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# Metaverse: Concept, Key Technologies, and Vision

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## ABSTRACT

Metaverse is a collective term for all economic and social activities in the space where the physical world, digital world, and consciousness world are interactively integrated and mutually empowered. The metaverse is the advanced stage of digital civilization and the future formation of human society. The basis for developing metaverse is general digital technologies such as high-performance network, high-performance storage, high-performance computing, high-performance security, and artificial intelligence. On the basis of the above, the key to developing the metaverse lies in researching core technologies such as digital life technologies, trusted collaborative network technologies, natural interaction technologies, ubiquitous operating system technologies, technologies and methods for computational experiments, and theories and technologies for crowd intelligence science. We should take typical metaverse application scenarios as entry points, such as the key fields of agriculture, industry, service industry, military, social governance, and other economic and social areas, to break through key metaverse technologies and implement pilot demonstration projects of metaverse. Through the demonstration, we can systematically promote the application of metaverse in economy and society from point to line, and continuously iterate and evolve the metaverse technology to advance the metaverse to a higher stage. This paper systematically analyzes the current development status and future directions of metaverse from the concept, key technology, and vision of metaverse, paving the way for the subsequent research of metaverse.

## KEYWORDS

metaverse; digital twin; trusted collaborative network; natural interaction; ubiquitous operating system; computational experiments; crowd intelligence science

The metaverse, a combination of the words "Meta" and "Universe", is a concept derived from the American science fiction novel *Snow Crash*, in which humans are able to enter a virtual space parallel to the real world through their terminal devices. This virtual space is called "metaverse". In 2021, Roblox, an American game company, went public and became the "first metaverse stock", and Meta, Microsoft, Apple, and other industry giants ventured into the metaverse industry. The concept of metaverse has quickly become a global hotspot for technology and business, and has received great attention from governments and enterprises around the world.

The US government has not yet explicitly proposed an outline document on metaverse development, but US companies continue to push the US government to strengthen the awareness of metaverse in order to shape a favorable competitive and innovative environment for the metaverse. For example, technology giants such as Meta are actively collaborating with US policymakers, scholars, and partners to map out a metaverse development blueprint. European countries have a highly cautious approach to the metaverse. European Union (EU) regulations such as the Artificial Intelligence Act, the Digital Services Act, and the Digital Marketplace Act illustrate the possible positions and tendencies of regulators towards the metaverse, including increased transparency, respect for user choice, strict privacy protection, and restrictions on some high-risk applications. In addition to Europe and the United States, other developed countries and emerging economies have attempted to use the metaverse to achieve rapid development of the digital economy by publishing strategic documents, establishing industrial and technological alliances, and promoting the comprehensive construction of the metaverse system. Seoul, Republic of Korea, has released the Metaverse Seoul Basic Plan. The Meta-Universe Promotion Association, which includes more than 20 companies such as Mitsubishi Corporation, is working with the Japanese Financial Services Agency and other administrative agencies to promote Japan as a developed country in the field of metaverse by discussing the legal system for the use of metaverse, making policy recommendations, and initiating market development. The UAE released the Dubai Metaverse Strategy, which plans to double the number of metaverse-related companies in the country in the next five years, making the UAE one of the top 10 metaverse economies in the world. In China, more than 20 provinces and cities, including Beijing, Shanghai, Chongqing, Zhejiang, Guangzhou, and Shenzhen, have issued their own policy documents to support the development of the metaverse.

The public information discloses that the global head companies in metaverse-related fields have laid out the future development of metaverse in different fields through different ways such as investment and financing, and mergers and acquisitions. The head companies involved include Meta (Facebook), Roblox, Microsoft, NVIDIA, Google, Unity, Samsung, Tencent, Alibaba, Baidu, Byte Jump, etc. The main areas or directions of deployment cover: games, social, entertainment, office, etc. The technical equipment or platforms

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involved are open collaboration platforms for content creation, operating systems, tool software, extended reality (XR) equipment, etc.

The global development of the metaverse is in a transitional stage from perception to cognition, from observation to deployment, and from conception to practice. This paper addresses the following questions: How to understand and recognize the metaverse? What are the core technologies that support the development of metaverse? What is the vision for metaverse development?

In this paper, we present the concept of metaverse by analyzing the development and impact of metaverse and related technologies. Then we will analyze the various kinds of subjects involved in the meta-universe and the interactions between the subjects, and get the ways in which the physical world, the digital world, and the conscious world integrate and promote each other and the required technologies. Finally, this paper will analyze and prospect the application scenarios of metaverse.

## 1 Concept of Metaverse

The concept and connotation of metaverse do not yet have a consensus, and the understanding of metaverse is still in infancy. In order to deeply understand the metaverse and then use it to serve the real society, we need to analyze the metaverse from the perspective of development. First, we need to evaluate the development of metaverse and its transformative impact on economy and society; second, it is important to recognize the limitations of the current concept of metaverse; and third, we should enrich and develop the concept of metaverse.

### 1.1 Trend of metaverse

The most important significance of the proposal and development of the metaverse is that it points out the development of digital civilization and the future shape of human society.

