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Synergy Between Science And Technology In University-Industry Innovation Ecosystems: A Cross-National Comparison Of Elite Academic Partnerships In China, Germany, And The United States

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Abstract

University-industry collaboration serves as a critical driver of technological innovation, significantly contributing to national economic growth and enhancement of global competitiveness. This study addresses the pivotal challenge of optimizing such partnerships and improving the commercialization efficiency of scientific breakthroughs through an empirical investigation of 26 elite universities from China's C9 League, Germany's Universities of Technology Alliance, and the United States Ivy League (2000-2020). Grounded in the knowledge spiral framework, the research employs integrated bibliometric analysis and social network mapping to systematically compare cross-national innovation ecosystems. Findings indicate that while German and American institutions demonstrate superior performance in knowledge co-creation dynamics, Chinese universities lead in patent authorization volume yet face challenges in university-industry collaboration rates and commercialization outcomes. Network analysis reveals distinct structural patterns: Chinese co-authorship networks exhibit institutional dominance with limited enterprise engagement, whereas patent collaboration forms university-centric clusters maintaining exclusive enterprise partnerships. These insights provide actionable pathways for enhancing knowledge transfer mechanisms and inform evidence-based policy formulation in national innovation systems.

Introduction

With the evolution of the new round of scientific and technological revolution, technological innovation has increasingly become an important means for countries to promote economic development and enhance competitiveness. At the same time, scientific research has shown the characteristics of interdisciplinarity and comprehensiveness. Significant breakthroughs in scientific research rely

increasingly on interdisciplinary, cross-domain, cross-institutional, and cross-national cooperation. Research cooperation has become a significant trend in global scientific research progress. To promote technological innovation and research cooperation, governments worldwide have placed scientific and technological innovation at the core of national development and promulgated policies to enhance national scientific and technological innovation capabilities. In the 1980s, the United States introduced the Bayh-Dole Act (Kenney & Patton, 2009) to address the problem of idle research achievements and reduce economic competition pressure, encouraging universities and enterprises to cooperate in research projects and promoting technological innovation and technology transfer. Germany has always attached great importance to technological innovation and formulated strategies such as the High-Tech Strategy to provide policy guidance for the cooperation between universities and enterprises. It also builds innovation clusters and platforms to construct an innovation network and promote interdisciplinary cooperation. In recent years, China has increasingly emphasized the transformation of scientific and technological achievements and university-industry cooperation(P. s. R. o. China, 2021, 2022). Universities and enterprises around the globe are proactively exploring and implementing innovative cooperation patterns under the guidance of established policies.

As an important driver of technological innovation, universities are regarded as an important source of new knowledge for enterprises (Rast, Khabiri, & Senin, 2012). Universities serve as knowledge producers and guides, supplying enterprises with the latest theories and insights. By absorbing diverse knowledge from universities and offering technical support, organizations facilitate the transformation of research outcomes into practical applications. Consequently, the "university-enterprise" cooperation pattern has emerged as a crucial method for universities to produce, utilize, and transform knowledge within the framework of open innovation. Internationally, leading universities in Germany and the United States boast exceptional research talent and facilities, forming strong partnerships with local businesses. The foundation of university-industry cooperation in Germany stems from the "dual system" of vocational and technical education, which has significantly enhanced collaboration among industry, academia, and research institutions and the application of scientific research findings (Xiao, 2016). The United States, as the birthplace of industry-academia-research teaching, has received substantial government support for university-industry cooperation (Foundation, 2018). Universities actively explore and practice university-industry cooperation patterns, from joint research to company incubators, forming various university-industry cooperation paths.

Currently, relevant research on scientific and technological innovation cooperation between universities and enterprises at home and abroad mainly focuses on cooperation patterns, cooperation performance evaluation, cooperation network

evolution, and technology transfer. X. Wang, Wang, and Liu (2005) proposed six cooperation patterns based on league forms and participating entities. Ding, Huang, and Guo (2010), based on the practice of university-industry cooperation in higher vocational colleges, proposed university-industry cooperation patterns led by enterprises and universities respectively. Kwon, Park, So, and Leydesdorff (2012) based on the triple helix theory, constructed innovation indicators to analyze the structural pattern of Korean universities' participation in university-enterprise cooperation. S. Wang (2020) constructed a pattern for evaluating the technological innovation performance of universities. F. Liu, Ma, and Jiang (2011) studied the evolution path of the industry-university-research cooperation network based on "985 universities" from patent cooperation data. Dang, Jasovska, Rammal, and Schlenker (2019) analyzed the knowledge transfer between university-enterprise cooperation by studying the university-industry cooperation methods of ten Australian universities. Scholars' research on university-industry cooperation is mainly based on "patent" data. The sample universities in the research generally focus on specific regions (such as the Yangtze River Delta region in China) or specific fields (such as Australian business schools). The data on innovation cooperation achievements lack diversity, and there are few industry comparisons among international top universities. As one of the important forms of the achievements of university-enterprise innovation cooperation, co-authored articles of industry and academia are also an important indicator reflecting the characteristics of university-enterprise cooperation (Jianjie Guo, Xie, Wang, & Wang, 2019).

