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Model Construction and Empirical Research of China's Science Structure and Science Development

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Abstract
Science structure is defined as the organic structure formed by the long-term development and change of scientific knowledge. In addition to the structure of the global scientific network, each country has its own national science structure. We firstly reviewed representative research on science structure from different fields. Secondly, we constructed a model of science structure at the national level from four dimensions focusing on the research field of scientometrics. Thirdly, empirical research was carried out using more than 40 years of literature data, revealing the development and growth trend of China's science. Finally, the role of China's science in the world science development and its position in global scientific collaboration were observed, and brief suggestions were provided for the development of science in China.

Introduction
With the rapid development of science, the structure of science is constantly evolving. Based on the relevant research of Kuhn(1962), Wei Junchao (2011), Li Jie (2016), Zhang Ruihong and Chen Yunwei (2019) and other scholars, science structure is defined as an organic structure formed by the long-term development and change of scientific knowledge, which is not subject to one's will. It can reflect the logical relationship of science as a whole, and the knowledge structure of a single research field.
How to objectively quantify or study the evolution of science structure, deeply observe and summarize its evolution laws and characteristics, and lay the foundation for the efficient and high-quality development of science has become one of the important topics studied and discussed by many philosophers, information scientists, economists, et al. (Tian Q, Chen Y, Zhang Z, 2024). According to Fortunato S, Bergstrom C, Borner K (2018), science can be described as a complex, self-organizing, and evolving multiscale network. Science is multi-dimensional, requiring the analysis of the scientific performance of individuals, teams and countries from multiple dimensions (Vinkler P, 2010).
From the perspective of scientific networks, there is only one global scientific network. Outside of the global network, each country has its own national science system (Wagner C S, Park H W, Leydesdorff L, 2015). In order to observe the development and evolution of scientific models, we can research from multiple dimensions such as time (e.g., decade, year or month span), space (e.g., global, China, reference country), research field (e.g. subject, discipline, research area), collaborators (e.g., collaboration country, collaboration institution) and so on

(Scharnhorst A, Börner K, Besselaar P, 2012). This paper aims to construct science structure model at the national level, focus on the development and growth trend of China's science (including the development and evolution trend of major fields of science in China), and observe the role of China's science in world science development and its position in global scientific collaboration.

Literature review of science structure

The concept of science structure has been studied by scholars in many fields such as scientific philosophy, scientometrics, and scientific economics, which respectively affirmed the existence of science structures and constructed some models, quantified global science structure and discipline layout in a country, and expanded the research content of science structure to focus on scientific efficiency.

Science structure research from philosophy of science

One of the basic tasks of philosophy of science is to comprehensively reveal the structure, functional transformation and scientific development laws of the entire human science (especially the modern scientific system) (Liu B, Deng P, 1989). After researchers affirmed the existence of science structures (Shen X, Liu S, Zhao H, 1981), they continued to construct the model/levels of science structure.
Leydesdorff (2001) proposed a multi-dimensional scheme to describe "world of science"(Figure 1).

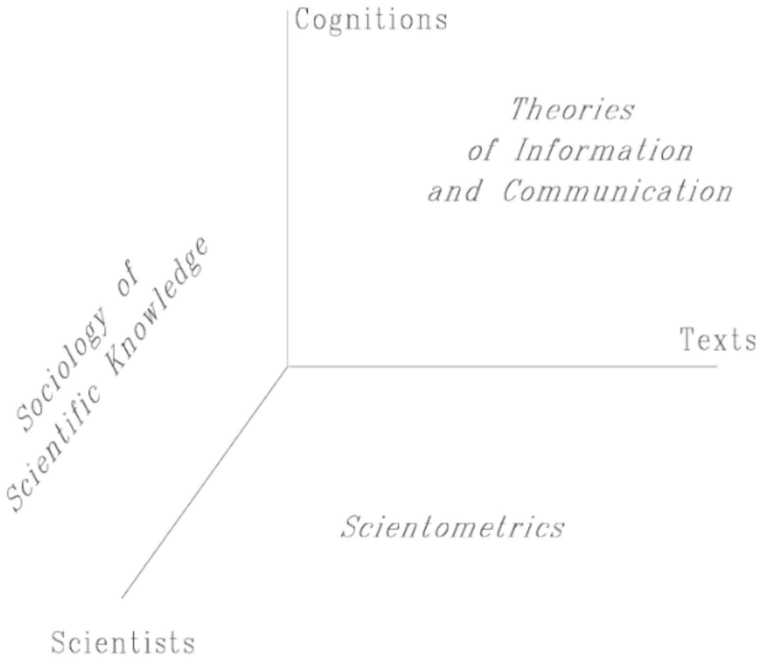

Figure 1. Study of the science as a multidimensional problem.

Thomas R. Blackburn (1973) described science structure as 3 levels, including level of material structure (scientific institutes, material conditions for scientific work, etc.), level of social structure (scientists, social networks) and level of intellectual structure (scientific knowledge, scientific research).

Science structure research from scientometrics

In the field of scientometrics, researchers investigated ways (Table 1) to quantify global science structure and discipline layout in a country, to reveal global collaboration network and its evolution, to analyze knowledge units such as keywords and themes.

Table 1. Science structure representative research from scientometrics.

Representative researchers (Publishing Year)	*Research aims*	*Years under investigation*	*Main contents or conclusions*
Zhao Hongzhou (1990)	to quantify global science structure and discipline layout in a country	1981-1985	USA, West Europe, Japan etc., their structures of subject become “Polarized” ones, focusing life science; In other, USSR, East Europe, etc. has a “tripartite” science structure, basing on biology, physics and chemistry.
GLÄNZEL (2008)		1991-2005	China joined the triad formed by the USA, EU and Japan, and has transformed the triad into a tetrad.
LI Ning (2019)		1996-2015	China differs significantly from the world’s major nations in their research output distributions. China has constantly been comparatively strong in all major fields of physical sciences but weak in areas of life, health, and social sciences.
LIU Yun (2001)	to reveal global collaboration network and its evolution	1994-1998	Systemically measured and evaluated the situation of international collaborating of Chinese basic research from six aspects.
ZHOU Ping (2010)		1997-2007	The authors analyze the dynamics and the national characteristics of China’s co-operation in a global context.