Technological development has given birth to the metaverse, and metaverse is giving birth to a new technological revolution. The development and operation of metaverse system not only involves many major theories and technologies of natural science, social science, life science, computer science, Internet, cloud computing, big data, Internet of Things, Blockchain, 5G, human intelligence, artificial intelligence, hybrid intelligence, etc., but also is giving rise to transformative technologies such as digital life, natural interaction, ubiquitous operating systems, trusted collaborative networks, and computational experiments. The metaverse system covers a wide range of scientific fields, disruptive technological innovations, and unprecedented technological crossover complexity. It is foreseeable that the metaverse, like the computer revolution and the Internet revolution, will trigger a new round of scientific and technological revolution in the world.

The metaverse is expanding the new momentum of economic development. The metaverse is opening up digital space, forming a new space for human economic and social activities where physical space, digital space, and consciousness space merge. The metaverse is nurturing new workers such as digital twins, developing new labor tools such as digital equipment, and mining new labor objects such as data, in order to form new productive forces for human economic and social activities. The metaverse is nurturing new mechanisms for the triadic interaction and integration of the physical world, the digital world, and the conscious world, which form new production relations for human economic and social activities. The metaverse is nurturing new models, new business modes, and new industries in the new space of the triadic interaction and integration of the physical, digital, and consciousness worlds, which forms a new direction of economic and social development. In summary, the metaverse is not only conducive to sustainable economic and social development, but also to fundamentally alleviate the pressure of many bottlenecks and challenges such as climate change, environmental pollution, and resource scarcity.

The metaverse is shaping new ways of social interaction. The "cosmic citizen" has become the new trend instead of the "Internet citizen". The US technology company Goldner predicts that by 2026, 25% of the world's population will spend at least 1 h a day working, shopping, educating, socializing, and entertaining in the metaverse. With the advancement of metaverse-related technologies and the growth of Generation Z (the generation born between 1995 and 2009), the time humans spend immersed in the metaverse will be greatly elongated, even reaching 24 h a day online. The metaverse platforms such as Horizon Worlds developed by Meta and XIRANG developed by Baidu are all dedicated to creating new experiences for human socialization and entertainment, and the metaverse will reshape human social interactions and lifestyles.

The metaverse is leading digital civilization into a new stage of development. Looking back at human history, humanity has gone through primitive, agricultural, and industrial civilizations, and is entering the era of digital civilization. There is often a long period of overlap and transition between the old and new civilizations. In retrospect, at the beginning of industrial civilization, agricultural civilization still dominated. With the advancement of industrialization, industrial civilization has gradually detached itself from agricultural civilization and replaced it to occupy the dominant position of social civilization, thus becoming the mainstream civilization formation of human society. By the same token, human society is at the early stage of digital civilization, and industrial civilization, which has undergone several industrial revolutions, still dominates. Before the arrival of the metaverse era, digital civilization cannot yet be compared with the first three civilizations. In the long run, the computer era, the Internet era, and the artificial intelligence era, which are stripped from the industrial civilization, have formed the primary stage of digital civilization. With the continuous development of the metaverse, the steady progress of digital technology and the increasing degree of digitization, the physical world, the digital world, and the conscious world will continue to integrate and symbiosis. Digital civilization, which is born from industrial civilization, will follow industrial civilization and become the mainstream civilization of human society in the future. The metaverse era will be the advanced stage of digital civilization.

### 1.2 Critical evaluation of the prevailing concept of metaverse

The metaverse has attracted the attention of many scholars and experts, organizations, enterprises, etc., and the positioning and connotation of the metaverse have been widely discussed. Summarizing the existing relevant views, the popular views on metaverse are mainly in the following four categories: One is to position the metaverse as a digital space that interacts, integrates, and mutually empowers with the physical world, and this view emphasizes to gradually form a relatively independent economic and social operation system in the digital space[1]. Second is to position the metaverse as the future Internet[2]. Third, the metaverse is regarded as Internet applications and social forms. The fourth is the concept of metaverse oriented to specific fields[3], such as industrial metaverse, industrial metaverse, game

metaverse, social metaverse, etc. Oriented to the development of metaverse, the common limitations of these views are manifested in the following three aspects.

The subject in the digital world is not highlighted. For the subject in the digital world, the current concept of metaverse only involves the digital twin mapped one by one with the subjects such as people, enterprises, institutions, and objects such as equipment and facilities in the physical world. The subject in the digital world is not emphasized or not emphasized comprehensively and sufficiently. In fact, subjects in the digital world include not only digital twins, but also digital companions that provide services to subjects in the physical or digital world (mainly manifested in the formation of intelligent software robots, such as ChatGPT, etc.) and the basic models and building blocks for creating digital twins and digital companions (we call them digital specimen). The purpose of highlighting the subject in the digital world is to cultivate "digital workers" in the digital world, who can combine with objects such as data (labor objects) and digital tools (labor tools) to form a new type of digital productivity.

The intelligence of the metaverse is not only expressed as the human or artificial intelligence possessed by various subjects in the physical and digital worlds, but also manifests itself as the intelligence emerging from the interactions among many subjects, which we call the crowd intelligence. All kinds of intelligence and their interactions exist in the consciousness world of all kinds of subjects in the physical and digital worlds, so the metaverse is not only a binary space formed by the interaction and fusion of the physical and digital worlds, but also an intelligent ternary space formed by the interaction and fusion of the physical, digital, and consciousness worlds.

