A Study on the Connotation, Characteristics, and Forms of Knowledge Evolution of Distinguished Scientists

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Abstract

【Purpose/Significance】Meritorious scientists have not only made outstanding contributions to the development of major national weapons but also carry the cultural genes of the Republic' s excellent scientific and technological traditions. Investigating the knowledge evolution throughout their life courses and the intrinsic relationships between various stages is of great significance for deeply understanding this cohort.【Method/Process】This study takes 27 meritorious scientists as research subjects, employs the procedural coding approach of grounded theory, and extracts and synthesizes a theoretical framework for the knowledge evolution of meritorious scientists from full texts of lengthy biographies totaling over 6 million words, and analyzes its connotations, characteristics, as well as the forms and values of knowledge.【Results/Conclusion】The knowledge evolution stages of meritorious scientists include knowledge absorption, knowledge creation, knowledge application, knowledge inheritance, and knowledge permeation; these stages exhibit nonlinear characteristics of temporal intersection, causal linkage, and intergenerational flow; the changes in the form, function, and value of knowledge during the evolution reflect the knowledge-based nature, historicity, and endurance of "meritorious achievements". This research offers reference value for inspiring studies on Chinese scientists, cultivating outstanding contemporary scientific and technological talents, and organizing new narratives of Chinese scientists' stories.

Full Text

The Knowledge Evolution of Chinese Meritorious Scientists: Connotations, Characteristics, and Forms

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Abstract: [Purpose/Significance] Chinese meritorious scientists have not only made outstanding contributions to the development of key national technologies but also carry the cultural genes of the Republic' s excellent scientific traditions. Studying the knowledge evolution in their life courses and the intrinsic relationships between its stages is of great significance for a deeper understanding of this group. [Methods/Process] This study focuses on 27 meritorious scientists and uses a procedural coding approach based on grounded theory. From over 6 million words of full-text biographies, a theoretical framework for the knowledge evolution of Chinese meritorious scientists (KEoCMS) was synthesized and summarized, and its connotations, characteristics, and transformations of knowledge forms and values were analyzed. [Results/Conclusion] The stages of knowledge evolution in meritorious scientists include knowledge absorption, knowledge creation, knowledge application, knowledge inheritance, and knowledge penetration. These stages exhibit nonlinear characteristics such as temporal overlap, causal linkage, and intergenerational flow. The transformations of knowledge forms, functions, and values during the evolution reflect the knowledge-based, historical, and lasting nature of their "meritorious contributions." This research offers reference value for inspiring studies on Chinese scientists, cultivating contemporary outstanding scientific talents, and organizing new narratives about Chinese scientists' stories.

Keywords: Chinese meritorious scientists; biographical and memoir resources of scientists; knowledge evolution; grounded theory; knowledge value

1 Introduction

"Meritorious contributions" refers to achievements, particularly significant contributions to the nation and its people. Chinese meritorious scientists (CMS), as identified in academic literature and authoritative media reports, denote the older generation of scientists who have made outstanding contributions to national scientific development, such as the recipients of the "Two Bombs, One Satellite" Merit Medal and the "Republic Medal" [1]. They not only played historic roles in major national scientific and technological breakthroughs like the "Two Bombs, One Satellite," hybrid rice, and artemisinin but also shaped the Republic' s scientific traditions and forged a spirit of scientists that continues to guide China' s scientific advancement [2]. Deepening research on this group is crucial for understanding the cultural characteristics of China' s scientific soil.

Knowledge constitutes the core element of scientists' life journeys. Their mission is to create new knowledge for humanity and contribute their knowledge and wisdom to social progress and national construction. Existing research on outstanding scientist groups, including meritorious scientists, has focused on external aspects such as growth environments [3], developmental patterns [4-5], and capability traits [6], while lacking theoretical exploration and understanding of life courses centered on knowledge. This limitation constrains the theoretical and practical cognition and value excavation of Chinese meritorious scientists. Meritorious scientists learn, apply, and disseminate knowledge within a unique national context. As they age and their roles change, the forms of knowledge and its functions also evolve. How can we construct a theoretical framework for the knowledge evolution of meritorious scientists? What are the connotations of different stages in knowledge evolution? What characteristics do they exhibit? What value enhancement does the transformation of knowledge forms bring? These questions urgently require academic answers.

To address these questions, this study focuses on 27 meritorious scientists, drawing upon full-text biographical materials and employing procedural grounded coding techniques to construct a theoretical framework for the knowledge development trajectory of meritorious scientists, named the Knowledge Evolution of Chinese Meritorious Scientists (KEoCMS) theory. This theory presents the logical framework of knowledge evolution for meritorious scientists, the non-linear characteristics of the evolutionary process, and the value enhancement brought by transformations in knowledge forms. Visualizations and case studies are used to concretize theoretical understanding. This paper exploratorily distills new theory from scientists' documentary resources, which is beneficial for leveraging the value of library and information science in understanding Chinese scientists and contemporary scientific culture.