LIU Chengliang (2017)		2014	They also study research profile and citation impact of international collaboration with respect to the corresponding domestic ‘standards’. International scientific collaboration network presents a core-periphery structure with hierarchies, which is composed of 13 core countries and the periphery of 198 countries.
Jyoti Dua (2023)		2000-2020	USA, Germany, England, and China remain the top collaborating partners of India in terms of volume of papers, however, the relative intensity of collaboration with South Korea and Saudi Arabia has increased significantly.
GE Fei (2012)	to analyze knowledge units such as keywords and themes	---	Several principal research methods of science structure and evolution are introduced, including the method of citation analysis, the method of content words analysis and the method of bibliometric combining with content words analysis. The authors suggest that the hybrid method can be applied in researching science structure and evolution and detecting the emerging trends.
LU Wanhui (2019)		---	This paper discussed the application and challenges of knowledge network mining technology in the fields of knowledge organization and management, the construction of scientific knowledge map and the monitoring of discipline development situation by combing the related research of knowledge network concept and type, characteristics and performance, evolutionary

WANG Xiaomei (2024)	2016-2021	analysis methods and indicators. The highly cited papers and 12,620 research frontiers were extracted, and 1,389 research areas were obtained through co-cited cluster analysis, forming a global perspective of science structure map, visually showing the macro structure of scientific research and its internal relationships.

Science structure research from scientific economics

Chinese scholar Gu Xingrong (2006) innovatively proposed that the fundamental task of science and technology was to use scientific and technological progress to offset the marginal rate of diminishing returns in economics. On the basis of the input-output relationship in the economic field, he proposed the structure of "three stations and two transformations" of scientific and technological input-output shown in Figure 2.

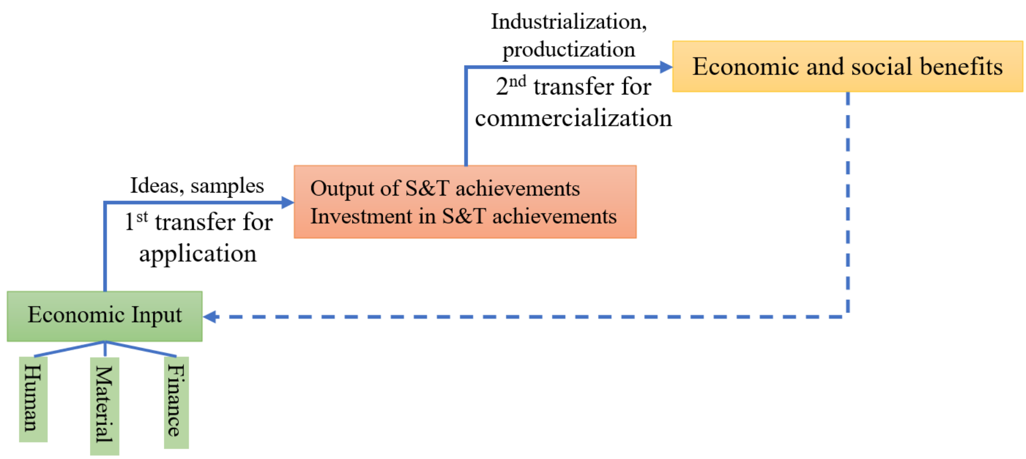

Figure 2. Structure of "three stations and two transformations" of scientific and technological input-output.

May R M (1997) proposed that comparison of scientific output relative to government money spent on research and development (R&D) might be the best measure of the cost effectiveness of spending in support of basic and strategic research. He came to the conclusion of countries' scientific productivity rank descending as: Great Britain, Switzerland, Denmark, Sweden, France, Italy and Germany.

Model construction of China's science structure and its development

Research papers and related changes can reflect how science is organized at an aggregated level (Yang T, 1984). Based on the qualitative and quantitative research of information scientists and scientometrics researchers on the scientific structure and national science, we focused on the research field of scientometrics and constructed a model of the development and evolution of China's science structure in 4 dimensions, including science productivity, science impact, science equilibrium, and science collaboration. The specific dimensions and indicators are listed in Table 2. In terms of time scale, it includes not only long-term annually data and summary data for 42 years from 1980 to 2021, but also evolutionary data for 4 consecutive decades (1980-1989, 1990-1999, 2000-2009, and 2010-2019). At the spatial scale, in addition to focusing on China, it also includes global or USA data for reasonable comparison, which not only reveals the development and internal logic of China's own science structure, but also better presents China's position in the global scientific network.

Table 2. The 4 dimensional model for development and evolution of China's science structure.

Dimensions	*Indicators*	*Time Scale*
Productivity of China's science	Number of international papers per year, Global share (%), annual growth rate (%)	42 years (annually)
Impact of China's science	Number of citations per paper, Number of top 1% cited papers, Global share (%); (and compared with the corresponding data in the USA) Category Normalized Citation Impact, CNCI; (and compared with the corresponding data in the USA)	42 years (annually)
Equilibrium of China's science	Number of international papers in each field of science, Global share (%), Revealed Comparative Advantage, RCA across major fields of science; CNCI each field of science (and decade evolution); Weight and polarization degree of each field of science (and decade evolution)	42 years (annually) 4 decades
Collaboration of China's science	Number of international collaborative papers, Share of China's total paper (%), Global share (%); Top 10 collaboration countries (and decade evolution); Collaboration networks and evolution (and compared with the corresponding data in the USA)	42 years (annually) 4 decades

Data source and method

Data was downloaded from the InCites platform of Clarivate Analytics Web of Science (WOS) database, including the annual number of papers (limited to article and review) from 1980 to 2021 in China (not including data from Hong Kong, Macao and Taiwan) and the world, the number of papers in 22 fields of science according to the Essential Science Indicators (ESI) categories, and the number of citations. In addition to the aggregate analysis from 1980 to 2021, the comparative analysis of data from 4 consecutive decades (1980 to 1989, 1990 to 1999, 2000 to 2009, and 2010 to 2019) was also carried out. In order to analyze China's position and its evolution in the global science collaboration network, the Science Citation Index (SCI) and Social Science Citation Index (SSCI) in the WOS core database (excluding data from Hong Kong, Macao and Taiwan) were used to retrieve the data of international scientific research collaboration. Full counting method was adopted, which was the main choice in most national bibliometric studies (Chen L, Yang L, Ding J, 2018; Braun, T, Glänzel, W, & Schubert, A, 2005; Leydesdorff L, 1988).