The multiplying effect brought by the mutual empowerment of the physical world, digital world, and consciousness world is not highlighted. On the one hand, based on the digital twins of various economic and social activities in the physical world, timely tracking, diagnosis, and optimization of these activities in the digital space through computational experiments can yield relatively satisfactory or optimized results, which in turn can provide feedback control or give optimization suggestions to these economic and social activities in the physical world. On the other hand, carrying out high-quality economic and social activities requires the continuous development and improvement of production, operation, and governance technologies, such as farming technologies in agriculture, manufacturing technologies in industry, production technologies in service industries, and social governance technologies. At present, most of these technologies are developed and perfected in physical space, which is characterized by high consumption of physical resources, high cost, long cycle time, and low efficiency. Supported by the metaverse, based on the production, management, and governance technology and related knowledge in the physical world, new production, management, and governance technologies can be developed or refined in the digital space through computational experiments and applied to the physical world. In the process of mutual empowerment between the physical world and the digital world, human intelligence and artificial intelligence in the consciousness world are also playing an important role. Through the mutual empowerment of the physical world, digital world, and consciousness world, the metaverse would generate a multiplying effect in terms of resource saving, cost reduction, increased efficiency, and quality improvement.

In general, in the current metaverse concept, the subject of the digital world is not emphasized much, the importance of the subject's intelligence is not fully explored, and the mutually empowering nature of the physical world, digital world, and consciousness world needs to be highlighted.

### 1.3 Enriching and developing the concept of metaverse

Based on the existing concept of metaverse, from the advanced formation of digital civilization and the future development of human society, and by analyzing the development of metaverse and its comprehensive impact on technology, economy, and society, we believe that metaverse is the collective name of all economic and social activities in the space where the physical world, digital world, and consciousness world are mutually integrated and empowered. The metaverse is the advanced stage of digital civilization and the future formation of human society.

**(1) Physical world**

The physical world, or the real world, consists of subjects (individuals, enterprises/government and institutions, etc.) and their objects (natural objects, man-made objects, and spiritual and cultural goods and services). All economic and social activities in the physical world are manifested in the production, circulation, and consumption of various objects through various mechanisms and technologies among subjects.

**(2) Digital world**

The digital world is composed of digital subjects and digital objects. All possible activities and behaviors in the digital world are expressed as the production, circulation, and consumption of various digital objects among digital subjects through various mechanisms and technologies.

Digital subjects in the digital world are composed of digital specimen, digital twins, and digital assistant. All digital subjects are directly or indirectly subordinated to the subjects or combinations of subjects in the specific physical world. The subjects in the physical world are the "ancestors" of the digital subjects. In other words, all digital subjects are directly or indirectly managed and controlled by the subjects in the physical world. The interrelationship between the subjects in the physical world and the digital specimens, digital twins, and digital assistants shown in Fig. 1.

Digital specimen is the digital configuration of the underlying structure, function, and behavior of a subject or object in the physical or digital world. Digital specimens are created cooperatively by one or more subjects in the physical or digital world and are subordinate to the creator subject. Digital specimens cannot be self-generated. Digital specimens can be traded and circulated.

Different types and granularities of subjects and objects in the physical or digital world can have corresponding digital specimens. The smallest granularity digital specimens are organs

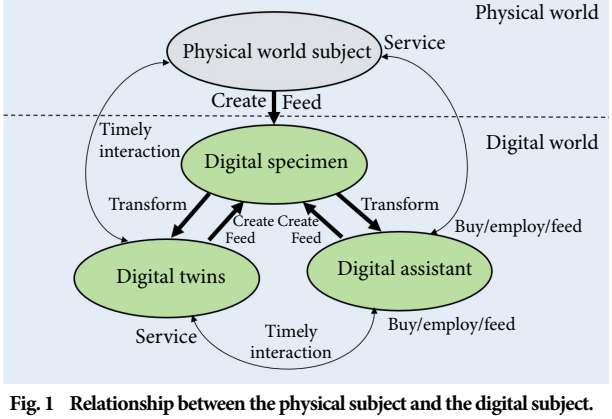


**Fig. 1 Relationship between the physical subject and the digital subject.**

(for humans, animals, and plants), devices or parts (for physical systems) that are not divisible or necessary to be divisible. On the basis of the minimum granularity digital specimens, digital specimens of larger granularity can be constructed, e.g., digital specimens of people, digital specimens of machines or objects, and digital specimens of systems composed of people, machines, and objects.

The main functions of digital specimens are: (a) to abstract the basic structure, functions, and behaviors of various subjects or objects in the physical or digital world; (b) to generate digital twins and digital assistants at low cost and in batch. After being fed with specific data, digital specimens can be transformed into digital twins and digital assistants, making them "alive" and generating behaviors with the ability to think, interact, and act.

A digital specimen usually consists of interconnected structural, behavioral, data, mechanistic, perceptual, and representational models, as shown in Fig. 2.