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2 Literature Review

2.1 Research on Outstanding Scientists

Outstanding scientists typically possess significant academic achievements, drive scientific and social change, and enjoy notable social reputations, making them popular subjects of academic research. These include recipients of the "Two Bombs, One Satellite" Merit Medal [1][3], members of the Chinese Academy of Sciences [7-8], Nobel laureates [9], and recipients of the National Science Fund for Distinguished Young Scholars [10].

Existing research primarily concerns the growth environments and patterns of outstanding scientists. Studies suggest that "Two Bombs, One Satellite" meritorious scientists often grew up in a "four-excellence" environment characterized by cultural accumulation, family scholarly traditions, guidance from master teachers, and a favorable atmosphere [1]. Liu et al. [10] divided scientists' growth stages into gestation, development, accumulation, and maturity periods based on their knowledge reserves and research capabilities, and measured the differential roles of various regions in cultivating scientists. Zhou [5] analyzed the effects of external factors such as educational background, overseas experience, employment institutions, and project funding on scientists' development, examining the pros and cons of the "superposition of haloes" effect on outstanding talent cultivation.

The capability elements in outstanding scientists' growth have also been explored. For instance, Cui et al. [6] constructed a strategic scientist capability model using China' s 34 dual-academicians (including meritorious scientists like Hsue-Shen Tsien, Zhu Guangya, and Wang Daheng) as samples, proposing that "national mission" forms the center of the capability model, with theoretical research capability, engineering practice capability, and strategic planning capability as its three core components. Beyond capabilities, the intellectual values of scientists have also been excavated. Since the 1990s, Professor Liu Zeyuan has written a series of papers introducing Hsue-Shen Tsien' s discipline-building work and scientific thought [24].

In terms of research methodology, scientists' biographies/resumes [13], publicly available reports, and original data collected through questionnaires and interviews are commonly used for qualitative or quantitative research. As early as the 1960s, Zuckerman employed interviews and other methods to conduct pioneering research on the life patterns of American Nobel laureates [14]. Evidently, these research findings and methods on scientists' life experiences, growth patterns, capabilities, and thoughts have laid the foundation for this study. However, research on meritorious scientists from a knowledge perspective remains insufficient.

2.2 Exploration of the Relationship Between Scientists and Knowledge

Observing and understanding scientists'thought patterns through their complete life courses has prompted scholars to move beyond simplistic understanding of the complex relationship between scientists and knowledge based solely on research outputs (such as papers, monographs, and reports).

From a micro-level perspective, scientists' knowledge acquisition behavior marks the starting point of their scientific careers. Jaimie et al. encoded and organized Darwin' s reading notes to conduct quantitative research, tracking how Darwin balanced exploration and exploitation during reading to understand the micro-mechanisms of his learning and knowledge discovery [15]. As their knowledge grows, scientists begin creating new knowledge, with research on knowledge output being the most abundant. Scholars widely use mathematical models to measure scientists' knowledge output, summarizing underlying patterns and discovering that factors such as workplace mobility [16], social cognitive abilities [17], and external collaborative relationships [18] are important influences on knowledge output. Additionally, transmitting knowledge to the next generation of scientific workers is a crucial responsibility of scientists. The formation of academic pedigrees accompanies intergenerational changes in knowledge [19], and cross-disciplinary mentorship relationships promote knowledge fusion across different disciplines [9].

From a macro perspective, scientists' knowledge not only helps individuals or academic communities fulfill scientific missions but also interacts with national, social, and cultural environments. Kuhn emphasized the critical role of scientists in driving transformations of knowledge systems in *The Structure of Scientific Revolutions* [20], where only a few scientists make major contributions at nodes of scientific paradigm change. Scientific knowledge is not only stored in academic ivory towers but also widely disseminated in society through interaction with the public, influencing public scientific literacy and promoting social progress [21]. Joubert found that scientists' active engagement with society not only enhances personal influence but also promotes the development of science itself [22]. Furthermore, scientists interact with government and other management institutions, influencing decision-making through policy recommendations and thereby bringing significant changes to social welfare and economic development [23]. This demonstrates that knowledge means far more to scientists than just "publications." Wang et al. confirmed the persistence, cross-temporal nature, and cultural significance of scientists' knowledge impact by tracking the historical achievements and influence of great physicists throughout history (Newton, Einstein, etc.) [2].

To integrate and preserve scientists' knowledge lives, scholars have begun compiling scientists' documentary resources and constructing knowledge models, structuring scientists' memories while discovering their knowledge value. For example, Liu et al. [11] constructed a knowledge model for Tsung-Dao Lee and established a digital resource center. However, these models focus on scientists' external characteristics (time, place, people, relationships, etc.), lacking in-depth modeling from the perspective of knowledge content.

2.3 Research Review

In summary, despite rich existing research findings, several important questions remain to be explored: (1) Although outstanding scientist groups have been extensively studied, there is insufficient understanding of meritorious scientists, particularly systematic induction of the complex interaction between meritorious scientists and knowledge from a knowledge perspective. (2) Although the relationship between scientists and knowledge has been diversely studied from perspectives such as learning, output, inheritance, and dissemination, these studies remain unsystematic, fragmented, and piecemeal, and have not yet formed an effective theory to explain scientists' knowledge trajectories.

