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China's e-Science Blue Book 2023

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China’s e-Science Blue Book 2023

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Preface

According to the report of the 20th National Congress of the Communist Party of China, momentous changes of a like not seen in a century are accelerating across the world. A new round of scientific and technological revolution and industrial transformation is well under way, and a significant shift is taking place in the international balance of power, presenting China with new strategic opportunities in pursuing development. In the new stage of development, scientific and technological innovation plays a key role in the global development pattern and competition pattern. In recent years, with a high-speed development trend, the new generation of information technology, as a key area of technological innovation, intensively and extensively integrates with various industries and fields, driving the transformation of production models and highlighting its guiding and supporting role in the high-quality development of the economy, society, and technological innovation. Sizing up the trend of events with great foresight, the CPC Central Committee, with Comrade Xi Jinping at its core, has set up a national strategic development goal of "building a strong network country and a digital China". It attaches great importance to informationization work and has repeatedly emphasized that "informationization has brought a golden opportunity once in a blue moon to the Chinese nation" and "we must keenly seize the historical opportunity of informationization development."

The e-Science is typical of research environment and activities in the information age. It is an important part of China's informationization construction and a powerful means to improve research productivity, promote technological innovation, and produce significant results. Presently, e-Science plays an important role in promoting the convergence and sharing of scientific and technological resources, triggering changes in research organization and modes, and promoting technological transformation.

The e-Science is an accelerator for significant technological breakthroughs. As scientific research advances towards the super-macro and super-micro directions, information technology is increasingly closely linked with scientific research activities, gradually becoming an indispensable driving force for technological achievements. For example, the research on "complex physical systems" which won the 2021 Nobel Prize in Physics successfully predicted the trend of global warming. The achievement was made with the method of physics simulation, which relied heavily on the application of the e-Science.

The e-Science is the driving force behind the paradigm shift in scientific research. As human society enters the era of big data, scientific research has also entered the fourth paradigm characterized by "data-intensive" and "AI + big data". The application of information technology represented by big data and artificial intelligence can not only help scientists improve the productivity of scientific research, but also overturn traditional scientific research modes, leading to paradigm shifts and driving advancements in the field. For example, in 2021, the DeepMind introduced AlphaFold2, an artificial intelligence program capable of accurately predicting the 3D structure of proteins, ushering in an era in which biologists use computational structure prediction as a research tool.

The e-Science is a crucial pillar in the pursuit of becoming a technologically advanced nation. Currently, all countries and regions around the world attach great importance to the construction of research informationization and consider research informationization as a strategic measure to enhance innovation capacity and international competitiveness. The e-Science is the foundation for the interconnection of major scientific and technological infrastructure, supercomputing centers, scientific data centers, field scientific stations, as well as research institutes, universities, enterprises, and other research elements in China. The national-level research informationization infrastructure platform, known as the "China Science & Technology Cloud" integrates and converges fundamental resources like networks, computing, storage, and software. It promotes the open sharing of scientific and technological resources, provides integrated cloud services of discovery, access, use, and delivery for scientific and technological professionals, and greatly enhances the ability and efficiency of converting scientific data into knowledge discovery. Moreover, this platform also offers critical support for major scientific and technological innovation activities.

Under the strong leadership of the Central Committee of the Communist Party of China, China's e-Science has made great strides. Recent years have witnessed a series of new progress, new achievements, and new breakthroughs in the field of research informationization supporting scientific and technological innovation and promoting output of achievements. Research informationization technology and infrastructures have provided storage, computing, and transmission solutions for massive data generated by major scientific and technological infrastructures such as the Five-hundred-meter Aperture Spherical Radio Telescope (FAST), the Large High Altitude Air Shower Observatory (LHAASO), and the High Energy Photon Source (HEPS), and supported the international cooperation between China Spallation Neutron Source (CSNS) and the European Organization for Nuclear Research (CERN). The e-VLBI technology based on high-speed networks guarantees the tracking and positioning of China's lunar and planetary exploration projects. The multi-star and multi-task parallel information system based on "one network and two platforms" supports the massive data processing of space science series satellites such as the "DAMPE", "Practice 10", "QUESS", and "HXMT". The Scientific Observing Network of the

Chinese Academy of Sciences (CASSON) in the western Pacific Ocean has overcome the world's difficult problem of real-time transmission of deep-water and long-time-sequence subsurface buoy data. The application of research informationization in the fields of industry, agriculture, energy, and environment continues to deepen, constantly promoting the development of the national economy and industrialization, supporting disaster prevention and reduction research under the "Belt and Road" initiative, driving the digital and intelligent transformation of agriculture, and the study on the possibility of China's economic low-carbon transformation. The deep integration and application of information technologies, especially big data, artificial intelligence, and the Internet of Things in the fields of medicine, biology, and genomics have made positive explorations in and contributions to the research and development of the COVID-19 vaccine and epidemic prevention and control.

The world is currently experiencing a new round of deepening technological revolution and industrial transformation; fueling the need for the reform of the new scientific research paradigm and the restructuring of the innovation model. Information technology is at the forefront, driving innovation and redefining our core competitiveness. In order to summarize and showcase China's experience and achievements in e-Science in the past two years, and to further promote the development of e-Science in China, the Chinese Academy of Sciences, together with the Ministry of Education of the PRC, the Ministry of Science and Technology of PRC, the China Association for Science and Technology, the Chinese Academy of Social Sciences, the Chinese Academy of Engineering, the National Natural Science Foundation of China, and the Chinese Academy of Agricultural Sciences jointly compiled and published the "China's e-Science Blue Book 2023". The book has been highly valued and strongly supported by the leadership of participating parties. The book includes 29 articles written by authoritative experts in the field of e-Science in China, covering the trend strategy, application practice, and infrastructure construction of scientific research informationization. It presents the development state, application achievements, and construction status of e-Science in China in the past two years from different perspectives. The book is rich in content, with detailed cases, and boasts both theoretical significance and practical reference value, which can be read and referred to by the leadership, administrators, and frontline scientific researchers engaged in informationization or scientific research work in scientific research institutions, universities, and related enterprises.