The structural model describes the composition of digital specimens from lower-level digital specimens and the logical relationships in terms of space, timing, and control. The structural model of the smallest granularity digital specimen contains only itself and does not involve the related logical relationships in space, timing, etc. The perceptual model describes the main input information of the digital specimen, its behavior, and its manner. The behavioral model describes the main output information of digital specimens, their behaviors, and their modalities. The mechanism model describes the physiological, mental, mechanical, electrical, and material properties of the digital specimen and its dynamic change process. The mechanism model determines the dynamic characteristics and the level of intelligence in the whole life cycle of the digital twin and digital assistant corresponding to the digital specimen. The data model stores and manages all the data in the life cycle of the digital specimen and its corresponding digital twin and digital assistant. The representational model describes the external representation of the digital specimen, such as the appearance of a real person, a cartoon image, the appearance of machines or objects, etc.

A digital twin is a digital mirror that corresponds to the subject and object in the physical or digital world. The digital twin is created by feeding historical and real-time data of a particular subject in the physical or digital world, and is subordinate to that particular digital specimen subject. Data feeding is the basis on which the digital twin survives and thrives. The digital twin can only sustain its mirroring characteristics by maintaining timely interaction with its corresponding subject or object. Digital twins cannot be traded or circulated.

The main roles of the digital twin are: (a) to display the image characteristics of its corresponding subject or object through the digital world so that it can be easily recognized and understood by other subjects and objects in the physical or digital world; (b) to assist or represent its corresponding subject or object in all possible activities with other subjects and objects in the physical or digital world.

A digital assistant is a digital subject with a specific skill or function created by one or more subjects in the physical or digital world by feeding the data of a specific digital specimen. Digital assistants are subordinate to the creator subject. Most of the manifestations of digital assistants are intelligent robots. Data feeding is the basis on which digital assistants survive and develop. Digital assistants can be traded and circulated. The main roles of digital assistants are: (a) to demonstrate the specific skills or functions they have through the digital world to facilitate the awareness and understanding of other subjects and objects in the physical or digital world; (b) to assist the subjects or objects in the physical or digital world to which they belong to carry out all possible activities.

Digital objects are data, model algorithms, and software generated by one or more subjects in the physical or digital world. As shown in Fig. 3, digital objects are subordinate to one or more subjects in the physical or digital world. Digital objects can be traded and circulated. The main roles of digital objects are (a) to serve as raw materials or semi-finished products for creating digital subjects, (b) to feed digital subjects, and (c) to support the operation of digital subjects.

All possible activities and behaviors in the digital world are expressed as: (a) production, circulation, consumption, and sales activities of digital specimen, digital assistant, and digital objects; (b) computational experiments of digital production, management, and governance technologies (digital breeding technologies and techniques, manufacturing technologies and techniques, production technologies and techniques of service industries, governance of government, military exercises, etc.); (c) circulation and application of digital production, management, and governance technologies; and (d) all digital services such as data cleaning, model improvement, software maintenance, troubleshooting, and assisted decision-making.

**(3) Conscious world**

The conscious world is composed of various types of intelligence such as human, machine, and object. Any intelligence is subordinate to a specific subject in the physical or digital world. All kinds of intelligence perceive and integrate with each other, promote each other, and evolve together. All possible activities in the conscious world are manifested in the measurement, fusion, and calculation of various types of intelligence.

**(4) Economic and social activities in the metaverse**

The economic and social activities in the metaverse are:

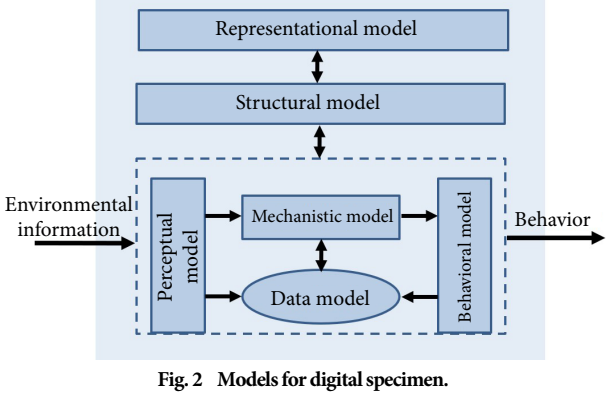


**Fig. 2 Models for digital specimen.**

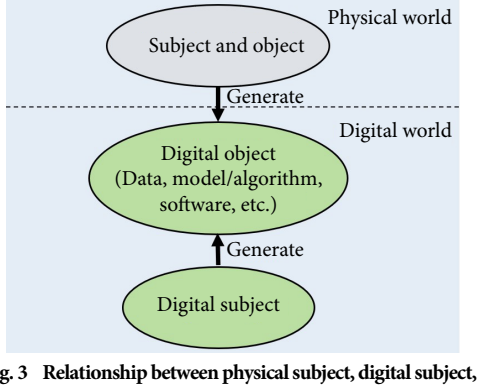


**Fig. 3 Relationship between physical subject, digital subject, and digital object.**

(a) physical space and all possible activities in it; (b) digital space and all possible activities in it; (c) conscious space and all possible activities in it; (d) all possible activities and behaviors through interaction and integration among the physical world, digital world, and conscious world. The activities between the physical world, digital world, and conscious world mainly include: (a) the subject in the physical world creates the subject and object in the digital world; (b) all transactions and interactive activities carried out between the subject in the physical world and the subject in the digital world; (c) the cognitive activities in which the conscious world, the physical world, and the digital world perceive each other, influence each other, and promote each other.