Existing literature predominantly examines the scientific (articles) and technological (patents) dimensions in isolation, with limited focus on their synergistic relationship. Additionally, there is a lack of research on university-industry collaboration in top universities across different countries. As leading academic institutions in China, Germany, and the United States, the C9 Alliance, TU9, and Ivy League universities have significant domestic and international influence. These universities are well-established in research mechanisms and highly active in industry collaborations, and university-industry collaboration models in these institutions are highly representative. Therefore, this study aims to combine university paper data and patent data to analyze the state of scientific innovation cooperation between university alliances and industry in China, Germany, and the United States from an international perspective. The findings will offer valuable insights to promote university-industry cooperation and accelerate the technological innovation process.

Conceptual Model and Framework

Conceptual Model

The cooperation between universities and industries primarily revolves around the transfer of knowledge. In this process, both universities and companies invest

various resources, including scientific research personnel, research facilities, funding, technical support, and diverse knowledge. The goal is to create new knowledge and achieve innovative results, such as enhancing the value of knowledge, fostering scientific and technological advancements, and developing talent. Numerous scholars have examined this process from different angles and have proposed various theoretical models to explain it. The "Triple Helix Model" proposed by Etzkowitz and Leydesdorff emphasizes the important roles of universities, enterprises, and government in the process of knowledge production and dissemination (Etzkowitz & Leydesdorff, 1996). Hu, Zhu, and Ma (2011) systematically analyzed the interrelated constraints among various factors in university-industry-research cooperation and constructed a system dynamics model of university-industry-research cooperation. R. Wu, Liu, and Li (2021) combined the SECI theory in knowledge management theory and the knowledge collaborative innovation mechanism to construct a SECI (Socialization, Externalization, Combination, Internalization) knowledge transfer model based on the "collaborative pool" to reveal the knowledge transfer phenomenon in the process of university-enterprise cooperation. The SECI knowledge spiral theory proposed by Nonaka and Takeuchi in 1994 (Nonaka, 1994), is considered one of the most classic theoretical models in the field of knowledge transfer. They believe that knowledge creation is essentially a continuous transformation, recombination, and utilization process of tacit and explicit knowledge. Tacit knowledge includes untextualized experiences such as thinking patterns and intuition, while explicit knowledge refers to knowledge that can be textualized and disseminated. The SECI model believes that the process of knowledge transfer includes four stages: socialization, externalization, combination, and internalization. Explicit and tacit knowledge interact and transform in different stages, forming a virtuous knowledge creation cycle. The SECI model can systematically summarize the knowledge flow pattern between universities and enterprises and provide a theoretical basis for understanding the knowledge creation process in university-industry cooperation. Therefore, this study introduces the SECI knowledge spiral theory and combines the input-output elements in university-enterprise cooperation to construct a university-industry cooperation model based on the SECI knowledge spiral theory, as shown in Figure 1. In this model, universities and enterprises contribute resources that facilitate the interaction and transformation of their diverse knowledge, leading to knowledge creation and innovative outcomes. These innovative achievements can be represented by both quantifiable elements, such as the number of co-authored articles and cooperative patents, as well as non-quantifiable elements, including talent development and institutional competitiveness.

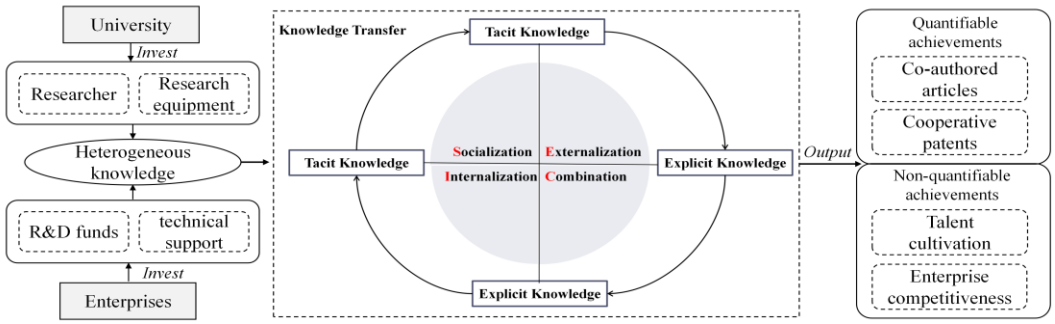


Figure 1. University-Industry Cooperation Model based on the Knowledge Spiral Theory.