Given this, this paper introduces the concept of knowledge evolution [25], focusing on Chinese meritorious scientists to explore the universal laws of knowledge evolution in scientists' life courses from a theoretical perspective, discovering its stages, connotations, characteristics, and forms of value. This research enriches theoretical understanding of the relationship between "meritorious contributions" as a representation of "national mission" and "national honor" and scientists' knowledge, offering insights for important practices such as cultivating contemporary scientific and technological talents.

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3 Construction of the KEoCMS Theory Framework

This section discusses the selection of research subjects, data collection and processing, research methods, and the process of forming the KEoCMS theoretical framework based on procedural grounded theory.

3.1.1 Selection of Meritorious Scientists

This study selected recipients of two types of meritorious medals: the "Two Bombs, One Satellite"meritorious scientists and recipients of the Republic Medal. The former comprises 23 individuals, the latter 6, with Yu Min and Sun Jiadong receiving both, totaling 27 scientists (Figure 1). They represent outstanding exemplars of all scientists who have established great meritorious contributions to the Republic' s scientific and technological endeavors. First, their professional fields are broad, including respiratory medicine, pharmacology, agricultural science, nuclear physics, materials science, optics, aerodynamics, modern meteorology, etc., providing rich disciplinary and knowledge backgrounds for the study. Second, they led major scientific and technological breakthrough projects of national and global significance, including artemisinin, hybrid rice, nuclear submarines, atomic bombs, hydrogen bombs, and the Dongfanghong satellite. These differentiated research scenarios shaped distinct knowledge application trajectories, enhancing the reliability of the study.

Figure 1 Knowledge domains and scientific research projects of CMS [Figure 1: see original paper]

3.1.2 Data Sources and Processing

Existing compilation work on documentary resources of meritorious scientists provides reliable and unique qualitative data for this study. Specifically:

(1) Data reliability. Through systematic investigation, biographical books on meritorious scientists were downloaded and purchased from sources including academicians' libraries, scientist museums, academic resource databases, and book websites. Careful selection and comparison identified biographies with integrity, objectivity, and authority. One biography was established for each scientist, totaling 27 biographies sourced from the Old Scientists' Growth Data Collection Project [26] (4 volumes), the Chinese Academy of Engineering Academicians Biography Series (4 volumes), "Two Bombs, One Satellite" Meritorious Scientists Biographies (6 volumes), the Chinese Aerospace Academicians Biography Series (4 volumes), scientist oral histories (1 volume), and other reliable sources (8 volumes).

(2) Data uniqueness. The 27 biographies are primarily memory-based, narrative texts compiled from original materials obtained through interviews, audio recordings, video recordings, oral accounts, and recollections. These biographies comprehensively and meticulously document the scientists' growth trajectories and knowledge contributions, effectively compensating for the inability to conduct in-depth interviews. Unlike typical interview data that tends to be brief, these biographies are rich in content. Among the 27 biographies, the longest contains 580,000 words and the shortest approximately 6,400 words, totaling over 6 million words with an average of 223,000 words per biography.

(3) Data processing methods. In addition to full-text electronic materials, data processing followed the sequence of initial reading, intensive reading, comparative reading, and procedural coding. Biographies generally employ sequential narrative techniques, which facilitates reading and coding, somewhat reduces challenges posed by the large volume of text, and helps discover unified patterns underlying the texts.

3.2 Research Methods

This study aims to construct KEoCMS, a new theoretical framework that reveals the complex backgrounds and dynamic mechanisms underlying scientists' behaviors of absorbing, creating, applying, and disseminating knowledge [27], making it suitable to employ the power of grounded theory, a classic qualitative method. Among different grounded theory schools, the procedural coding approach emphasizes the processual and standardized nature of coding, advocating theory generation through systematic coding steps to ensure rigor and reproducibility in data analysis. This approach is thus better adapted to this study' s context of multiple scientists and large-scale texts [13].

The research procedure involves: organizing and analyzing textual materials describing scientists' knowledge life courses, and using three-level coding to construct the KEoCMS theoretical framework from the bottom up. Based on this framework, an inductive approach is adopted to explain the stages and connotations of knowledge evolution within the theoretical framework, and theoretical analysis is used to discover the characteristics of knowledge evolution and the enhancement of knowledge functions and values accompanying changes in knowledge forms. Statistical reference point counting and visualization methods are used throughout the discussion to concretize theoretical understanding.

3.3.1 Open Coding

Open coding utilizes raw materials for coding, forming initial categories through continuous extraction, comparison, modification, and summarization of codes. First, biographical texts were analyzed sentence by sentence to extract key statements involving scientists' knowledge narratives. Second, statements were analyzed and concepts refined, yielding 77 initial concepts (b1-b77), with coding examples shown in Table 1 . Finally, based on these initial concepts, 19 initial categories (B1-B19, see Table 2) were formed through comparative integration, such as concept b10 in Table 1 being integrated with three other concepts to form the initial category "B2 Knowledge Accumulation."