**(5) Mutually empowering activities of the physical, digital, and conscious worlds in the metaverse**

The main manifestations of the mutual empowering activities of the physical, digital, and consciousness worlds in the metaverse are: (a) the use of artificial intelligence technology to "subjectify" the objects in the physical and digital worlds can enhance the enabling ability of the objects and make them have a certain level of intelligence; (b) subjects and objects in the physical world and digital assistants in the digital world can mutually assist each other through interaction and achieve synergistic evolution through the fusion effect of homogeneous or heterogeneous intelligence (especially human intelligence and artificial intelligence) in the conscious world, thereby jointly enhancing the enabling ability; (c) computational experiments in the digital world track, diagnose, and optimize various economic and social activities in the physical world in a timely manner, provide feedback control of these activities, and give suggestions for optimal operation; (d) the real production, operation, and governance technologies in the physical world and the digital production, operation, and governance technologies in the digital world support each other, empower each other, and evolve synergistically, so as to improve the efficiency and quality of economic and social operations.

## 2 Key Technology of Metaverse

Based on the concept of metaverse and its connotation proposed in Section 1.3, the realization of metaverse for various scenes requires not only the support of general digital technologies, but also the research and development of a series of key technologies closely related to the concept of metaverse, as shown in Fig. 4.

General digital technologies encompass a large number of digital technologies involved in the development of information technology and support the advancement of information networks. The key technologies, on the other hand, are mostly preverbal technologies that are indispensable to the development of the metaverse.

### 2.1 General digital technology

General digital technology covers a wide range of technologies, including all digital-related technologies. Broadly speaking, it mainly includes high-performance network technology, high-performance storage technology, high-performance computing technology, high-performance security technology, and artificial intelligence technology. Among them, high-performance network technology involves Internet, telecommunication network, broadcasting network, satellite network, Internet of Things, Blockchain, etc.; high-performance storage technology involves big data and its storage and management technology; high-performance computing technology involves cloud computing, edge computing, space technology, etc.; high-performance security technology involves data security, system security, network security technology, etc.; artificial intelligence technology involves computer vision, natural language processing, machine learning technology, etc.

### 2.2 Key technology

The key technologies closely related to the concept of metaverse mainly include digital life technology, trusted collaborative network technology, natural interaction technology, ubiquitous operating system technology, technology and methods of computational experiments, and theory and technology of crowd intelligence science.

**(1) Digital life technology**

The main problem to be solved by digital life technology is how to create, manage, survive, grow, and maintain digital subjects such as digital specimens, digital twins, and digital assistants.

Digital subject creation technologies include technologies for the creation of digital specimens, digital twins, and digital assistants.

Since digital specimen mainly consists of interconnected structural models, behavioral models, data models, mechanistic models, perceptual models, and representational models, the digital specimen creation technology mainly addresses the

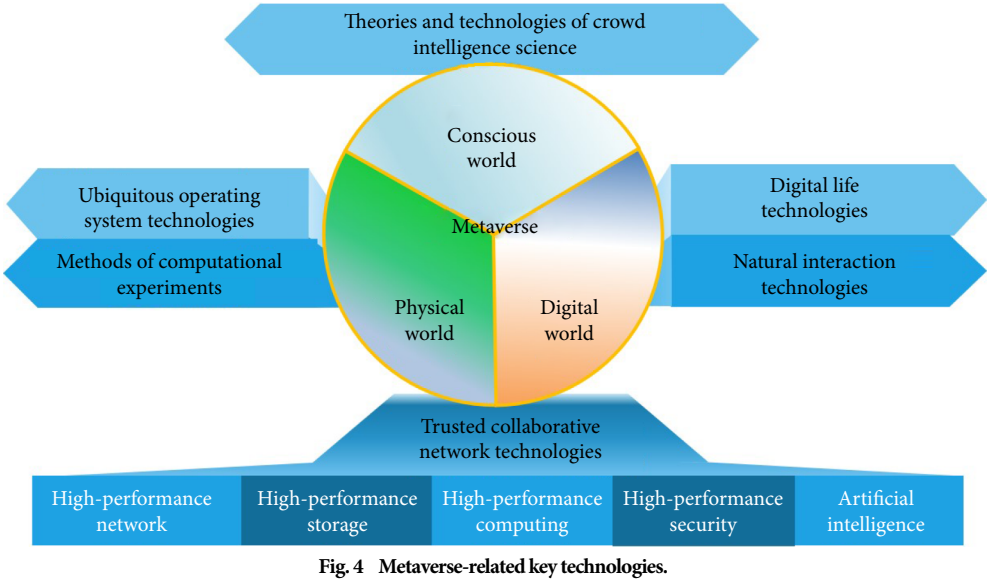


**Fig. 4 Metaverse-related key technologies.**

problems of establishing, maintaining, and managing digital specimen-related models. One of the key points and difficulties is the construction of mechanistic model. The possible technical routes are building knowledge-based models, data-based models, and models driven by knowledge and data together[4].