Finally, due to a brief working cycle and limited access to complete information, the content of this book may not fully and comprehensively reflect the work and achievements of scientific research informationization construction at all levels in China. We apologize for any shortcomings in this regard. However, we highly value feedback and suggestions from readers from all walks of life, and we are committed to continuous improvement in our future work. Your valuable opinions and suggestions are most welcome as we strive to enhance our content and deliver better results in the future.

Beijing, China
March 2023

The Committee for the Compilation of
China's e-Science Blue Book 2023

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Situational Strategies

E-Science—A Key Driver for Scientific Research Paradigm

Jiulin Sun, Xuehai Hong, Yang Wang, and Yan Ban

Abstract Scientific research paradigm is an important driving force to promote the transformation of scientific paradigm. At present, it is of great significance to actively explore the transformation of scientific research paradigm for improving the efficiency of scientific research, promoting the output of major achievements and promoting the reform of scientific and technological mechanism and system. This paper expounds the connotation and characteristics of scientific research paradigm, and explains the types of transformation of scientific research paradigm, its manifestations in different scientific fields and its multi-dimensional expression. It is pointed out that scientific research informatization promotes the transformation of scientific research paradigm in different scientific fields, and that scientific research informatization is an important driving force to promote the transformation of scientific research paradigm. Finally, the paper proposes that the construction of scientific research informatization should adapt to and promote the transformation of scientific research paradigm.

Keyword Scientific paradigm · Scientific research paradigm · Scientific research informatization · Paradigm elements · Transformation

On May 28, 2021, General Secretary Xi Jinping pointed out in his speech at the 20th Congress of the Chinese Academy of Sciences, the 15th Congress of the Chinese Academy of Engineering and the 10th National Congress of the Chinese Association for Science and Technology that the current new round of scientific and technological

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revolution and industrial change is advancing rapidly, scientific research paradigms are undergoing profound changes, the interdisciplinary integration of disciplines is developing, and the integration of science and technology and economic society development are accelerating [1]. This shows that the paradigm shift in scientific research has become a new situation for the scientific community, which requires a concerted effort to adapt to and achieve a major paradigm shift in the mindset, methods and organization of research activities.

Scientific research informatization is the informatization of scientific research elements in research management and research activities, and is an important support and driving force for achieving changes in the scientific research paradigm. Since mankind entered the age of informatization, the methods, paths and evaluation systems of scientific research have undergone significant changes, and these changes are very different from the previous paradigm of scientific research. Some old establishments, methods, tools and research paths are no longer adopted, a new set of rules is rapidly emerging and old scientific research paradigms are being replaced. Therefore, in the Blue Book on China's Research Informatization 2015, which was jointly prepared by CAS and the State Internet Information Office, the Ministry of Science and Technology, the Ministry of Education, the Ministry of Industry and Information Technology, the Academy of Social Sciences and the National Natural Science Foundation of China, CAS academician Tan Tieniu has clearly pointed out that research informatization will further promote the change of research paradigm. He also pointed out that scientific research is currently facing more profound and complex challenges in both micro and macro directions, and that several data-intensive scientific fields such as astronomy, meteorology, geophysics, earth system science, biology, genomics, etc. need new and more advanced interdisciplinary tools and informatization platforms to manage and analyze massive amounts of scientific data and solve complex scientific problems [2].

In the current environment of increasingly fierce global competition in science and technology, it is of great significance to the development of science and technology innovation in China as to how to make full use of the platform, environment, data and mechanism of research informatization to further improve the efficiency of scientific research, how to achieve rapid scientific discoveries and breakthroughs in major scientific and technological problems, and to promote the changes of paradigm in scientific research in China.

1 The Meaning and Characteristics of the Scientific Research Paradigm

1.1 Connotations of the Scientific Research Paradigm

The term Paradigm is an abstract concept introduced by the American scientist Thomas Kuhn in his book *The Structure of Scientific Revolutions* [3]. It is primarily concerned with scientific paradigms. According to Thomas Kuhn, one of the hallmarks of a scientific paradigm (or disciplinary paradigm) is that if a discipline relies primarily on monographs to advance knowledge, it has no paradigm, suggesting that everyone needs to start with basic questions; disciplines with paradigms rely primarily on journal articles to advance knowledge production. Disciplines that have a consensus on paradigms rarely discuss paradigms, while disciplines that do not have a consensus on paradigms often have paradigm debates in which people prefer to use the term 'paradigm' when describing themselves or the camp they support. Those paradigms that do not yet reach the level of normal science expand into the term 'research paradigm'. This can easily lead to confusion in understanding and expressing the terms 'scientific paradigm' and 'research paradigm'.

In a narrow sense, the paradigm proposed by Thomas Kuhn should be a scientific paradigm. A scientific paradigm is a theoretical system that is commonly believed and accepted by the contemporary scientific community as a theoretical presupposition for conventional scientific work in the disciplines. For example, the scientific research activity of mankind today is still generally confined to the basic theoretical framework established by the revolution in physics at the beginning of the twentieth century, and is far from being in a period of theoretical decline. In this sense, the scientific paradigm in today's world has not changed much.