Table 1 Example of open coding (using Zhou Guangzhao as an example)

Original biographical text paragraph	Knowledge-related statement extraction
"Zhou Guangzhao was born on May 15, 1929, in Changsha, Hunan, into an intellectual family. His father, Zhou Fengjiu, was a former professor at Hunan University and director of the Highway Bureau. ···From an early age, Zhou Guangzhao was influenced by his father and developed a strong interest in revealing the mysteries of nature."	Extract first and last sentences of this paragraph
"In the 1950s, Zhou Guangzhao was mainly engaged in high-energy physics research. ···The partial pseudovector current conservation law in weak interactions he proposed directly promoted the establishment of current algebra theory, ···received international recognition and high praise, with his achievements reaching world-advanced levels at that time···"	Extract first two sentences of this paragraph
"Cultivating young talent is something Zhou Guangzhao has always emphasized and practiced. He befriended young people as equals, using heuristic language to guide them in establishing lofty aspirations, respecting predecessors, working steadfastly, and being proactive···"	B1 Knowledge Acquisition
	B2 Knowledge Accumulation

Table 2 Open coding results (initial categories and connotations)

Initial concept number	Connotation
b1-b9	Through exploration, learning, and exchange, acquiring new knowledge from various channels (family learning, universities, international sources) [15].
b10-b13	Through continuous learning and practice, integrating knowledge to form systematic knowledge structures and reserves [9].
B3 Interdisciplinary fusion	Engaging in learning across different disciplines to lay foundations for exploring interdisciplinary fields or solving complex problems.
B4 Research achievements	Innovative theoretical achievements (papers, monographs, etc.) [17].
B5 Scientific and technological innovation	Creating new things, proposing new methods, and inventing new technologies.
B6 Scientific exploration	Systematic, creative activities to reveal natural laws or solve difficult problems.
B7 Knowledge foresight	The ability to grasp scientific frontiers and predict future technological development trends and innovation directions.
B8 Knowledge application	Applying knowledge to solve practical problems in scientific and technological breakthroughs, promote scientific and technological innovation, and connect theoretical knowledge with practice [6].

Initial concept number	Connotation
B9 Knowledge synergy	Among individuals, teams, or institutions, achieving maximized knowledge energy through resource sharing and collaborative work [18].
B10 Knowledge exchange	Sharing, transmitting, and understanding knowledge through language, text, and other means to enhance scientific breakthrough efficiency.
B11 Knowledge transformation	Transformation of knowledge forms, enhancement of knowledge value, and expansion of application scope.
B12 Knowledge transmission	Transmitting disciplinary knowledge and practical experience to learners through teaching activities.
B13 Talent cultivation	Cultivating talent with specific knowledge, skills, and innovation capabilities through systematic education and training.
B14 Academic pedigree	Transmitting knowledge, methods, and spirit across generations through mentor-student relationships [19].
B15 Discipline construction	Accumulation, updating, and improvement of disciplinary knowledge to form theoretical disciplinary systems.
B16 Knowledge dissemination	Media channels disseminating scientists' deeds and new knowledge, theories, and technological achievements [21-22].

Initial concept number	Connotation
B17 Knowledge recognition	Affirmation and appreciation of scientists' work by the state, society, or professional groups.
B18 International influence	Scientific knowledge generating influence on the international stage.
B19 Knowledge memory	Widespread dissemination and popularization of scientific knowledge across time and space, achieving cross-domain and cross-border knowledge transfer and spillover [2].

3.3.2 Axial Coding

Axial coding builds upon open coding by aggregating thematically similar initial categories into broader categories. For example, knowledge acquisition, knowledge accumulation, and interdisciplinary fusion all describe how scientists absorb knowledge, which is summarized as the main category "Knowledge Absorption." Following this logic, five main categories T1-T5 were ultimately formed: Knowledge Absorption, Knowledge Creation, Knowledge Application, Knowledge Inheritance, and Knowledge Penetration. These five main categories represent five stages of knowledge evolution, with their connotations shown in Table 3 .

Table 3 Axial coding results (Main categories and connotations)

Main category	Connotation
T1 Knowledge Absorption (B1-B3)	The process of systematically learning and mastering professional knowledge through family education, university studies, and overseas study.
T2 Knowledge Creation (B4-B7)	Exploring scientific frontiers, proposing new theories, inventing new technologies or methods, and solving major scientific problems.

Main category	Connotation
T3 Knowledge Application (B8-B11)	Applying lifelong learning to the research and development of key national technologies and cutting-edge technologies, as well as closely related organizational coordination and exchange work.
T4 Knowledge Inheritance (B12-B15)	Transmitting knowledge, experience, and spirit to the next generation through teaching, training, and guiding young scientific researchers.
T5 Knowledge Penetration (B16-B19)	The process of knowledge diffusing to and influencing broader society.