The process of creating a digital twin of a specific subject or object in the physical or digital world is actually the process of fitting the historical data of a specific subject or object into the corresponding digital specimen data model of that subject or object. Processing the historical data of a specific subject or object to conform to the specification requirements of the digital specimen data model is the main problem to be solved by the digital twin creation technology.

The process of creating a digital assistant is actually a process of training a digital specimen mechanistic model using domain-specific data. Refining or personalizing the digital specimen mechanistic model based on the training data is the main problem to be solved by digital assistant creation technology.

The survival and growth technologies of digital subjects are mainly for digital twins and digital assistants. The process of survival and growth of digital subject is actually the process of running and evolving its mechanistic model. Digital subject survival and growth technologies mainly solve the problem of updating and evolving the mechanistic model of digital subjects.

**Digital subject circulation technology.** Digital specimen and digital assistant are tradable. The main ways of trading can be buying, selling, renting, etc. The transaction mode, pricing, and management of the transaction process for digital subjects are the main problems to be solved by the circulation technology of digital subjects.

It is worth noting that the concept of digital twin mentioned in this paper is quite different from the existing concept of digital twin in terms of connotation, extension, and realization paths of the concept[5].

**(2) Trusted collaborative network technology**

The existing Internet and Internet of Things connects subjects and objects such as people, machines, and things in the physical world, which is actually a type of network that is not fully trusted due to the lack of mechanisms and protocols to identify the authenticity of the connected objects. In the metaverse, it is not only necessary to connect subjects and objects in the physical and digital worlds, but also to ensure the trustworthiness of the connected subjects, objects, and the interaction process between subjects and objects. We need to develop trustworthy collaborative network technology to provide the basis for efficient operation of all possible economic and social activities in the metaverse.

The main research directions of trusted collaborative network technology include: research and design of trusted collaborative network topology; research and design of trusted collaborative network interconnection mechanism and protocols; technology to guarantee the trustworthiness of both physical and digital subjects and objects and their interaction processes; technology for distributed identity management for physical and digital subjects; technology for unique association of physical subjects and objects and their corresponding digital subjects and objects; technology for information security and autonomous control of physical and digital subjects, etc.

**(3) Natural interaction technology**

Natural interaction technology is the expansion and deepening of the current human-computer interaction technology[6], especially the interaction between physical subjects and digital subjects, between digital subjects and digital subjects, and between digital subjects and digital objects.

In the metaverse, the interacting agents include subjects and objects in physical and digital space. The content of interaction includes multimodal information such as text, speech, image, vision, touch, and taste. The mode of interaction includes automatic, semi-automatic, and subject-intervention interaction. The process of interaction includes real-time interaction, periodic interaction, on-demand interaction, etc. Based on existing technologies, the research goal of natural interaction technology is to make the interaction information and processes between subjects and objects in physical and digital spaces timely, accurate, consistent, reliable, secure[7], and efficient.

The main research directions include: (a) adaptive user interface technology, including building a user model based on user characteristics, identifying different users, and adopting different interaction methods based on the user model; building a task model based on task types, identifying different task types, and adopting different interaction methods; (b) multi-channel multi-modal interaction technology, which interacts by input and output multi-modal information such as visual, auditory, tactile, kinesthetic, verbal, gesture, expression, or neural; (c) perception-based interaction technology, which obtains multi-modal information in physical space based on sensing devices, etc. for interaction; (d) mixed reality based interaction technology, which interacts based on virtual reality, augmented reality, mixed reality, and other devices; (e) subject dialogue interaction technology, including natural language recognition and synthesis, emotion recognition, dialogue system design, etc; (f) interaction technologies based on interfaces and protocols, mainly oriented to automatic interaction technologies between digital subjects and digital subjects, and between digital subjects and digital objects.

**(4) Ubiquitous operating system technology**

At present, the main operating systems for personal computing are Microsoft Windows, Google's Android, and Apple's iOS. However, with the progress of technology and the change of computing environment, it is inevitable that the operating system will be updated and new operating systems will be born.

In 2018, Mei and Guo[8] proposed the concept of Ubiquitous Operating Systems (UOS), arguing that a new generation of ubiquitous computing models and scenarios requires new and diverse operating systems. In the metaverse space, ubiquitous operating systems manifest as personalized and intelligent portals for specific physical subjects. Based on the trusted collaborative network, the ubiquitous operating system should be (a) the only portal for physical subjects to enter the metaverse space; (b) the management platform for physical subjects to manage all resources such as subjects and objects of their metaverse space; (c) the display platform for physical subjects to show the digital twins of subjects and objects and their interrelationships in the physical space they belong to; (d) the operation platform for physical subjects to carry out all economic and social activities in the metaverse space; (e) the operating system that can support a variety of terminal devices such as personal computers and cell phones.

The main research directions of ubiquitous operating system technology include: (a) research and design of ubiquitous operating system architecture and operation mechanism; (b) identification information management technology for physical and digital subjects; (c) management and display technology of supply resources from physical and digital subjects; (d) management and display technology of demand information for physical and digital subjects; (e) management and display technology of socio-economic relationship among physical and digital subjects; (f) management technology of scenarios and

processes for transactions and interactions among physical and digital subjects and objects.

