multiple locations to collaboratively explore data, change the parameters of these data, run simulations and create complex cuts through data in multiple dimensions.

Visualization in the metaverse can go beyond the analysis of data to further enable the creation of research programmes that are otherwise difficult to realize. Freed from limitations on experimental conditions in laboratories and observational rooms, the metaverse could enable behavioural scientists to devise virtual and immersive environments that are prohibitively expensive to develop in real laboratories, violate physical laws or have new dimensions of complexity. For example, a research team has created FreemoVR[3], a virtual reality platform to run animal experiments. Using this platform, animals move freely within the experimental room and the walls and floors display computational projections that change according to the behaviour of the animals. This enables scientists to study the brain activity and responses of the animals. A similar set-up for humans could offer behavioural researchers a vast array of interactive experimental options. Furthermore, the metaverse may also help scientists to immerse themselves in remote, hazardous or extinct environments, such as the landscape of Mars. Imagery obtained by the Curiosity rover already enables scientists to wander the Martian terrain, assisting in planning rover drives, exploring the planet and running simulations with astronauts. Using the metaverse could further enable researchers from around the world to synchronously occupy and explore the virtual Martian landscape[10]. Such technology is extensible to a wide range of inaccessible environments – including potentially exploring microscopic phenomena in the mode of the 1966 classic science fiction film 'The Fantastic Voyage'.

Challenges of the metaverse for science

Amidst the potential opportunities for science, the metaverse will also pose new hazards and ethical dilemmas. These challenges include potential harms to the physical and mental health of research participants, conflicting incentives of corporations and metaverse developers and researchers, trust and standardization, high costs and affordability, privacy, harassment and biases. We outline these challenges in greater detail in Box 1. If the history of technology is any guide, more problems will emerge with time and none of them will be addressed in full. Unless handled properly, these challenges could overwhelm the potential benefits outlined in the preceding section.

Future of the metaverse for science

The future of the metaverse remains uncertain and continues to evolve, as was the case for many technological advances of the past. Now is the time for scientists, policymakers and research institutions to start considering actions to capture the potential of the metaverse and take concrete steps to avoid its pitfalls. Proactive investments in the form of competitive grants, internal agency efforts and infrastructure building should be considered, supporting innovation and adaptation to the future in which the metaverse may be more pervasive in society.

Government agencies and other research funders could also have a critical role in funding and promoting interoperability and shared protocols among different metaverse technologies and environments. These aspects will help the scientific research community to ensure broad adoption and reproducibility. For example, government research agencies may create an open and publicly accessible metaverse

BOX 1

Key challenges for the use of the metaverse in science

Health issues

The use of the metaverse in science will raise physical health concerns, such as nausea, fatigue and physical injuries, as well as mental health risks, such as addiction or isolation. Scientists will need to conduct extensive testing of metaverse applications before they can be put into regular use, whether for training and collaboration or within experimental settings. They must also consider alternatives for those who do not want or cannot use these technologies, such as using 2D projections or cave automatic virtual environments (CAVEs).

Corporate control

Expertise and resources to build the metaverse are concentrated in large corporations, and their business goals may not be aligned with the interests of science. If these companies exclusively drive the efforts to develop metaverse technologies and platforms, the access of scientists to metaverse advantages may depend on corporate agendas and financial interests, and scientific work may depend on the concurrence of corporations. The research community will need to either establish funding mechanisms to support independent metaverse capabilities or establish strong protections to ensure the needs of the research enterprise are met.

Code fidelity

As experiments in the metaverse will be mediated by hardware and software, scientists will need to build and create consensus on the fidelity and veracity of science conducted on the metaverse. Scientists will need to establish, maintain, validate, and publish the encoded rules that govern the environment of any metaverse experiment. Researchers must create trust mechanisms to accept and adopt new knowledge produced in the metaverse, and protocols for the associated metadata. This sort of standard environment will prove critical to ensuring the reproducibility and replicability of studies in the metaverse.

Resource disparities

Using the metaverse will demand upfront investments in hardware and software, as well as extensive training. This will advantage well-funded science institutions, and scientists elsewhere may struggle to obtain the resources to leverage the metaverse for their work. To unleash the potential of the metaverse and to do so in an equitable manner, governments and funders will need to support under-resourced research groups in adopting the metaverse (for example, by direct funding programmes or by investing in open infrastructure).

Privacy and surveillance

Activities and interactions in the metaverse will generate massive amounts of data, which raises privacy issues that will require careful development of governance decisions, privacy policies and new community norms. Of particular note, scientists will need to adapt the workings of compliance review committees, such as the Institutional Review Board and Institutional Animal Care and Use Committee in the USA, to account for new avenues of potential harm to humans and animal subjects that are much more expansive owing to the virtual, persistent and highly networked nature of the metaverse.

Biases and discrimination

Immersive online environments will suffer from preexisting biases, harassment and discrimination similar to those that exist in other settings. Furthermore, in the metaverse, virtual avatars and other depictions may become targets of racism and distrust, and concerns for sexual harassment may be heightened in virtual environments. Simply transforming the identities of researchers could oversimplify the role of race and gender in their work — for example, leading to the 'whitening' or masculinization of researchers' identities — and triggering aggression and antisocial behaviour. Explicit safety norms and codes of conduct, which have been recognized as critical to safe research environments around the world, will need to be adapted and extended to all metaverse activities.

platform with open-source code and standard protocols that can be translated to commercial platforms as needed. In the USA, an agency such as the National Institute of Standards and Technology could set standards for protocols that are suitable for the research enterprise or, alternatively, an international convention could set global standards. Similarly, an agency such as the National Institutes of Health could leverage its extensive portfolio of behavioural research and build and maintain a metaverse for human subjects studies. Within such an ecosystem, researchers could develop and implement their own research protocols with appropriate protections, standardized and reproducible conditions, and secure data management. A publicly sponsored research-focused metaverse — which could be cross-compatible with commercial platforms — may create and capture substantial value for science, from augmenting scientific productivity to protecting research integrity.

There are important precedents for this sort of action in that governments and universities have built open repositories for data in fields such as astronomy and crystallography, and both the US National Science Foundation and the US Department of Energy have built and maintained high-performance computing environments that are available to the broader research community. Such efforts could be replicated and adapted for emerging metaverse technologies, which would be especially beneficial for under-resourced institutions to access and leverage common resources. Critically, the encouragement of private sector innovation and the development of public–private alliances must be balanced with the need for interoperability, openness and accessibility to the broader research community.

At the same time, more research is needed to better inform policy and practice. In addition to the development of the underlying technologies, the range of ethical, legal and social issues that are implicit in the metaverse suggest that social and behavioural science research efforts will be crucial for better understanding human behaviour in a virtual social environment. Proactive efforts to aid the research community in pursuing research about the metaverse will probably also advance practical applications, providing a tremendous opportunity to advance the core premises of the metaverse concept and to influence aspects of the metaverse outside of the research realm.

At present, the research community is not yet engaged in a broadly coordinated effort to develop open, accessible and interoperable metaverse platforms for science, leaving an important opportunity on the table. Charting both the opportunities and hazards of science in the metaverse will help us to make the most of the coming future.

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Published online: 18 May 2023

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Competing interests

The authors declare no competing interests.