3.3.3 Selective Coding

First, through repeated reflection on the connotations of the main categories and their interrelationships, the core category that can coordinate the five main categories was identified as: Knowledge Evolution of Chinese Meritorious Scientists (KEoCMS). KEoCMS aligns with meritorious scientists' life courses as physical beings while highlighting "knowledge" as the core element flowing through scientists' life courses. Second, from the perspective of knowledge flow scope [28], the five categories were divided into three levels: individual scientists, academic communities, and the state and society. Knowledge Absorption represents knowledge inflow toward individual scientists; Knowledge Creation and Knowledge Inheritance represent outflow of scientists'knowledge to the academic community level; and Knowledge Application and Knowledge Penetration represent the transfer of scientists' knowledge to the state and society level. Finally, by sorting out and excavating the temporal and causal relationships among the five categories and placing them within intergenerational flow, a new substantive theoretical framework was developed, as shown in Figure 2 [Figure 2: see original paper].

Figure 2 The overall framework of KEoCMS theory [Figure 2: see original paper]

3.3.4 Theoretical Saturation Testing

Theoretical saturation is generally considered achieved when raw materials can no longer provide new categories and relationships, verified through three or more additional documents. If no new categories or relationships are discovered, theoretical saturation is indicated. This study used four reserved texts to verify theoretical saturation. Following the same grounded analysis procedure, 71 concepts and 19 initial categories were obtained, which matched existing concepts and categories, with the five main categories stably reproduced. Based on this, the theoretical framework and category system were determined to have reached saturation.

Furthermore, 4,262 reference points marked during the coding process of biographical texts were counted and visualized to present the distribution of scientists' knowledge stages (as shown in Figure 3 [Figure 3: see original paper]), further verifying the reliability of the theory. In Figure 3, the vertical axis represents the absolute number of reference points, the bar length is determined by biography text length and reference point quantity, the horizontal axis lists scientists sorted in reverse chronological order by birth year, and knowledge stages are marked with different colors.

Figure 3 Visualization of knowledge evolution stages of 27 CMS [Figure 3: see original paper]

Analysis of Figure 3 reveals: (1) Commonalities: Although the 27 scientists grew up in different micro-environments, engaged in different professional fields and scientific breakthrough projects, and the biographies documenting their life courses were not uniformly produced, their knowledge evolution encompasses all five knowledge stages. On average, knowledge absorption accounts for 18.6%, knowledge creation 20.7%, knowledge application 39.8%, knowledge inheritance 10.2%, and knowledge penetration 10.7%. This result confirms the reasonableness of the constructed KEoCMS theoretical framework and reflects the universal characteristics of meritorious scientists at the level of knowledge evolution. (2) Differences: Relatively speaking, knowledge application has the largest average proportion because biographical texts focus on recording scientists' work in developing key national technologies, which also reflects meritorious scientists' contributions to national scientific and technological construction. At the individual level, different scientists emphasize different stages, such as Tu Youyou and Yuan Longping, whose personal proportions in knowledge creation are most prominent at 34.5% and 29.6%, respectively, consistent with their impressions of scientific exploration in artemisinin discovery and hybrid rice cultivation. These distribution differences reflect the richness of characteristics within the meritorious scientist group.

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4 Analysis of Connotations, Characteristics, and Forms of CMS' s Knowledge Evolution

Building upon the theoretical framework construction (the "logical skeleton"), this section provides in-depth explanations of the five main categories (i.e., knowledge evolution stages) to achieve "content filling" of the theory.

4.1 Stages and Connotations of Knowledge Evolution

(1) Knowledge Absorption

Knowledge absorption comprises three aspects: Knowledge acquisition emphasizes broad pathways for obtaining new knowledge. Meritorious scientists often possess strong family educational foundations, receive excellent primary and higher education, and mostly studied abroad under master teachers in their fields [1]. Knowledge accumulation emphasizes the effectiveness of knowledge absorption. Meritorious scientists are generally diligent and skilled learners with strong autonomous and continuous learning motivation, thereby achieving solid and broad knowledge reserves. Interdisciplinary fusion highlights the importance of multi-disciplinary knowledge absorption in providing knowledge foundations and scientific thinking modes for later solving complex scientific and technological problems. For example, during his studies abroad, Hsue-Shen Tsien "attended Theodore von Kármán' s lectures on aerodynamics, ···went to the physics department to understand frontier physics knowledge, ···often listened to Linus Pauling (Nobel laureate in Chemistry) lecture on structural chemistry, and also attended Thomas Morgan' s genetics lectures in the biology department."

(2) Knowledge Creation

Building upon knowledge absorption, scientists are passionate about creating new knowledge. The knowledge creation of meritorious scientists is multidimensional, encompassing four aspects: Research achievements represent explicit knowledge forms for communicating with academic peers, presented as papers, monographs, reports, etc. For instance, Cheng Kaijia published multiple papers in *Nature*, one of which "elucidated our superconductivity theory and pointed out errors in Heisenberg' s theory." Scientific and technological innovation includes proposing new theories, methods, and major improvements to key technologies. Many such innovations are not published as academic works but are integrated into the research and development of key national technologies. For example, in developing "Dongfeng-2," Ren Xinmin "changed the control system from a radio-inertial hybrid guidance system to a full-inertial guidance system, greatly improving the missile' s operational performance." Scientific exploration emphasizes scientists' enthusiasm for exploring nature and challenging difficult problems. For example, at Cornell University, Guo Yonghuai "focused his main efforts on viscous fluid mechanics, ···viscous flow being the most difficult part of modern fluid mechanics." Knowledge foresight reflects meritorious scientists' profound insights into future scientific and technological development directions [6]. For example, "Yang Jiachi, with keen vision, examined new trends in international scientific and technological development and contemplated strategic directions for China' s scientific development. He proposed a series of new ideas for aerospace technology development."