**(5) Technology and methods of computational experiments**

In 2004, Wang[9] proposed the concept of computational experiments, and formed the method of "artificial system-computational experiments-parallel execution", which emphasizes the circular feedback optimization relationship between the artificial system and the actual system. In the metaverse, computational experiments are mainly used to solve two types of problems: (a) tracking, diagnosing, and optimizing the actual operating systems in the physical world; (b) developing digital production, operation and governance technologies, such as digital breeding, seed breeding, and field management in agriculture; digital assembly, process, and production process management in industry; digital surgery and other technologies in service industry; and policy simulation, public opinion management and control, and other technological solutions in government governance.

The framework of the technology and methods of computational experiments is shown in Fig. 5. With the support platform for computational experiments, a runnable experimental system is designed and formed for a specific problem, on the basis of the digital twins of the actual operating system in physical space and various optimization models and algorithms. Based on the experimental system, specific experiments are conducted, and the experimental process and results can be analyzed. According to the analysis results, it is possible to adjust and optimize the experimental system, and the satisfactory or optimized experimental results are obtained. The experimental results output different forms of optimization solutions, including feedback and control of the actual system, optimization suggestions for the real system, and technical solutions for production, operation, and governance.

The main research directions of computational experiments technology and methods include: (a) optimization models and algorithms for domain-specific problems; (b) techniques and methods for experimental system design; (c) techniques and methods for experimental results analysis; (d) techniques and specifications of experimental result output, such as the methods and techniques of feedback control, the specification of the recommendation scheme for optimal operation, the specification of the technical scheme for production, operation and governance, etc.; (e) research and development of the computational experiments support platform.

**(6) Theory and technology of crowd intelligence science**

In the metaverse, all kinds of economic and social activities involve intelligence with different nature, including human intelligence, artificial intelligence, and intelligence emerging from the interaction among many subjects. The main problem to be solved by the theory and technology of crowd intelligence science is how to promote the full play of intelligence and make full use of intelligence with different nature, so as to enhance the intelligence level of economic and social activities, and then ensure the efficient operation of these activities.

The main research directions of the theory and technology of crowd intelligence science include: (a) research on the quantification of individual intelligence. Quantitative assessment of the intelligence of a specific subject lays the foundation for quantitative assessment of the intelligence level of a system composed of multiple intelligent subjects; (b) quantitative research on system intelligence. Multiple intelligent subjects achieve intelligence emergence through interaction. Quantitative research on the mechanism of intelligence emergence and its influencing factors provide the basis for quantitative assessment and regulation of the system intelligence level; (c) research on crowd intelligence optimization algorithm. Research on the optimization algorithms of many homogeneous or heterogeneous intelligent subjects with different intelligence levels can be used to optimize the process of economic and social activities in the metaverse space.

## 3 Vision of Metaverse Scenarios

Many people know that Meta, Roblox, Baidu, and other companies are developing metaverse platforms for games, social contact, entertainment, and other fields. They believe that by logging into the relevant metaverse platform with the help of different terminal devices to play games, socialize, and entertain themselves, they enter the metaverse space. However, this understanding about metaverse is one-sided.

In fact, from the perspective of the metaverse concept and its connotation proposed in this paper, we are already living and working in the metaverse space by entering the cyberspace for shopping, socializing, traveling, producing, and managing through cell phones, computers, and other terminal devices every day, only that this metaverse space is primary. We can say that we have already entered the primary stage of the metaverse.

For example, we often use navigation apps for driving trips. People (physical subjects) in the physical world drive cars (physical objects) on roads (physical objects) (activities of physical subjects in physical space). In the app (digital world) there are electronic maps (digital object, digital twin of the physical object road network), car icons (digital object, primary digital twin of the physical object car), location service function (can be considered as a digital assistant providing professional service of location), route planning function (can be considered as a digital assistant providing professional service of route planning), and voice navigation function (can be considered as a digital assistant providing professional service of voice navigation).

We give the starting point and the end point of driving, and the digital assistant who provides professional services of route planning gives the optional route based on artificial intelligence

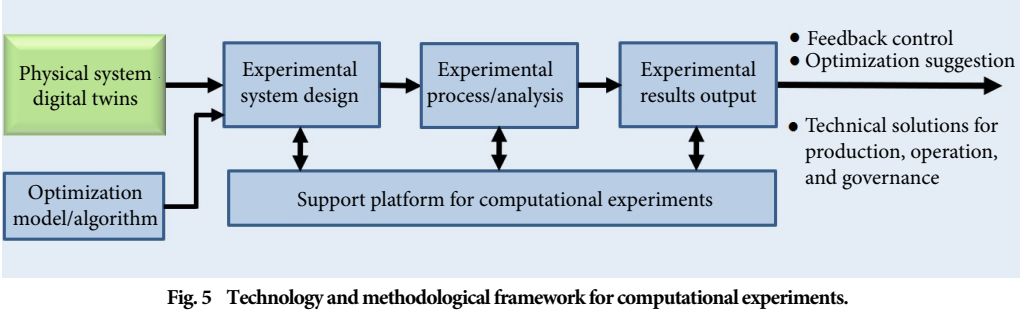


**Fig. 5 Technology and methodological framework for computational experiments.**

algorithms. The process and the result can be regarded as the optimal result obtained by the interaction between the human intelligence of the physical subject and the artificial intelligence of the digital subject in the conscious space after we confirm the driving path considering the cost, time, and other factors. The interaction process of navigation app and related subjects forms a metaverse space in which the physical world, digital world, and conscious world interact and merge. In this space, the driving activities carried out in the physical world are synchronously mapped into the digital space through the digital assistant that provides location services. The driving is expressed as the dynamic change of the car icon in the digital space. During the driving activity, the digital assistant providing location services in the digital world tracks the driving activity performed in the physical world in time. The digital assistant providing navigation service carries out timely diagnosis and optimization, and then makes suggestions for optimal driving. People in the physical world adjust their driving paths or directions according to the optimization recommendations timely. The physical world, digital world, and conscious world empower each other to achieve high-performance driving activities.