Empirical research of China's science structure and its development

Research dimension in productivity of China's science

Figure 3 plots the number of China's annual papers from WOS, 1980 to 2021, and the ratio of China's papers to the global total. The absolute quantity of China's scientific papers and relative ratio in global total papers have been increasing. In the past 40 years, the number of China's WOS papers has increased exponentially, which can be shown by the Exponential Trendline in figure 3.

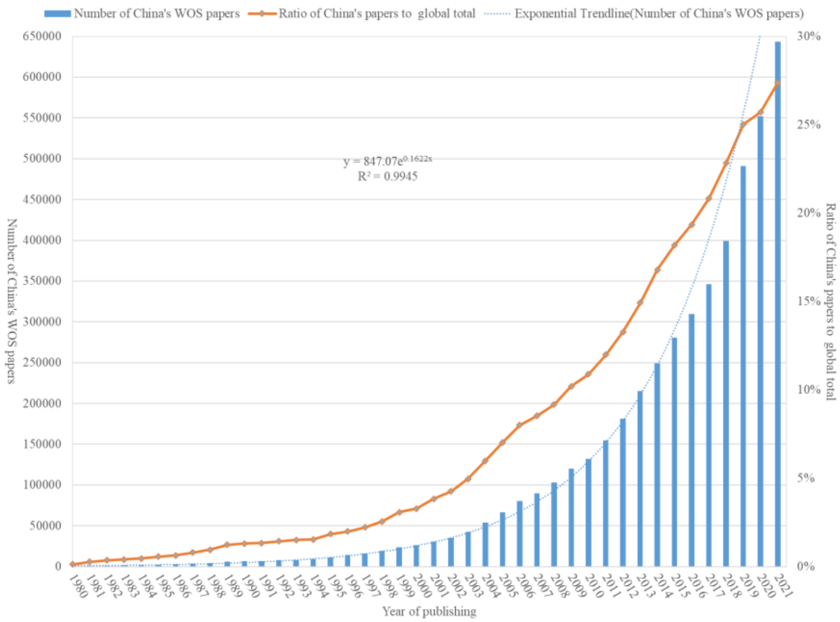

Figure 3. Time series trend of number of China's paper in WOS (1980 to 2021).

In the 21st century, the number of China's WOS papers has increased rapidly year by year, and the corresponding ratio of the global total has also increased rapidly. In 2008, the number of China's WOS papers exceeded 100,000, accounting for 9.16% of the world's total. In 2013, it exceeded 200,000 articles, accounting for 14.92% of the world's total; in 2016, it exceeded 300,000 articles, accounting for 19.35% of the world's total; nearly 400,000 in 2018; nearly 500,000 in 2019; in 2021, it exceeded 640,000 articles, accounting for 27.38% of the world's total. According to Mitutomo Y (1963) (a professor and a historian of science in Japan), who defined "center of scientific activity": a country whose scientific achievements account for more than 25% of the world's total, China can be regarded as one of the "world's scientific center of WOS papers" since 2019.

Research dimension in impact of China's science

In order to analyze the quality level and influence of scientific papers in China, this part observes and discusses the average citation frequency of papers, the ratio of the top 1% cited papers to the corresponding global value, and the Category Normalized Citation Impact (CNCI) from InCites platform.

(1) Citations per paper and top 1% cited papers

As shown in Figure 4, as the proportion of China's WOS papers to the world's total has increased year by year, the proportion of China's WOS papers citations to the world's total has also increased yearly, but the latter has been lower than the former from 1980 to 2013. In 2019, the proportion of China's WOS papers citations exceeded the corresponding value of the USA. From the perspective of the proportion of the top 1% cited papers to the world, the proportion of China's top 1% of cited papers to the world has been significantly lower than that of the USA for a long time. The proportion of China's top 1% cited papers has exceeded 20% since 2015, while the corresponding percentage of the USA has fallen below 50%. The gap has narrowed significantly, until 2020, the proportion of China's top 1% cited papers to the world has exceeded the corresponding proportion of the USA.

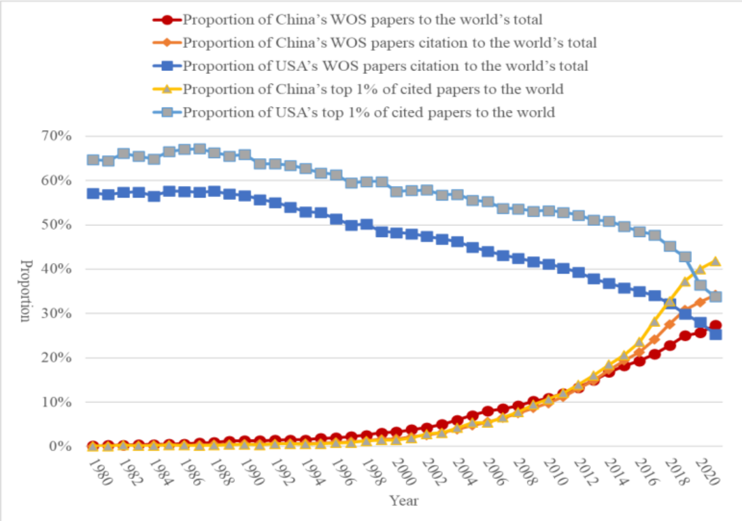

Figure 4. The proportion of China's and USA's top 1% cited papers to the world.