(3) Knowledge Application

This includes four aspects: Knowledge application involves scientists' comprehensive work in professional policy guidance, technical route planning, front-line research investment, and organizational management leadership throughout the scientific breakthrough process. This tests scientists' professional wisdom and capabilities while also implying great sacrifice. For example, Deng Jiaxian, “though extremely weak at this time, ···had to go because this was a principle-based new nuclear test ···the state had major expectations for nuclear testing.” Knowledge synergy refers to organizing and coordinating various resources to form joint efforts for scientific breakthroughs, maximizing knowledge energy [29]. For example, “In the early stages of atomic bomb development, Wang Ganchang was responsible for physical experiments, Peng Huanwu for theoretical design, and Guo Yonghuai for technical leadership in mechanics.” Knowledge exchange refers to 系列活动 such as academic discussions, technical demonstrations, and international investigations conducted for breakthrough purposes. Full exchange and promotion of academic democracy are particularly important in cutting-edge scientific breakthroughs. For example, “Yu Min felt one of his main responsibilities was to master correct technical approaches. To achieve this, he needed to allow everyone’ s opinions to be expressed, mutually inspire each other, pool collective wisdom, and then make decisions.” Knowledge transformation emphasizes the practical application of breakthrough results. Knowledge value is fully realized in increasing social and human welfare. For example, artemisinin developed under Tu Youyou’ s leadership “has already saved millions of lives, ···with approximately 240 million people in sub-Saharan Africa benefiting from artemisinin combination therapy.”

(4) Knowledge Inheritance

This involves four aspects: Knowledge transmission refers to systematic teaching work. For example, “During his time at Peking University, Zhu Guangya devoted great enthusiasm to frontline teaching, simultaneously lecturing on optics and general physics courses.” They not only transmit textbook knowledge but also excel at influencing and shaping students’ abilities and spirits to love knowledge and dare to innovate. Talent cultivation includes building talent teams and caring for, promoting, and motivating young talent growth. Academic pedigree refers to scientists cultivating master’ s and doctoral students [19]. For example, Wu Ziliang “strictly required graduate students’ theses, carefully reviewing and revising them sentence by sentence,” and “batches of graduated students have taken up positions in research and teaching frontlines, taking over the heavy responsibility of revitalizing the nation through science and education from the older generation.” Discipline construction refers to systematizing and theorizing disciplinary knowledge to assist future learners and even create new disciplines. For example, Wang Xiji “devoted great effort to writing *Engineering Design* and *Satellite Design*, hoping to chart a path from decades of design practice to help future generations avoid detours.”

(5) Knowledge Penetration

The knowledge of meritorious scientists is not only inherited by the next generation but also penetrates into broader social environments, mainly through four methods: Knowledge dissemination refers to spreading scientists’ deeds through various media forms. For example, after the systematic reportage literary work *A Glorious Yet Unknown Life* documenting Huang Xuhua’ s life and deeds was published, Huang Xuhua' s story with China' s nuclear submarines gradually became widely known. Knowledge recognition highlights incentives from the state and society for scientists' work. For example, the awarding of the "Two Bombs, One Satellite" Medal and the "Republic Medal" greatly promotes public awareness of scientists. International influence involves scientists actively participating in international activities, promoting global understanding of Chinese science and enhancing the nation' s international discourse power and influence. For example, hybrid rice has been tested and cultivated in over 70 countries and regions, and Yuan Longping often traveled abroad for guidance and exchange, making "hybrid rice a trump card that ⋯greatly improved our international status." Knowledge memory refers to solidifying oral memories of scientists into lasting memories through biography publications, film and television productions, organized commemorative activities, and infrastructure construction [30], condensing scattered knowledge into networks and facilitating scientists' knowledge to transcend temporal, spatial, and cultural limitations.

4.2 Nonlinear Characteristics of Knowledge Evolution

Building upon the explanation of knowledge stage contents, this section analyzes the nonlinear characteristics of each knowledge stage' s evolution in KEoCMS theory.

(1) Temporal Overlap

As time passes, scientists absorb knowledge in their early years; after accumulation, they create new knowledge; subsequently, they devote themselves to national scientific and technological construction, which constitutes knowledge application; they cultivate scientific and technological talent through multiple methods; and due to the absolute confidentiality of their work, their deeds are not reported until their later years, when knowledge penetrates society. This forms the sequential order marked by "→" in the overall framework Figure 2. Unlike the linear process of natural life cycles experiencing gestation, growth, maturity, and decline [10], the sequential order among stages in meritorious scientists' knowledge evolution is relative and cross-cutting, representing a nonlinear state. For example, when encountering difficulties during the knowledge application stage, scientists may re-absorb new knowledge and create new theories, methods, and technologies; the knowledge application stage may also involve talent cultivation to achieve continuous construction of national scientific and technological strength. As shown in Figure 4 Figure 4: see original paper, the inward direction of the circle indicates enhancement of knowledge value, with knowledge stages exhibiting spiral evolution characteristics oriented toward value goals.