The size of the metaverse space varies with the perspective of observation. From the perspective of the whole nature and human society, the metaverse covers the whole physical world, the digital world, and the conscious world. From the perspective of individuals, enterprises, government departments, or institutions, each actor has a corresponding metaverse space, which can be called the actor's metaverse, depending on the scope and nature of economic and social activities of the actor. The actor lives in its own metaverse. All of the actors' metaverse are interconnected by a trusted collaborative network to form a complete metaverse space.

Looking into the future, human beings will enter the advanced stage of metaverse. All subjects and objects of the physical world and their related economic and social activities will be completely mapped into the digital world, forming complete digital twins of the physical world. A large number of digital assistants exist in the digital world, providing all kinds of professional services for the economic and social activities in the physical world and the digital world. At the same time, computational experiments can track, diagnose, optimize, manage, and control the economic and social activities in the physical world in a timely manner, and improve the efficiency and quality of these activities. On the other hand, the research results of digital production, operation, and governance technologies can be put into practice in the physical world.

The metaverse has considerable potential for applications in a wide range of fields[10,11]. For example, in the energy sector, the increasing demand for sustainable energy and the rise of the metaverse have provided an opportunity to develop a secure and sustainable energy trading system using Smart Grid (SG), Virtual Power Plants (VPP), Digital Twins (DT), and Blockchain[12]. In terms of online shopping, metaverse stimuli attributes (i.e., effectiveness, vividness, and interactivity) have a positive significant influence on metaverse organismic experience (i.e., telepresence). Additionally, metaverse telepresence has a significant positive influence on customers responses (i.e., perceived product knowledge, and purchase intentions)[13].

## 4 Conclusion

Based on the current concept and connotation of metaverse, this paper proposes the concept of metaverse, which is innovatively defined as a collective term for all economic and social activities in the space where the physical world, the digital world, and the world of consciousness are integrated and empowered by each other. We provide a detailed description of the digital specimen, digital twins, and digital assistants that make up the digital subject. By examining the connotations and connections between the various types of subjects, this paper analyzes the relationship between the three worlds and the key technologies involved in the metaverse.

This paper enriches the connotation of the metaverse and emphasizes that the metaverse should highlight the subjectivity of the digital world. The digital subjects in the digital world are created in large quantities to form digital laborers in digital space. Digital laborers are combined with digital objects and digital labor tools to form a new type of digital productivity of the metaverse. The intelligence of the metaverse should be emphasized. The human intelligence, artificial intelligence, and intelligence emerging from the interaction among many subjects in the physical and digital worlds should be fully utilized in order to enhance the intelligence level of the metaverse, and thus the effectiveness of various economic and social activities in the metaverse space. The multiplier multiplying of mutual empowerment among the physical world, digital world, and conscious world should be stressed. On the one hand, based on the digital twin of various economic and social activities in the physical world, these activities are tracked, diagnosed, and optimized in digital space through computational experiments in due course. Based on the relatively satisfactory or optimized results of computational experiments, feedback control or optimal operation suggestions are given to these economic and social activities in the physical world.

On the other hand, based on the foundation of production, operation, and governance technologies in the physical world and the knowledge of related fields, new production, operation, and governance technologies are developed or perfected in the digital space through computational experiments, and then applied to the physical world. In the process of mutual empowerment between the physical world and the digital world, human intelligence and artificial intelligence in the conscious world are playing an important role at the same time. By empowering each other among the physical world, digital world, and conscious world, a multiplying effect is generated in terms of resource saving, cost reduction, efficiency, and quality.

The development of metaverse cannot be separated from science and technology, especially digital science and technology. On the basis of general digital technologies such as high-performance network, high-performance storage, high-performance computing, high-performance security, and artificial intelligence, it is crucial for the development of metaverse to research and develop core technologies such as digital life technologies, trusted collaborative network technologies, natural interaction technologies, ubiquitous operating system technologies, technology and methods of computational experiments, and theories and technologies of crowd intelligence science.

We have now stepped into the primary stage of metaverse. On this basis, we should take typical metaverse application scenarios[14] as entry points, such as the key fields of agriculture, industry, service industry, military, social governance, and other economic and social areas, to break through basic, global, and forward-looking core technologies of metaverse and implement pilot demonstration projects of metaverse. Through the demonstration, we can systematically promote the application of metaverse in economy and society from point to line, and continuously iterate

and evolve the metaverse technology in order to accelerate the pace of metaverse development to higher stages.

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