(2) CNCI and annual comparison between China and USA

The Category Normalized Citation Impact (CNCI) (He C, Li W, 2022; Incites, 2025) of a document is calculated by dividing the actual count of citing items by the expected citation rate for documents with the same document type, year of publication and subject area. When a document is assigned to more than one subject area an average of the ratios of the actual to expected citations is used. The CNCI of a set of documents, for example the collected works of an individual, institution or country/region, is the average of the CNCI values for all the documents in the set. CNCI solves the problem of incomparability between different countries, years and fields of science. The world average is 1, and if the CNCI value is greater than 1, it means that the influence of the paper exceeds the world average.

For a single paper that is only assigned to one subject area, this can be represented as:

$$CNCI = \frac{c}{e_{ftd}}$$

For a group of papers, the CNCI value is the average of the values for each of the papers:

$$CNCI_i = \frac{\sum_i CNCI_{each\ paper}}{p_i}$$

Equation Key:
e: Expected citation rate or baseline;
c: Times cited;
p: Number of papers;
f: The field or subject area;
t: Year;
d: Document Type;
i: Entity being evaluated (institution, country/region, person, etc.)

From the perspective of the ratio of the top 1% cited papers to domestic papers in Figure 5, the percentage of China (circular markers) is continually lower than that of the USA (diamond markers). From the perspective of the influence of CNCI, this value in China (dotted column) was also lower than that of the USA (solid column), until 2020 it slightly exceeded but fell back in 2021. Judging from the trend of China's CNCI, the value continued to grow, surpassing the world average for the 1st time in 2012 at 1.021.

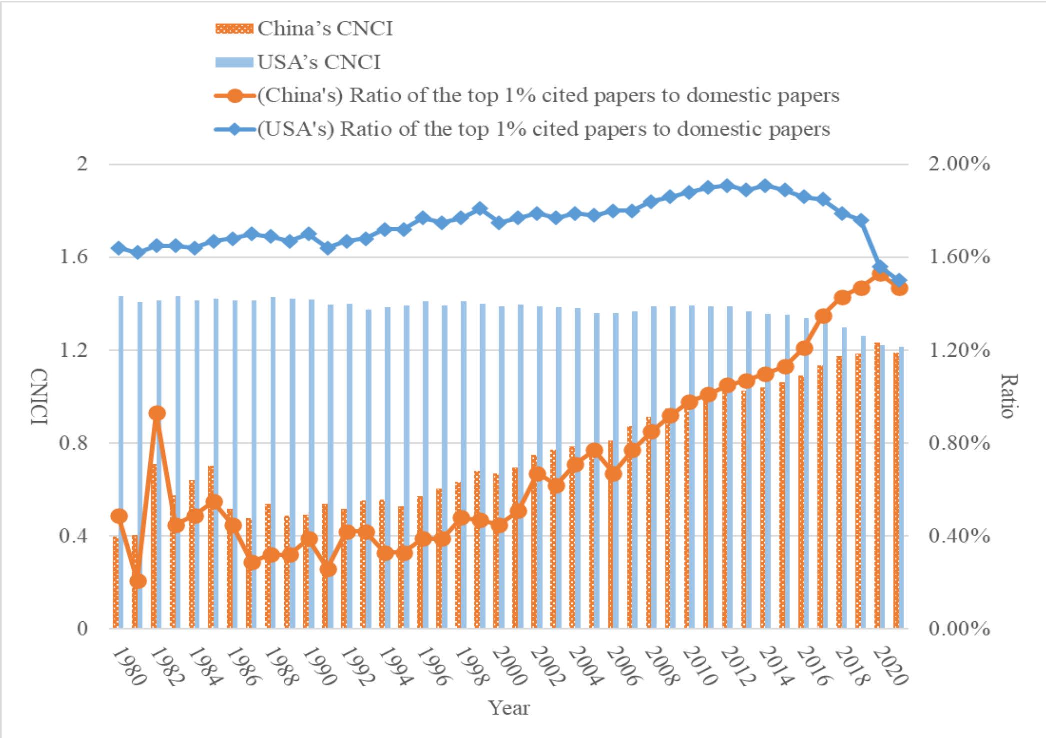

Figure 5. CNCI in China, USA and percentage of TOP 1% Citations in each country.

Research dimension in equilibrium of China's science

(1) The absolute value and Revealed Comparative Advantage of China's percentage of various fields of science

According to the absolute value of the percentage of China's each field of science from 1980 to 2021, the top five dominant fields of science in China are: chemistry, engineering, materials sciences, clinical medicine and physics. The percentages of these fields of science to the total number of China's papers are 17.561%, 13.694%, 11.610%, 10.199% and 9.608%, respectively. The corresponding percentages of other fields of science are less than 5%.

According to the difference between the percentage of China's each field of science and corresponding value of the world's from 1980 to 2021, China has 9 fields of science with a numerical advantage relative to the world (on the left side of the dotted line in Figure 6), and the top 5 fields of science are: materials sciences, chemistry, engineering, physics and computer science, which are 6.346%, 5.927%, 5.245%, 1.624% and 1.179%, higher than the corresponding global percentage, respectively. Although clinical medicine ranks the 4th in China in terms of absolute percentage, it ranks last in terms of percentage difference with the world, 8% lower than the corresponding global percentage.