A scientific research paradigm, also known as a scientific research paradigm or research paradigm, is how scientific research is conducted by the scientific community in a particular historical period, in line with the requirements of the inherent laws of science and technology innovation. We believe that a scientific research paradigm is a collection of rules and systems that the academic community relies on and generally adopts to make its daily scientific research activities efficient and orderly, including the establishment environment, research paths, evaluation systems, research methods, research tools, technical routes and research models. Although this definition is not a strict conceptual definition, the connotation of a research paradigm is clear: it is a collection of rules that are recognized or accepted by the academic community and are influenced by social, economic, cultural, and international environments and individual preferences. Accordingly, we believe that a research paradigm is a system of rules that contains a mixture of elements such as research methods, research approaches and paths, research resources, research organization, research evaluation and research systems for research activities. This system of rules does not necessarily have to be a hierarchical structure between the various mixed elements, but can also be a mesh structure. Different people can give their understanding and knowledge of the research paradigm in terms of different rule element dimensions, and define the process characteristics of the relevant research activities accordingly. Therefore, at present, research paradigms are more often summarized and described in terms of one element, such as data-intensive fourth research paradigm and national institutional research paradigm, in terms of research tools (e.g. research informatics), research resources (e.g. big data) and ways of organizing research activities (e.g. individual scientists or teams) and research management systems. Although these summaries and generalizations are useful for guiding the organization and management of current research activities, they can also lead to a one-sided understanding of research paradigms. Therefore, there is a need to systematically summarize the common features of research paradigms and the different characteristics of research paradigms in each discipline, to help guide the research activities in specific fields.

1.2 Characteristics of the Scientific Research Paradigm

A scientific paradigm has a degree of acceptance within an academic community and is a whole consisting of its fundamental laws, theories, applications, etc. Its existence provides scientists with an agenda to follow in their research. A breakthrough in a scientific paradigm can lead to a scientific revolution, which can give science a whole new look. For example, the energy science paradigm is a scientific paradigm change based on energy conversion, which triggered the transformation of traditional fossil energy sources to nuclear energy and led to the development from human-powered.

carriages to internal combustion engines. The breakthrough in the research paradigm will lead to changes in the means of research, improvements in the efficiency of research and changes in the organization and management of research. Unlike the scientific paradigm inherent in a discipline, a paradigm change in research does not lead to a change in the scientific mechanisms and laws inherent in a discipline. Research paradigms are characterized by several features.

(1) The scientific paradigm has characteristics that cannot be described by a scientific paradigm. A scientific paradigm cannot be characterized by the fact that research activities in all disciplines follow the same code of conduct. For example, a common code of conduct for research activities in the natural sciences cannot be applied to research and development activities in engineering and technology, nor to research activities in the humanities and social sciences.
(2) Research paradigms are individual in character. Research paradigms are different in different disciplines and even in different stages of development of the same discipline. For example, the scientific research paradigm of natural science research is not of the same type as that of engineering science and technology. Scientific research in the natural sciences lies in the creation or discovery of new knowledge and takes the form of papers and monographs that are carriers of knowledge. Engineering science and technology is usually technological

innovation and development research based on the basic principles and knowledge of the natural sciences, which takes the form of technology patents and products. For example, protein structure analysis in the life sciences, which was previously based on experimental equipment (e.g. cryo-electron microscopy), has now developed into a DATA + AI based research model.

(3) Scientific research paradigms are characterised by constant change and evolution. According to the characteristics of the different stages, scientific research paradigms are usually divided into the first, second, third, fourth and even fifth paradigms. These paradigms are a category of common characteristics that evolve in stages as scientific research activities progress, the complexity of the scientific problems faced grows, and the technological advances in research tools and instruments evolve.

As can be seen from the above description, a scientific paradigm is a theory, the knowledge, that a scientific community follows. Scientific Paradigm is a different approach or model of scientific research developed for a specific discipline, based on the scientific paradigm of a discipline. A scientific paradigm is the unification of the content and methods of a discipline, and a scientific research paradigm is the methodological part of a paradigm discipline. A scientific paradigm and a research paradigm are not the same concept. In general, a scientific paradigm provides successful precedents for scientific research that can be imitated, as a tool that relies on its successful demonstration, a method for solving problems, an artificial paradigm, or a constructive paradigm. For example, the current paradigm of relying on "big data + artificial intelligence" to drive research activities in various disciplines is a paradigm that has been derived from the scientific paradigm of artificial intelligence and the use of big data technology to adapt to the needs of research activities in many disciplines and is a paradigm shift caused by a change in the research resources element of the research paradigm. It is a paradigm shift in research caused by changes in the resources of the research paradigm. Therefore, changes in some elements of this type of research paradigm give rise to new research paradigms, which is the theoretical basis for why research informatics can contribute to contemporary paradigm shifts in research. The development of research informatics, for example, has the potential to provide the elemental changes needed to facilitate paradigm change in research.

2 Paradigm Shift in Scientific Research and Its Multidimensional Manifestations

2.1 Paradigm Shift in Scientific Research

The paradigm shift in scientific research is based on two main drivers. One is the intrinsic drive for developments in the field of science. The other is the extrinsic drive to improve research methods as a result of technological advances, typically the computerization of research. In the history of human scientific research, four paradigm shifts have taken place. From the first paradigm, which used simple experimental methods, to the second paradigm, based on theoretical deduction, to the third paradigm, based on computer simulations, and the fourth paradigm, driven by massive amounts of data. Currently, the concept of a fifth paradigm is being proposed in the scientific community. These scientific paradigms are not substitutes for each other. Each research paradigm shift inherits the strengths of the previous generation of research paradigms and is parallel and may co-exist in various subject areas. Table 1 shows a comparison of the paradigm shifts at each stage, including the attributes of the scientific research problem, the research tools, and typical examples.