(2) Causal Linkage

Knowledge stages possess richly connotative causal relationships. Knowledge absorption lays the foundation for knowledge creation; the value of knowledge creation manifests in knowledge application, while conversely, the belief in using knowledge to build the nation also drives scientists to create new knowledge under extremely difficult material conditions; the transition from knowledge application to knowledge inheritance transmits not only knowledge but also the spirit of scientists, continuing the Republic' s excellent scientific and technological genes; knowledge inheritance influences professionals, while knowledge penetration reaches the general public, shaping and cultivating the next generation of scientific talent and soil (Figure 2).

(3) Intergenerational Flow

The knowledge life courses and scientific and technological ecological environments of the previous generation of scientists influence the growth of meritorious scientists, shaping their knowledge structures, subjective beliefs, and behavioral choices [17]. Simultaneously, the knowledge, thoughts, and behavioral qualities of meritorious scientists also shape the nation' s new scientific and technological ecological environment, thereby influencing the next generation of scientists [2]. Therefore, the constructed theoretical framework possesses dynamic and open characteristics. Dynamism manifests in the intergenerational flow of knowledge, spirally driving scientific and technological development and social progress; openness manifests in knowledge flow not being a closed system but rather a system that fully interacts and exchanges with domestic and international scientific communities and societies across history and the present (Figure 4(b)).

Figure 4 (a) Nonlinear pattern of knowledge evolution of CMS; (b) Intergenerational flow of CMS' s knowledge promoting social progress [Figure 4: see original paper]

4.3 Knowledge Forms, Functions, and Value Enhancement

Building upon the characteristic analysis, this section further explores the connotation of "knowledge" in the theory. Existing research has extensively discussed the forms, functions, and values manifested in knowledge evolution at the enterprise or organizational level [25,31]. Drawing upon these research findings, this paper analyzes the forms, functions, and value connotations of knowledge during scientists' knowledge evolution at the individual level, summarized in Figure 5. Specifically, Figure 5 presents the following connotations:

(1) Transformation of Knowledge Forms

In the knowledge absorption stage, scientists acquire foundational knowledge that is transferable, acceptable, and learnable; knowledge creation generates principle knowledge that is presentable, shareable, and exchangeable; knowledge application employs technical knowledge that is applicable, repeatable, and transformable for cutting-edge scientific research and development; accumulated comprehensive knowledge that is transferable, acceptable, and learnable is inherited by the next generation; and knowledge penetrates society to form cultural knowledge that is disseminable, shapeable, and multipliable. Drawing upon Nonaka' s SECI model [31], scientists' knowledge absorption is a socialized learning process; knowledge creation represents externalization of knowledge to the academic community; knowledge application involves complex combinations of knowledge from different fields; through professional talent cultivation, knowledge is internalized in new-generation scientists; and ultimately, deep socialization forms cultural memory. Knowledge forms across all stages can be summarized as explicit principle knowledge and implicit experiential knowledge [32]. Explicit knowledge possesses carrier properties, reusability, and transferability, such as theories, methods, and technological achievements created by scientists. Implicit knowledge is difficult to document, possessing experiential and vivid qualities, such as the spirit of scientists and experiences in scientific research.

(2) Enhancement of Knowledge Functions and Values

Knowledge functions evolve with transformations in knowledge forms. For example, principle knowledge formed through knowledge creation functions as academic innovation, while technical knowledge in knowledge application focuses on solving complex problems in scientific and technological construction. In summary, knowledge functions sequentially evolve into learning, innovation, application, and cultural functions. Form transformation also affects value connotations. For example, knowledge absorbed in scientists' early stages primarily serves personal knowledge equipment, while technical knowledge formed during career maturity serves national security. In summary, knowledge values sequentially become personal growth, scientific and technological progress, national mission, and cultural symbolism. Functions and values are linked: learning functions correspond to personal growth, innovation functions to scientific and technological progress, application functions serve national missions, and cultural functions form cultural symbols that promote social change. Knowledge functions and values elevate from the individual level to the academic community and further to the national, social, and cultural levels. Knowledge value far exceeds mere knowledge quantity or publication counts.

Figure 5 The forms, functions, and value of knowledge in the process of knowledge evolution [Figure 5: see original paper]

(3) Knowledge Value and the Connotation of "Meritorious Contributions"

Through the above analysis, we find that meritorious scientists' knowledge exerts tremendous value during evolution. "Meritorious contributions," facilitated by knowledge pipelines, exhibit knowledge-based, historical, and lasting characteristics. The knowledge-based nature forms the foundation of "meritorious contributions" ; historicity reveals the weight of "meritorious contributions" ; and lastingness indicates the continuous cultural value of "meritorious contributions." The connotation of "meritorious contributions" lies in achievements made for the nation and people and in shaping the nation's scientific culture and influencing the future. Although scientists who receive "medals" are extremely few, scientists possessing "meritorious" characteristics are numerous. Therefore, for those scientists who silently contribute to the nation, the value created by knowledge becomes the foundation for measuring their achievements. Simultaneously, for contemporary scientific and technological workers participating in building a scientifically powerful nation, the logical connotations of knowledge forms, functions, and values also serve as evaluation criteria for their self-growth and value realization.