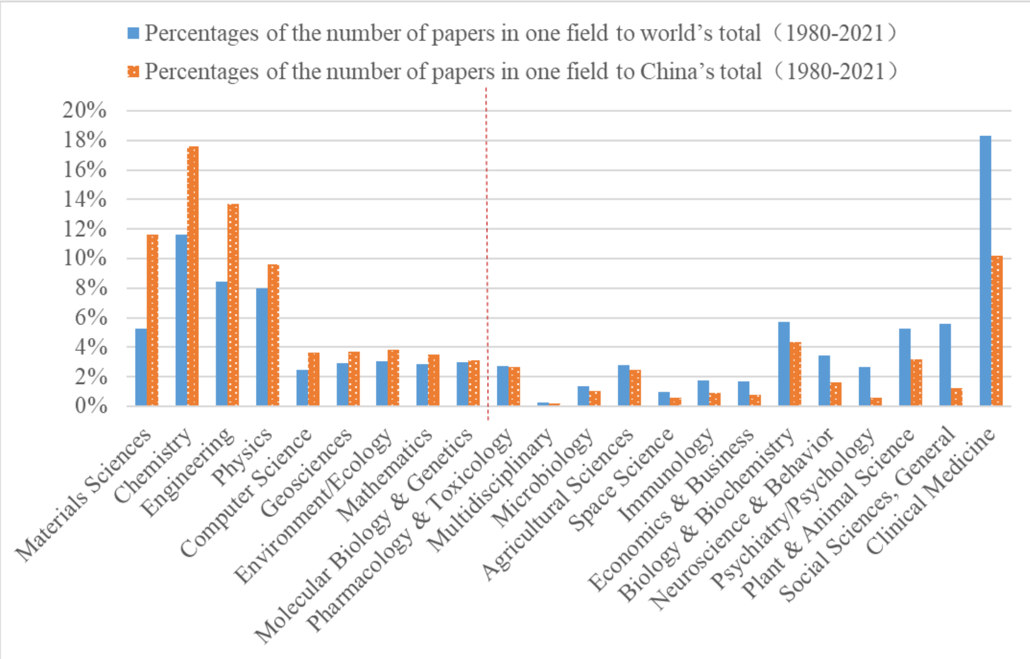

Figure 6. Comparative chart of China's and the world's field of science percentages (in descending order by the difference) (1980 to 2021).

Compared with the development of various fields of science in the world, what is the competitive advantage of China's each field of science? The Revealed Comparative Advantage (RCA) of China's each field of science compared with the world can be calculated as: RCA = the percentage of a certain field to China's total / the percentage of a certain field of science to the world's total. If the RCA value is greater than 1, this field in China has a significant comparative advantage to the world.

According to table 3, shown in descending order of RCA of China's various fields of science from 1980 to 2021, there are 9 fields with RCA values greater than 1 (background filled), namely: materials sciences, engineering, chemistry, computer science, geosciences, environment/ecology, mathematics, physics, and molecular biology & genetics.

According to the RCA values (**in Bold**) of the 4 consecutive decades, there are a total of 6 China's fields (with underline) that show the comparative advantage of numerical explicitness of papers, namely: materials sciences, engineering, chemistry, geosciences, mathematics and physics.

Table 3. RCA value and evolutionary dynamics of China's various fields of science.

Fields of science & RCA	*1980-2021*	*1980-1989*	*1990-1999*	*2000-2009*	*2010-2019*
Materials Sciences	**2.21**	1.51	2.47	2.53	1.86
Engineering	**1.62**	1.53	1.32	1.22	1.46
Chemistry	**1.51**	1.52	2.22	2.05	1.49
Computer Science	**1.48**	1.00	0.67	1.09	1.42
Geosciences	**1.26**	1.40	1.03	1.19	1.21
Environment/Ecology	**1.24**	0.55	0.53	0.85	1.05
Mathematics	**1.23**	2.92	2.63	1.73	1.15
Physics	**1.20**	2.80	2.14	1.67	1.30
Molecular Biology & Genetics	**1.05**	0.28	0.24	0.53	1.14
Pharmacology & Toxicology	**0.98**	1.34	0.77	0.79	1.01
Agricultural Sciences	**0.87**	0.34	0.35	0.59	0.84
Biology & Biochemistry	**0.77**	0.25	0.50	0.69	0.96
Microbiology	**0.75**	0.34	0.27	0.56	0.80
Multidisciplinary	**0.66**	1.89	5.88	0.68	0.82
Plant & Animal Science	**0.61**	0.36	0.46	0.61	0.67
Space Science	**0.61**	1.48	0.96	0.87	0.65
Clinical Medicine	**0.56**	0.61	0.29	0.32	0.60
Immunology	**0.52**	0.23	0.15	0.35	0.56
Neuroscience & Behavior	**0.48**	0.27	0.23	0.33	0.54
Economics & Business	**0.44**	0.21	0.17	0.19	0.41
Psychiatry/Psychology	**0.22**	0.10	0.11	0.09	0.20
Social Sciences, General	**0.22**	0.39	0.21	0.13	0.19

(2) Decade evolution of CNCI in China's various fields of science

From the perspective of longitudinal temporal evolution (Figure 7), from the 80s of the 20th century (triangle markers) to the 20s of the 21st century (diamond markers), the number of CNCI higher than 1 in China's various fields of science increased from 2 fields to 14 fields.

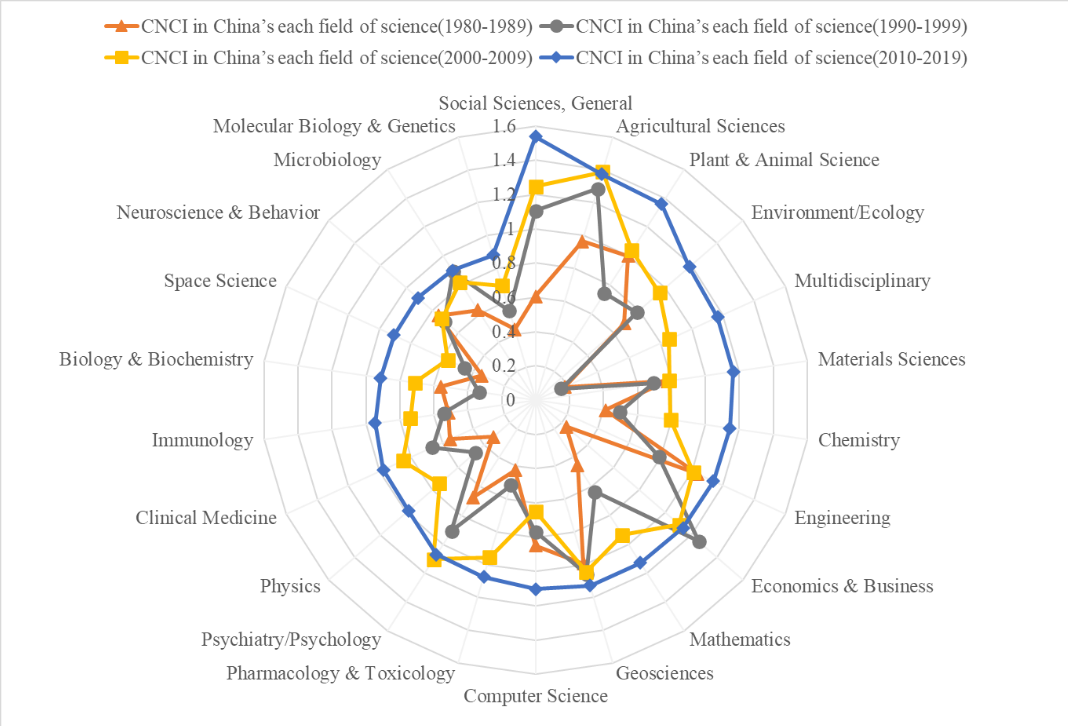

Figure 7. Dynamic of CNCI value evolution in China's various fields.