In general, the third paradigm is a combination of "human brain + computation", where the human brain is the main character and computational methods are auxiliary. The fourth paradigm is a combination of "computer + human brain + data", where the computer is the main character, the human brain is the dominant character and the data is the auxiliary material. The "fifth paradigm", as pointed out by Xueqi Cheng et al. in their article[4], is based on an ontological understanding of data science; the "fifth paradigm" emphasizes an ontological perspective on data, considering that data itself contains the laws of natural intelligence, and is also the carrier and product of new types of intelligence. It is expected that while data drives intelligence, it will break through the boundaries of the existing capabilities of computational intelligence and construct a new paradigm of intelligence with the help of natural intelligence.

The evolution of the scientific research paradigm as described above shows that the characteristics of the various stages of the scientific research paradigm actually blend the concepts of scientific and research paradigms. The first and second paradigms, which essentially follow the general consensus of the scientific paradigm, are of an acceptable nature, i.e. there is a research paradigm of experimental observation and theory in any scientific study. The third and fourth paradigms, on the other hand, are actually paradigm shifts in scientific research, formed by changes in the paradigm elements of scientific tools and data, and are paradigmatic (Exemplar), existing only in certain fields of scientific research. The fifth paradigm is a paradigm shift in research across a wide range of disciplines, triggered by the great development of computing power and the breakthroughs in AI, which is also essentially a paradigm shift in the elements of research. As can be seen from the evolution of the paradigm described above, computing has played a role in the paradigm shift in research by providing elements of tools and resources, which lays a solid basis for the theory that research information technology promotes the transformation of the research paradigm.

2.2 Paradigm Shifts in Different Scientific Fields

From a macro perspective, research paradigms vary and shift in different disciplinary fields as the elements of the research paradigm change in various research activities. Research paradigms in the natural sciences, in engineering and technology, in humanities and social sciences all vary, and there are even different stages of

Table 1 Comparison of paradigm shifts in research by phase

	Properties of scientific research questions	Research tools and typical cases
First paradigm	Experimental science: the discovery of natural laws. Such as heat from fire, gravitational acceleration, etc., characterized by the recording and description of natural phenomena. Natural phenomena are characterized by Modern discoveries of natural physical mechanisms. The Higgs boson, the "God particle", is mainly through experimental recording of data and analysis of the intrinsic Mechanisms	Early experiments such as drilling for fire and Galileo's Tower of Pisa ball tossing. Modern large scientific instruments and large scientific installations, such as the Large Hadron Collision Accelerator
Second paradigm	Theoretical science: limited by experimental conditions, it is difficult to achieve a more precise and complex understanding of natural phenomena. Theoretical science. Scientists have tried to remove minor distractions and leave only the key factors to simplify the experimental model as much as possible and then Theoretical science This paradigm of research continues to this day. This paradigm has continued to this day	Based on mathematical equations for calculation and reasoning. For example, Newton's three classical laws of mechanics, Maxwell's theory of electromagnetism, and quantum mechanics and relativity
Third paradigm	Computational simulations: As it became increasingly difficult and economically expensive to verify classical and modern physical theories (requiring large installations), scientific research began to enter a phase of intractable problems. The emergence of computers with the von Neumann architecture led to the rapid spread of the use of computers to simulate scientific experiments, allowing complex phenomena to be simulated and simulated, and complex problems to be clearly explained	Based on physical theory, computational theory and computational techniques. Typical examples are simulated nuclear tests, weather forecasting, etc. As the use of computer simulations increasingly Replaces experiments, they are becoming a regular mode of modern scientific research

(continued)

Table 1 (continued)

	Properties of scientific research questions	Research tools and typical cases
Fourth paradigm	Data Intelligence: With the rapid development of modern information technology and the explosive growth of data, it is possible to discover scientific knowledge and the laws of nature and physical society from the vast amount of data, i.e. to mine the data for correlations, cause-effect relationships and knowledge of various things and events and to make predictions. This paradigm is a unique "data-intensive knowledge discovery research paradigm" separated from the third paradigm	Based on big data theory and technology and computing technology, we use algorithms such as data mining and machine learning. Typical examples are the discovery of potential human diseases based on high-throughput genomic test data, the discovery of gravitational waves based on cosmic observation data, the discovery of interpersonal relationships based on online social data, etc.
Fifth paradigm	AI for Science: To overcome the "black box" problem of machine learning in the fourth paradigm, which relies solely on data-driven approaches, and to overcome the problems of modeling complex systems in the real world, understanding high-dimensional spaces and making effective predictions in engineering practice, by integrating physical knowledge, using algorithms related to artificial intelligence and advanced computing techniques, to solve problems describing complex. This paradigm is a new development in the intersection and synthesis of the second, third and fourth paradigms, and is a research paradigm under exploration	Pre-training and inference techniques using machine learning neural networks based on big data and physical knowledge and laws (including deep learning networks, convolutional networks and physical information networks, etc.). Typical examples are DeepMind's AlphaFold2 for protein de novo structure analysis and prediction, large-scale equation prediction, large-scale equation set compression, and physics-based information neural networks for the application of Navier–Stokes equations for solving Navier–Stokes equations, etc.

research paradigms in different disciplines. At each stage in the history of human research activity, the research paradigm has changed in line with its own scientific and technological progress. This means that the organisation and management of research activities cannot be driven by the same research paradigm, nor by the same type of research elements. This is the motivation and basis for the paradigm shift that research informatics can facilitate. However, regardless of the subject area, the objectives of the research paradigm are: to achieve rapid scientific.

discoveries, to solve major economic and social development problems, to effectively improve the efficiency of research and to optimise the objectives of research tasks.