4.4 Case Presentation of Knowledge Evolution

To intuitively demonstrate the stages, connotations, characteristics, and knowledge values of meritorious scientists' knowledge evolution, this study uses Hsue-Shen Tsien as an example to map his knowledge evolution narrative, promoting concrete understanding. Figure 6 [Figure 6: see original paper] uses events from Tsien' s life experiences as anchors, linking involved entities and attributes and connecting events through temporal and causal relationships.

Note: Events marked with # in the figure are background events; the rest are Tsien' s personal events.

Figure 6 The semantic process of knowledge evolution of CMS presented with Hsue-Shen Tsien as an example (partial) [Figure 6: see original paper]

Figure 6 schematically presents Tsien' s knowledge evolution process, concretizing the connotations of KEoCMS theory: Aeronautical and aerodynamics knowledge runs through all five knowledge stages, including early career choices, creating internationally influential original theoretical knowledge during his studies in the United States, leading missile development after returning to China, cultivating missile and aerospace scientific talent, and consequently receiving meritorious medals. The belief in "saving the nation through aviation" prompted Tsien to change the direction of his knowledge absorption; knowledge not only flows through his life course but is also transmitted to the next generation of scientists (for example, promoting and cultivating Wang Yongzhi, recipient of the 2024 Republic Medal) and diffused throughout the nation and the world, demonstrating the dynamic and open nature of knowledge flow. The value of "meritorious contributions" is manifested in his creation of new knowledge for humanity and its function in national construction. Even as a fragment, Figure 6 clearly presents the 脉络 and attraction demonstrated by his knowledge evolution. If narrative maps of hundreds or thousands of scientists were constructed and interconnected, in-depth mining research could be conducted supported by this knowledge landscape.

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5 Conclusion

This study focuses on Chinese meritorious scientists, distilling the KEoCMS theoretical framework from over 6 million words of scientists' biographical texts and discussing its connotations, characteristics, and knowledge values. The findings establish theoretical depth for explaining the knowledge-based, historical, and lasting nature behind "meritorious contributions." Like other great scientists worldwide [2], Chinese meritorious scientists and their knowledge attributes possess long-lasting leading value. As Han Zhen stated, "The more a nation or country leads in knowledge production, the more that nation or country walks at the forefront of world history [32]." As representatives who excelled at producing and applying knowledge in early national construction, meritorious scientists' deep relationship with knowledge has been exploratorily and systematically studied in this paper, offering reference significance for understanding Chinese scientists' traditions and patterns of knowledge production and application.

This research also holds much potential value. First, KEoCMS theory inspires new research on Chinese scientists, such as: exploring how older-generation scientists create new knowledge; scientists' behavioral patterns in major national scientific and technological breakthroughs; and commonalities and differences in knowledge connotations between Chinese scientists and other scientists worldwide. Second, the study offers new strategies for formulating current outstanding scientific talent selection and cultivation policies. Against the background of "breaking the five dimensions," emphasis should be placed on the knowledge value created by talent rather than merely the quantity of achievements. Systematic thinking should be employed to design talent growth guidance strategies centered on enhancing knowledge value, aiding breakthroughs in "bottleneck" technologies and building a scientifically powerful nation. Finally, the KEoCMS theoretical framework can serve as top-level metadata for organizing scientists' documentary resources. Combined with big data and artificial intelligence technologies, it can enable new digital and knowledge-based narratives about Chinese scientists, better telling Chinese scientists' stories to academic communities, the public, and the world.

This study has limitations. First, although substantial foundational work was conducted, the sample size remains insufficient. The 27 meritorious scientists covered focus on engineering and technology fields. Future research could expand the scope of scientists to include those who made outstanding contributions in basic scientific research and humanities and social sciences fields. Second, meritorious scientists' life courses possess particularities, and research conclusions may be influenced by era and historical environments. Future studies could add comparative research from multicultural perspectives to explore similarities and differences in scientists' knowledge evolution under different cultural and temporal backgrounds. Finally, based on rigorous qualitative research, combining quantitative methods such as text mining and mathematical models could enhance comprehensiveness and reliability. It is hoped that this exploratory work will stimulate new research landscapes.

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Wang Hao: Adjusted research framework, revised the paper and finalized the manuscript.

Appendix Data Access Address

Due to space limitations, the authors have uploaded the table of initial concepts (b1-b77) obtained through grounded coding and the correspondence table between initial categories and initial concepts to an accessible URL: https://github.com/HuiDeng-growth/KEoCMS-appendix, where readers can openly access them.

Note: Figure translations are in progress. See original paper for figures.