(3) Decade evolution of China's field weights and polarization degree

Zhao H (1990) defined indicators such as "field weight" and "field polarization degree" to measure the status and influence of a particular field in the overall science structure of a country. **The weight p** of a field in China and **the degree** α of polarization of the structure of a field in China can be calculated by the following two formulas.

$$p=\sqrt{a^2+b^2}$$

Note: a is the weight of China's each field compared to the global, and b is the weight of China's each field compared to China's all fields.

$$\alpha=1-\frac{p_{min}}{p_{max}}$$

Table 4 below lists the weights of China's 22 fields in multiple periods, the and the top three belong to materials science, chemistry and engineering.

Table 4. China's field weights in various periods.

Fields and their weights	*Various periods*				
	1980-2021	*1980-1989*	*1990-1999*	*2000-2009*	*2010-2019*
Materials Sciences	**0.308**	0.038	0.107	0.225	0.379
Chemistry	**0.263**	0.168	0.259	0.301	0.338
Engineering	**0.251**	0.094	0.099	0.128	0.314
Computer Science	**0.196**	0.017	0.019	0.086	0.277
Physics	**0.183**	0.243	0.217	0.199	0.269
Geosciences	**0.167**	0.042	0.036	0.094	0.237

Environment/Ecology	**0.166**	0.011	0.016	0.067	0.207
Mathematics	**0.163**	0.091	0.092	0.137	0.225
Molecular Biology & Genetics	**0.139**	0.008	0.009	0.042	0.223
Pharmacology & Toxicology	**0.130**	0.039	0.026	0.062	0.198
Clinical Medicine	**0.125**	0.121	0.054	0.064	0.159
Agricultural Sciences	**0.115**	0.010	0.011	0.047	0.165
Biology & Biochemistry	**0.109**	0.021	0.037	0.065	0.192
Microbiology	**0.098**	0.005	0.007	0.042	0.156
Plant & Animal Science	**0.085**	0.023	0.028	0.056	0.134
Multidisciplinary	**0.085**	0.022	0.127	0.050	0.159
Space Science	**0.079**	0.021	0.024	0.065	0.126
Immunology	**0.068**	0.004	0.004	0.026	0.110
Neuroscience & Behavior	**0.064**	0.009	0.010	0.027	0.106
Economics & Business	**0.058**	0.004	0.004	0.015	0.080
Social Sciences, General	**0.031**	0.024	0.011	0.011	0.038
Psychiatry/Psychology	**0.030**	0.003	0.004	0.007	0.040

Using the formula of calculating the polarization degree of a country's field structure, table 5 lists polarization degrees of fields in China and the USA in different periods. The value ranges from 0 to 1. The smaller the value, the more balanced field structure a certain country has. From 1980 to 2021, China's field polarization degree is higher than that of the USA. From the perspective of the longitudinal sequence of the 4 decades, the polarization degrees of China's fields shows a decreasing trend, indicating that the balance of field structure and layout has been improved.

Table 5. The field polarization degree and dynamic evolution of China and USA.

Field polarization degree	*Various periods*				
	1980-2021	*1980-1989*	*1990-1999*	*2000-2009*	*2010-2019*
China	**0.904**	0.987	0.986	0.978	0.900

Research dimension in collaboration of China's science

(1) Scale and trend of China's science collaboration

Judging from the number of international collaborations in China shown in Figure 8, the number of international collaboration papers in China shows a sustained and exponential growth pattern. With the advent and development of the era of big science, the proportion of global collaborative papers (circular markers) has increased year by year, and the proportion of China's collaborative papers to the world's collaborative papers (dotted line) is no exception. The proportion of USA collaborative papers to the world's collaborative papers (solid line) exceeded 50% from 1980 to 1989, but has been declining year by year since then.

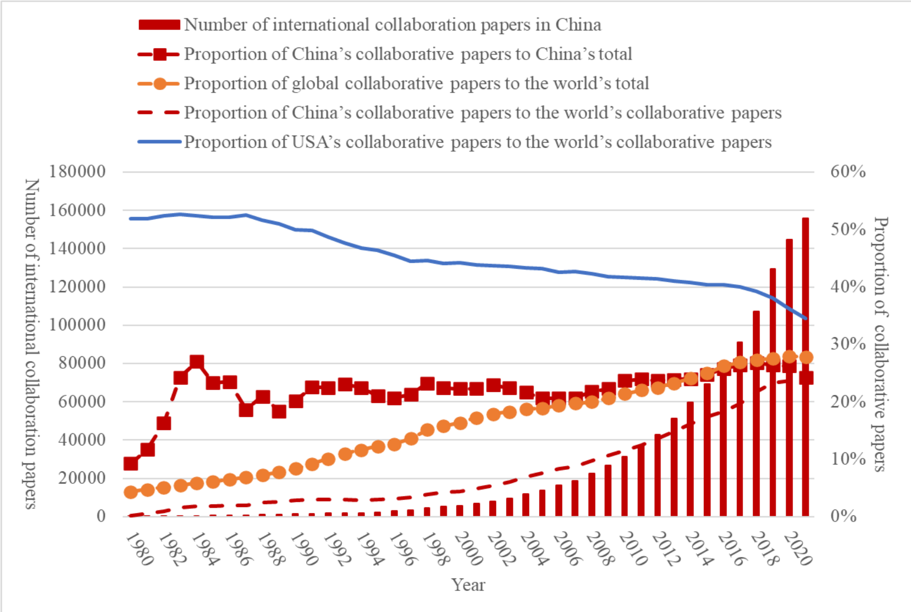

Figure 8. Number of WOS collaborative papers in China and collaboration proportion of China, USA (1980-2021).