In the field of natural science research, the transformation of research paths andmodels is one of the most common paradigm changes in scientific research. After the SecondWorld War, the paths and paradigms of scientific research changed fundamentally as the shape of scientific existence changed from small science to big science. In the era of small science, the paradigm of scientific research embraced individual heroism, which led to the achievement of numerous scientific wizards, such as Albert Einstein and Madame Curie, who, through their individual efforts, achieved outstanding scientific achievements. But in the era of big science, it is far beyond the power of a single individual to achieve major scientific achievements, such as the Manhattan Project, the Apollo moon landing, gravitational wave detection and China's Shenzhou spacecraft, etc. These costly scientific projects are all organically integrated by huge research teams through complex modern management techniques, and no individual is capable of completing them. It is easy to see that this is a shift in the paradigm of scientific research, triggered by changes in the human element and in the elements of scientific organisation and management models. Research activities in the era of big science are not "islands" of individual "solitary" and categorical research. The paradigm of "solo" and "all-inclusive" full-spectrum innovation is no longer adapted to the requirements of scientific innovation in the era of big science.

In the field of natural science, major natural science discoveries are increasingly dependent on major science and technology infrastructures, both at present and in the future. Major science and technology infrastructure is the material and technical basis for breaking through the frontiers of science and solving major scientific and technological problems for economic and social development and the country. This is a paradigm shift and an upgrade of scientific research triggered by changes in the tools and means of scientific research. The paradigm upgrade in scientific research shows that major scientific discoveries and technological changes increasingly rely on major scientific and technological infrastructure, innovation platforms and extreme experimental conditions and large scientific teams to collectively tackle them, which is also the policy foothold for the coordoinated use of national strategic scientific and technological forces and the realization of major scientific and technological innovations. In the future, we should further promote the upgrading of the scientific research paradigm through national strategic science and technology forces.

In recent decades, with the rapid development of information technology, high-speed high-capacity communications, the Internet of Things, big data, artificial intelligence, high-performance computing and other technological advances, a paradigm shift in data-driven natural science research has taken place in the field of natural science research, giving rise to a new paradigm of scientific discovery based on intensive data, the Fourth Scientific Research Paradigm. This is one of the elements of scientific research, the data element, which has changed the traditional scientific research paradigm of relying solely on experimental observation and theoretical deduction in natural science research.

Thus, the paradigm shift in scientific research in the natural sciences is essentially a change in the elements of the relevant scientific paradigm, which has triggered a paradigm shift in natural science research. The paradigm of scientific research is different from the traditional natural science paradigm in the past, such as the collection, management and exploitation of massive scientific data generated by major scientific facilities, and knowledge discovery. These paradigm shifts cannot be achieved without the support of tools, platforms, data and environments for research informatics.

In the field of engineering science and technology, engineering science is the study of various disciplines of engineering technology, which is a comprehensive body of knowledge used in engineering. The focus of engineering technology research does not lie in new scientific discoveries, nor scientific principle innovation, but mainly presents forms relying on scientific principles and knowledge in terms of innovation and progress in technological implementation. For example, in the field of information technology, people's knowledge of theories and knowledge of semiconductors belongs to knowledge discovery (such as the energy band theory of quantum mechanics), but relying on such theories and knowledge to make semiconductor devices requires innovation in engineering technology. In recent times, engineering technology has more directly linked scientific discoveries to industrial development and has become a major driver of economic and social development. Engineering science and technology has transformed knowledge into products, bringing unprecedented convenience to human production and life. Several major achievements in engineering science and technology, such as the "Two Bombs, One Satellite", manned spaceflight and lunar exploration projects, have greatly enhanced China's comprehensive national power and international status. The successful construction of a large number of major projects such as the Three Gorges Project, the Qinghai-Tibet Railway and high-speed railways has significantly enhanced the innovation capacity and level of China's basic industries, manufacturing industries and emerging industries. The innovation drive of engineering science and technology has been instrumental in this.

The distinctive feature of engineering science and technology is "engineering", which is the creation of "physical objects". From the perspective of whether there is a paradigm shift in scientific research, to observe whether engineering science and technology has achieved a paradigm shift, we need to pay attention to whether there is a shift in the relevant elements of the scientific research paradigm in "engineering", such as scientists, scientific research resources, scientific research tools, scientific research organization and management, research paths, research models and mechanisms, etc.

From the perspective of the human element, a distinctive feature of contemporary engineering science and technology is "large", which means that the realization of "engineering" is not achieved by a single scientist (technical expert), but requires a large scientific research team to implement it. From the perspective of the means, tools and resources for the realization of engineering science and technology, the realization of a project in modern engineering science and technology no longer relies only on a certain scientific research instrument or equipment, nor computer tools or data resources, but on various scientific research instruments, computer tools and various data resources, etc., whether in the pre-proof of engineering design, or various tools and resources used in the process of engineering realization, all are so. As a result, the paradigm elements of engineering science and technology have changed from a single element to a multi-element synthesis. From the perspective of the organization and management elements of engineering science and technology, which used to rely on the organization and management of a single person or unit, modern engineering science and technology are generally large projects that require complex organization and management, and have evolved into large team organization and multi-unit collaborative organization and management, or even transnational organization and collaboration. Even in contemporary large-scale natural science research, such as gravitational wave detection, celestial science discovery, human genome project, etc., it is still necessary to rely on large team building to complete the implementation of major scientific research basis of big science projects, on which the major research objectives of natural science can be achieved, which is essential for engineering science and technology.