From the perspective of China's collaboration rate (red dotted line), from 1980 to 1984 it was a rapid climbing stage, from 9.27% to 27.01%, and then a slight fluctuation trend of declining-growing was repeated. The collaboration percentages in the past 4 decades were 20.38%, 22.01%, 21.60% and 25.35% respectively.
Table 6 shows the changes in the number and proportion of China's international collaboration papers in the past 4 decades. With the number of global collaboration papers and the percentage of global collaboration continue to rise, China's international collaboration rate (the proportion of China's international collaboration papers to China's total) has remained between 20%~26% in the 4 decades. The number of cooperative publications has increased from more than 5,000 to nearly 700,000, an increase of about 139 times; China's collaboration percentage of global collaboration total has increased from 2.06% to 18.34%, and the percentage doubles almost every decade. On the whole, China's international scientific research collaboration is becoming more and more active.

Table 6. Number and related proportion of international collaboration papers in China and globally.

Number and proportion	*4 decade series*			
	1980-1989	*1990-1999*	*2000-2009*	*2010-2019*
Number of international collaboration papers in China	5052	26922	139885	699227
Proportion of international collaboration papers in China/%	**20.38**	**22.01**	**21.60**	**25.35**

Number of international collaboration papers	245674	767897	1785878	3813275
Proportion of international collaboration papers /%	6.12	12.31	18.86	24.91
Proportion of China's collaborative papers to the world's collaborative papers /%	**2.06**	**3.51**	**7.83**	**18.34**

(2) Countries distribution of China's collaborative papers

From 1980 to 2021, China carried out international science collaboration with more than 200 countries/regions, with a total of 1,171,904 international collaboration papers in China. The top 10 collaborative countries are shown in Figure 9.

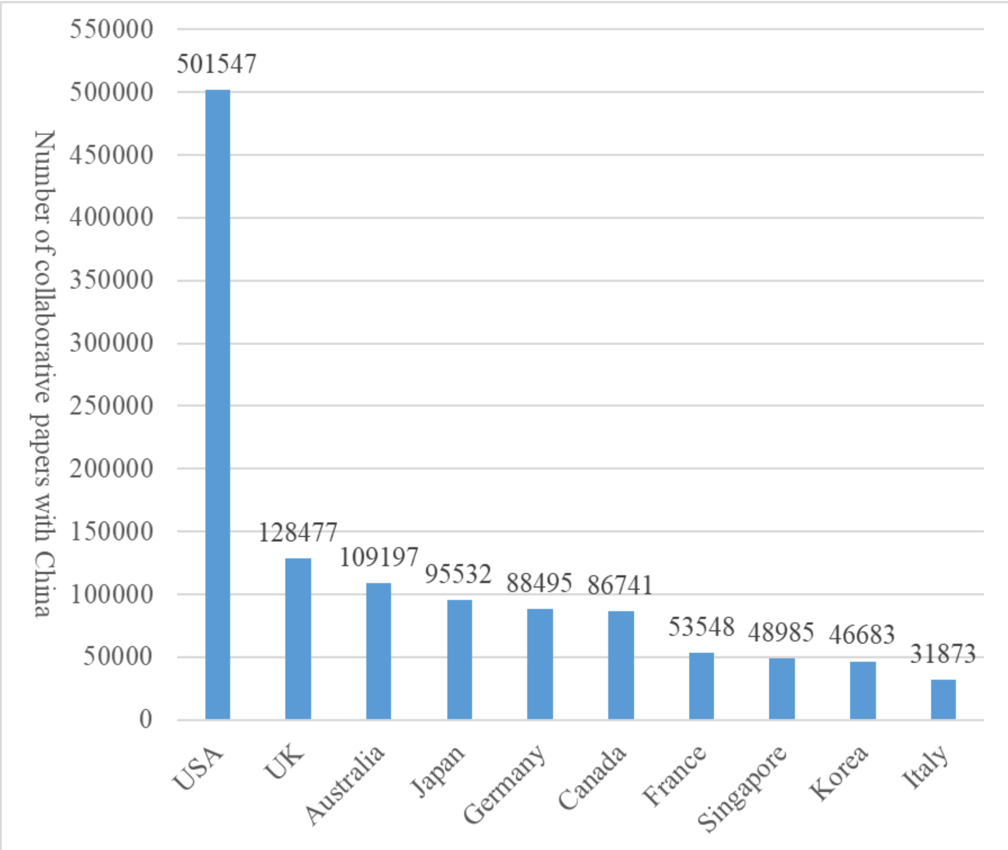

Figure 9. Top 10 countries and numbers of collaborative papers with China (1980-2021).

From the perspective of the evolution of top 10 collabrative countries and the number of papers in the 4 decades (Table 7), the USA occupied the first position in the number of collabrative papers with China for 4 consecutive decades, and Japan occupied the second position in the first 3 decades, and then gave way to the United Kingdom in the 4th decade (2010-2019).

Table 7. Top 10 countries and number of papers in collaboration with China (4 decade series).

Rank	*Country (number)*			
	1980-1989	*1990-1999*	*2000-2009*	*2010-2019*
1	USA（2702）	USA（9831）	USA（54442）	USA（322066）
2	Japan（567）	Japan（4380）	Japan（21038）	UK（74633）
3	UK（421）	Germany（3062）	UK（12912）	Australia（66735）
4	Canada（400）	UK（2694）	Germany（12630）	Canada（52046）
5	Germany（370）	Canada（2010）	Canada（9930）	Japan（51412）
6	France（297）	France（1682）	Australia（9026）	Germany（50762）
7	Australia（196）	Italy（1327）	France（7154）	France（31728）
8	Italy（145）	Australia（1250）	South Korea（6375）	Singapore（29566）
9	Sweden（117）	Netherlands（797）	Singapore（5935）	South Korea（27608）
10	Swiss（92）	South Korea（730）	Sweden（3419）	Netherlands（18368）

Following North American countries (the USA, Canada), European countries (the United Kingdom, Germany, France, Italy, Sweden, Switzerland), Australia in Oceania, and Japan in Asia, the Netherlands in Europe, South Korea and Singapore in Asia were also among the top 10 partner countries in China (Table 8). In the 2nd decade (1990-1999), the Netherlands (with underline) and South Korea (with underline) ranked among the top 10 collabrative countries. In the 3rd decade (2000-2009), Singapore (with underline) ranked 9th in the top 10 of China's collabrative countries.