From the above analysis, it is clear that with the advancement of modern technology, elements of the scientific research paradigm in engineering science and technology are achieving a shift. Each link and each stage of engineering science and technology may have its scientific research paradigm. As a result, the paradigm shift of scientific research in engineering science and technology, regardless of the stage of R&D in engineering science and technology, cannot be simply summarized as the first paradigm. In fact, in engineering science and technology, the first and second paradigms provide the immediate observational and theoretical basis, while the third and fourth paradigms and even the fifth paradigm provide the technology and methods for engineering realization. Each of these scientific research paradigms has a role to play in engineering. Therefore, each scientific research paradigm element may achieve a transformation in engineering realization, thus contributing to the scientific research paradigm shift in engineering science and technology. Therefore, we cannot simply use a single research organization and management model for the management of engineering science and technology. This requires us to change the "one-size-fits-all" approach to research management and policy formulation. At the same time, the distinctive feature of engineering science and technology is "engineering", and the intersection and integration of multiple disciplines within engineering science and technology is intricate and complex, which presents many opportunities for the realization of the value of research informatics.

At present, there are many "neck" problems in China, which essentially belong to engineering science and technology problems. What foreign countries are able to "neck" us are mature engineering technologies that have been developed for decades. The problem is not that we do not understand the scientific principles and knowledge, but that we have fallen behind in the "continuous improvement" stage. The improvement phase is the accumulation of small advances, each of which may not be at a very high theoretical level, but can improve the system. What needs to be changed is the organization, management and evaluation of the research paradigm and how to use research information technology to accelerate this paradigm shift.

In the field of social science and economic research, the American sociologist Riltz defines three different research paradigms in sociology[5]: the social fact paradigm, the social definition paradigm and the social behavior paradigm, a division that mainly indicates the different ways sociologists look at social phenomena or different perspectives of observation. The social fact paradigm (structural–functional school, conflict school, neo- Marxist school) emphasizes the objectivity of social phenomena. The social definition paradigm (symbolic interactionism, phenomenology, folklore methodology) emphasizes the subjective nature of social phenomena and the study of how people build society and act in it at a micro level. The social behavior paradigm (behavioral theory, exchange theory) emphasizes the objective and precise analysis of the social behavior of individuals. In our view, the scientific research paradigm in the social sciences is mainly a research model in which social science research scholars observe and summarize social development phenomena and trends and then abstract theoretical perspectives. On the whole, this belongs to the first paradigm. Of course, modern social science research emphasizes refinement, causality and interpretability of social phenomena, which inevitably leads to a trend of data-driven research, which will also promote the emergence of a data-intensive research paradigm for social science research (the fourth paradigm). At present, the scientific research activities of social science research based on internet big data are taking place in the field of social science and information science cross research.

Similarly, there are two dominant economic paradigms (scientific paradigms) in modern economics research: the "neoclassical" economic paradigm and the "neo-Keynesian" paradigm. These two paradigms are, on the one hand, observational and statistical, and, on the other hand, based on basic assumptions, followed by theoretical and explanatory studies of economic development using the respective theories. From the perspective of the scientific research paradigm, this is typical of the first and second paradigms. In macroeconomic research activities, more use is made of the development of theoretical mathematical models followed by computational and analytical research, which is the third paradigm. In microeconomic research activities, there is an increasing reliance on mathematical modeling and data-driven research, which is part of the fourth paradigm. It can be seen that these four research paradigms co-exist in economic research activities and that different research paradigms may exist at different research stages of the same research activity.

2.3 Multidimensional Manifestations of the Paradigm Shift in Scientific Research

As mentioned earlier, the current description and summary of the research paradigm are more often summarized in terms of one of the elements such as research tools (e.g. research informatics), research resources (e.g. big data), the way research activities are organized (e.g. individual scientists or teams) and the research management system. In the following, we summarize the paradigm shift in research in terms of several elements of the paradigm shift.

2.3.1 From the Organizational Dimension of the Researcher, the Paradigm Shift from Individuals to Small Teams to Large Teams in Research

In the beginning, human scientific research activities were driven by the interest of individual scientists and were mainly conducted by individual scientists using observation and experimental means, which belonged to the small scientific research paradigm. However, the increasing complexity and depth of scientific research problems have made it impossible to solve complex and in-depth problems by relying solely on the small scientific research paradigm of an individual scientist. Scientific problems that require the strength of a team (not just a small team, perhaps a team from a research institution, or even teams organized together across units and countries) to work together collaboratively to solve research problems. In the field of engineering science and technology, the large research model of teams is even more prominent. Thus, while the dynamic role of the individual scientist and the implementation of an interest-driven research model advocates the release of individual scientist energy, the collaborative research model of the research team is also emphasized, emphasizing team energy to achieve big scientific research goals. The 'elite-centric' research paradigm has recently been proposed, pointing out that the traditional research system has created a scientific paradigm centered on the scientific elite, citing then Harvard University President Conant In the words of Dr. James B. Conant: Ten second-rate people are not worth one first-rate person". This "elite-centric" paradigm emphasizes the role of the "scientific elite". This 'scientific elite' can be a single outstanding scientist or a 'group of innovators'. In modern research organizations, the paradigm of relying on a single 'scientific elite' still exists in some disciplines, particularly in purely theoretical and fundamental scientific research, such as mathematics, as well as in the social sciences and economics. However, more and more research areas, such as engineering and science, and large-scale natural science research, rely on the paradigm of 'team' organization.