Table 8. Top 10 collaboration countries with China and decadal evolution.

Top 10 collaboration countries with China	*4 decade series*			
	1980-1989	*1990-1999*	*2000-2009*	*2010-2019*
USA	√	√	√	√
Japan	√	√	√	√
UK	√	√	√	√
Canada	√	√	√	√
Germany	√	√	√	√
France	√	√	√	√
Australia	√	√	√	√
Italy	√	√		
Sweden	√		√	

Swiss	√			
Netherlands		√		√
South Korea		√	√	√
Singapore			√	√

(3) Changes in the pattern of China's global collaboration network

In order to reveal China's global collaboration network more clearly and compare it with the USA, Table 9 lists the node characteristics of China and the USA in the global scientific paper collaboration network in the past 4 decades (when calculating the international scientific research collaboration network, the edge of the collaboration relationship below 40 is removed). In graph theory and network analysis, Centrality is a metric to judge the importance/influence of nodes in a network. Degree centrality refers to the number of connections a node has. Betweenness centrality is defined in terms of the proportion of shortest paths that go through a node for each pair of nodes. Closeness centrality is the inverse of the sum of the shortest path lengths between a node and all other nodes in the network. Eigenvector centrality is related to the centrality of adjacent nodes of a node and it assigns relative scores to all nodes in the network based on the concept that connections to high-scoring nodes contribute more to the score of the node in question than equal connections to low-scoring nodes.

The USA has been at the heart of the network for the past 4 decades. China's degree, weighted degree, closeness centrality, betweeness centrality and eigen centrality in the network have all shown a monotonous growth trend in the 4 decades, and the gap between China and the corresponding values of the USA is gradually narrowing.

Table 9. Node characteristics of China, USA in global scientific collaboration network (4 decade series).

Node characteristics	*China*				*USA*			
	1980-1989	*1990-1999*	*2000-2009*	*2010-2019*	*1980-1989*	*1990-1999*	*2000-2009*	*2010-2019*
degree	14	47	73	**145**	84	122	154	**181**
weighted degree	13130	78656	368802	**2105508**	333156	927650	2100290	**5012286**
closeness centrality	0.498	0.595	0.639	**0.801**	0.796	0.855	0.923	**0.941**
betweeness centrality	0	30.603	231.177	**367.344**	2480.888	3005.583	3994.444	**2458.131**
eigen centrality	0.432	0.732	0.799	**0.966**	1	1	1	**1**

Conclusion of 4 decades evolution characteristics of China's science structure

From the empirical research and multi-dimensional analysis of the development process of China's science structure, one may conclude the development and evolution of China science structure in the past 4 decades as "starting-consolidating-improving-rising". Each key indicator selected from the 4 dimensions of productivity, impact, equilibrium and collaboration, could be used to show the development trends in the 4 decades (Table 10).

Table 10. Key indicators and conclusions of the development and evolution of China's science structure.

Dimension: Key indicator	*starting*	*consolidating*	*improving*	*rising*	*Key items*
	1980-1989	*1990-1999*	*2000-2009*	*2010-2019*	
Productivity: ratio of China's WOS papers to the global total	0.62%	1.96%	6.84%	18.02%	China can be regarded as one of the "world's scientific center of WOS papers" since 2019
Impact: CNCI	0.54	0.59	0.84	1.10	China's CNCI value continues growing, surpassed the world average for the 1st time in 2012 at 1.021; In 2020 China's CNCI slightly exceeded USA's but fell back in 2021.
Equilibrium: field polarization degree	0.987	0.986	0.978	0.900	Balance of field structure and layout in China has been improved.
Collaboration: number of countries collaborated more than 40 papers with China	14	47	73	145	More and more countries are collaborating with China.

The development of China's science structure, which is shown by the four dimensions of productivity, impact, equilibrium and collaboration, has continued to improve, especially in the past decade, and important breakthroughs have been made in the dimension of productivity. On the basis of the continuous expansion of the scale of scientific output, China's research field structure has been continuously improved.

But there are still some challenges in China's scientific development. First, although the scale of scientific output has made leaps and breakthroughs, basic science and technological breakthroughs still require long-term accumulation and resource investment. Second, although China has grown into a major country in scientific scale, the "qualitative" change and breakthrough has not yet been fully realized. Third, from the perspective of field structure, the overall equilibrium of China's fields structure is still obviously insufficient. Last, the scale of China's global scientific cooperation is expanding, but the gap is still large compared with the USA, which occupies the core position of the network.

In the future, China could continue to optimize its science structure, starting from various aspects such as scientific research investment, high-quality development, field layout, and international scientific collaboration, to promote the development of scientific undertakings, and achieve the goal of becoming a major science center in the world.

Research limitations and future research directions

This study has the following limitations, and future research can be further improved. (1) The three theoretical streams cited—philosophy of science, scientometrics, and scientific economics—do not effectively converge. The empirical study only focuses

on scientometrics.
(2) The data source is not comprehensive, and only WOS international papers are used to characterize the evolution of China's science structure.
(3) The study focuses on the analysis of the historical characteristics of China's science structure, which lacks future trend prediction and comparison with more countries.
(4) There is a lack of in-depth discussion of the current situation and causes, and a lack of comprehensive evaluation of China's science structure.
In the future, on the basis of existing scientometrics with the scientific papers as the core, more unstructured information and data from the science community such as science and technology policy, scientific research investment related to funding projects, researchers and financial resources data, more detailed disciplinary classification and knowledge data can be considered, so as to understand and explore the China's science structure more comprehensively and concretely.

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