2.3.2 From the Dimension of Tools (Platforms) and Resources on Which Research Activities Depend, there is a Paradigm Shift in Research From Using Simple Research Tools and Simple Small Data to Relying on Individual Large Devices and Big Data to Relying on Networked Devices

Earlier scientific research activities carried out by individual scientists and even by scientists in some current disciplines, used tools that may have been simple tools such as rulers, microscopes and one or a limited number of other scientific tools and small data. However, relying on major research facilities (installations) and big data for scientific research is now becoming a way to get ahead of the current level of research and to quickly contribute to the production of scientific results. For example, in the field of life science research, scientists rely on tens of millions of dollars a piece for cryo-electron microscopes, nuclear magnetic resonance equipment, etc. to conduct research in their disciplines. In the field of earth sciences, scientists rely on large supercomputing platforms and big data resources to carry out simulations and calculations of geophysical processes. In addition, in modern international transnational scientific research, as scientific research is organized in a networked manner, the equipment used is often also distributed in different countries, resulting in a networked scientific research organization model of shared equipment and data-intensive knowledge discovery with big data integration. Examples include global seismic observation networks for earthquake science research, and global ocean observation networks for marine environmental research.

2.3.3 The Change from a Single-Disciplinary to a Multidisciplinary Research Paradigm, in Terms of the Dimension of the Change in the Technical Lines of Research

The interdisciplinary research and mission-oriented research that has emerged since the Second World War has gradually condensed and evolved into fusion science in the early twenty-first century. The research of many major scientific problems is now faced with highly complex large systems and problems that cannot be solved by the research of a single discipline, for example, the research of major engineering science and technology problems, more often presents a scientific research paradigm of multidisciplinary integration, that is, fusion science is a new scientific research paradigm based on multidisciplinary integration to solve major problems, and is actively represented by the United States as a typical representative of the developed countries of science and technology Initiative[4].

The reform of China's science and technology sector in recent years has also been in line with the international trend towards a new paradigm of "convergent science". For example, the Chinese Academy of Sciences has proposed eight major areas of innovation in its 13th Five-Year Plan, based on the strengths of multidisciplinary integration, and the National Natural Science Foundation of China has promoted the establishment of the Department of Interdisciplinary Sciences and the reform of its support program. These strategic plans and the reform of the support program show that the paradigm of convergent scientific research has become the consensus of the academic community and continues to play a role in the scientific research activities in the field of engineering science and technology, as well as being systematically supported in the research activities in the field of natural science research.

In the history of science, the convergence of scientific paradigms is a phase in the evolution of scientific research paradigms. The history of science and technology in mankind is a process of the creation and even integration of ideas and branches of the discipline. When science is fragmented, there is an instinctive urge to integrate. For example, the history of scientific research began with a limited number of observations and experimental means of obtaining a limited amount of "small data" for scientific research. Today, scientific research activities have evolved to analyze big data, condensing it into small intelligence, deep intelligence, and precise knowledge for research. In the field of synthetic biology, the intersection of quantitative biology and synthetic biology in a complementary research approach will drive the change of synthetic biology from qualitative, descriptive and localized research to quantitative, theoretical and systematic. In the field of artificial intelligence research, its fusion of scientific thinking is an internal fusion and unification of research and thinking within multiple disciplines such as computer science, mathematics and physics, and is the key to spawning a new research paradigm.

2.3.4 From the Dimension of Change in Research Methodology, the Shift From a Single Research Paradigm in The Early Days to a Combination of Multiple Research Paradigms Alongside a Single Research Paradigm, Promoting the Integration of Reductionist and Holistic Research Paradigms

Scientific research methods are the tools and means of discovering new phenomena and things, proposing new theories and ideas, and revealing the inner laws of things in research. Due to the perspective of people's understanding of the problem, the complexity of the research object and other factors, it is difficult to have a completely unified understanding of the classification of research methods. However, they can generally be classified as empirical methods, theoretical research methods and systematic scientific methods.

Currently, in the scientific research activities of many disciplines, the model of a single scientific research paradigm still exists, as well as a combination of multiple research paradigms, depending on the different characteristics of the scientific research activities of different disciplinary attributes. According to Professor Rao Yi, the main scientific research paradigm in the life sciences is still at the stage of describing the phenomena of life, while further work is done to understand the basic description of the phenomena, processes and functions of biology, and then to promote life science research through a cross of mainly chemistry and physics. In the field of mathematics, scientists have instead taken the Keplerian paradigm of observational data-driven research more (the first paradigm) and the fundamentals-driven Newtonian paradigm (the second paradigm) are effectively combined for scientific research activities. According to Academician Weinan E, scientists currently strive to combine data-driven machine learning methods, fundamental principles, and fundamental principles in physics such as quantum mechanics and molecular dynamics to solve previously unsolvable scientific problems, achieving an upgrade from a small farmer's workshop model to an integrated large platform model, completing the combination of multiple research paradigms. By effectively combining the reductionist and holistic scientific paradigms through a large platform, the whole is first reduced to its components for study, and then complex system problems are studied at a high level in themselves and as a whole, so that the two scientific paradigms are no longer opposed to each other. Thus, the evolution from a combination of multiple research paradigms to a research paradigm that relies on a large platform promotes a combination of reductionist and holistic research paradigms, giving today's research paradigm a multi-paradigm fusion.

2.3.5 From the Dimension of Research Organisation and Scientific Evaluation, the Research Paradigm Has Changed from a Single Model to a Multi-modal

Different research systems will affect different models of research organization and, consequently, different paradigms of research. For our scientists, the more familiar system is that of the state (and now the new state system). The overall backwardness of China's science and technology in recent times has led to a shift from 'interest-driven' scientific research to the organization of major scientific and technological research activities around national goals, from 'what can be done'(interest-driven) before and after the reform and opening up to 'what should be done' (current). From "what can be done" (interest-driven) before and after the reform and opening up to "what should be done" (national goal-driven). From the "two bombs and one star" major science and technology projects in the past, to the current efforts to solve the "neck" problem, this is the paradigm of the national system of scientific research. Of course, under China's current research system, the state also encourages scientists to engage in a "research interest" driven research paradigm. Many of the surface research projects supported by the NSFC in China are driven by "research interests", but of course, such support falls within one of the "four types of attribute problems" supported by the NSFC.

In addition, the ongoing reform of the research system will cause a shift from a 'centralized' to a 'decentralized' research paradigm. The literature [6] suggests that the 'elite-centric' paradigm of scientific research, which revolves around a scientific elite, will be transformed into a 'decentric' paradigm. The research paradigm has dominated the international scientific community since the.

middle of the twentieth century. Its main features are the professionalization of scientific research, the hierarchy of researchers and the specialization of scientific communication. Although this "elite-centric" research paradigm has been successful to some extent, it has gradually evolved into a highly "involuted" and closed system, leading to a tendency to allocate research resources in a "four-only phenomenon. This has led to a tendency to allocate research resources in a "four-only phenomenon"(" paper-only, title-only, education-only and award-only tendency"). In a report, academician Xu Kuangdi said that "disruptive technologies, such innovations, are difficult to achieve under the current administrative approval and assessment system", referring to this "inward scroll". This is contrary to the spirit of encouraging scientific "freedom of inquiry". At present, the state is implementing a reform of the science and technology evaluation system - "breaking the four only" and implementing a multi-dimensional evaluation system of representative works and typical achievements, which also requires the exploration and establishment of a "decentralized" new paradigm of scientific research with a win–win effect. This also requires the exploration and establishment of a new paradigm of "decentralized" scientific research with win–win effects, unleashing the vitality of scientists and the tension of science. However, at present, this scientific research paradigm has not formed effectively, and the "four-only" scientific research paradigm and the "four-only" scientific research paradigm will continue to exist for some time.

3 Research Informatics for Paradigm Shift in Research

The term "informatization of scientific research" refers to the infiltration of information technology into scientific research activities, resulting in the informatization of the organization and management of scientific research and the informatization of the process of specific scientific research activities of individual scientists, teams and organizations. Both types of informatization rely on software and hardware systems, data resources, computing platforms, and supporting policies and systems for data and computing, networks and communications, information and security, and other information technology attributes. Research informatization has developed new research tools, research models, research platforms and research environments, which have effectively promoted the progress of various research work in contemporary times, whether in the field of natural science research, engineering science and technology research, and social science researchand become an important driving force for the paradigm shift in research in various disciplinary research fields.

3.1 Research Informatization Promotes a Paradigm Shift in the Research Paradigm of Research Organization and Management

Research organization and management are key elements of the research paradigm, and changes in any of these elements can bring about changes in the research paradigm. As mentioned earlier, in the early days of human research, research activities were mainly driven by scientists' interests, i.e. they existed mainly in the first and second paradigms, and research organization and management had little impact on scientists' research activities. In modern research activities, however, the organization and management of research have a huge impact on the efficiency and orientation of research. This is because the organization and management of contemporary research activities must be adapted to the country's scientific and technological institutions and mechanisms, which have a global impact and will directly lead to different models of research.

The development of management informatization in scientific research has effectively promoted the transformation of the research organization model, thus enabling the transformation of the research paradigm. Through various types of management information systems, the research organization model has broken through the boundaries of individual and small team research organization and management, and can efficiently support the formation of large, established and distributed research organization and management models, and in major research tasks can even form cross-organization and cross-national (international) research organization and management models. For example, the ARP (Academia Resource Planning) system, which has been built by CAS over the past 20 years, has effectively achieved full coverage of research management activities of over 100 research units and related management bodies across the CAS system. The system covers the management and sharing mechanism of information related to research management, such as projects, personnel, equipment and funding, and realizes the dynamic supervision of the implementation process of research projects and research results. The ARP system has effectively supported the organization and management of a series of major scientific research projects of CAS, such as the CAS Pilot Project, and has effectively improved the efficiency of scientific research management, accelerated the output of major scientific research results, and effectively ensured the role of CAS as an established team (large team) of national strategic forces in science and technology. At the national level, the Ministry of Science and Technology has built the National Science and Technology Management Information System Service Platform, which has greatly enhanced the efficiency of national science and technology organization and management, and provided solid support for the implementation of a nationwide large research organization model. The ARP system.

and the National Science and Technology Management Information System (NSTMS) service platform have successfully ensured and realized the transformation from the previous model of a small team research organization to the "national system" research paradigm of large teams.

3.2 Research Informatics for a Paradigm Shift in Natural Science Research

In the natural sciences, a scientific paradigm shift, also known as a 'scientific revolution', occurs when existing research paradigms fail to effectively address the challenges faced and a new paradigm approach is needed to address these challenges. The paradigm shift from the first 'experimental science' paradigm to the second 'theoretical science' paradigm took two to three centuries, but since the invention of the computer and the rapid development of information technology, the scientific paradigm has undergone a third paradigm shift in the last few decades. The "computational science" paradigm has evolved over the past few decades to the current fourth "data-intensive" paradigm and even the fifth "AI for Science" paradigm. This shows that the development of information technology and the construction and application of information technology in research have efficiently facilitated and ensured the paradigm shift in research.