Research Framework

This study commences from the article and patent data of universities and explores the characteristics and patterns of university-industry cooperation among different universities in China, Germany, and the United States through bibliometric and cooperation network analysis methods. Figure 2 shows the overall framework of this study. The study is divided into three sections: data collection and processing, bibliometric analysis, and social network analysis. Figure 2 shows the overall framework of this study. The bibliometric analysis focuses on article and patent data, comparing the proportion and temporal trends of university-industry collaboration in articles and patents to analyze the collaborative models and evolution of top universities in different countries. The social network analysis, on the other hand, examines the collaboration networks of universities in China, Germany, and the United States, based on articles and patents, to explore the structure, strength, and pathways of cooperation between universities and industry, providing insights into the distinct advantages and characteristics of university-industry collaborations across the three countries.

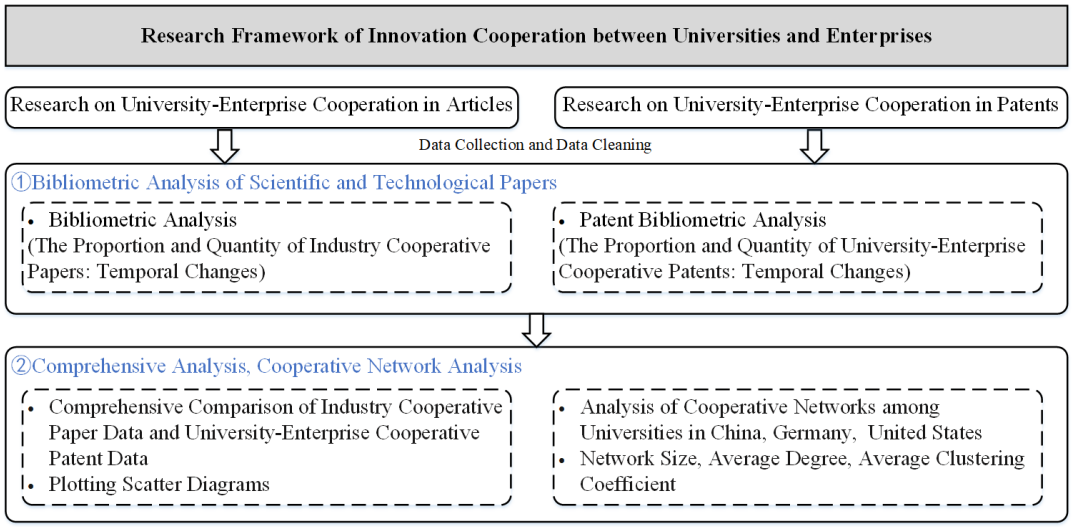


Figure 2. Research Framework of University-Enterprise Innovation Cooperation.

In terms of data collection and processing, this study intends to select the university-industry cooperation data of top universities in China, Germany, and the United States as samples for analysis. We have selected a total of 26 universities from China's C9 League, Germany's Universities of Technology (TU9), and the US Ivy League to research university-industry cooperation. This study aims to gain insights into the collaboration situations of top universities in each country. As leading institutions in China, Germany, and the United States, the C9 League, TU9, and Ivy League hold significant influence both nationally and globally. These universities have established robust scientific research mechanisms and actively engage in cooperation with enterprises. Analyzing the current state and patterns of university-industry cooperation in these institutions will provide valuable insights. We select the Incites and Web of Science databases to obtain university-industry cooperation data and the Derwent Innovations to obtain university patent data. Derwent Innovations is one of the world's most comprehensive patent information databases, providing unique patent indexing, which is helpful for studying the patent data of universities in various countries. Since the patent examination process generally takes 18 months after application, to ensure the accuracy and consistency of the data, we limit the retrieval time range of articles and patents to be unified between 2000 and 2020. There is no mark in the patent data indicating whether there is university-enterprise cooperation. In this study, "university-enterprise cooperation patents" are defined as patents jointly researched and applied by universities and enterprises, where universities and enterprises are in a partnership relationship, and the judgment basis is that both university and enterprise types are included in the patent applicant

field (X. Wang et al., 2005). After conducting a search based on specific terms, a total of 88,481 articles on industry cooperation were obtained. After excluding missing values and outliers and performing deduplication, we were left with 61,049 articles. For the patent data, we carried out cleaning, word segmentation, and filtering. We retained only those patents that listed both university and enterprise applicants, resulting in a final total of 15,892 patent entries.

Results

Quantity and Temporal Variation in Co-authored Articles

By analyzing the industry cooperation article data of universities, it is found that American and German universities perform well in co-authoring articles with enterprises. Harvard University has the highest number of industry co-authored articles, and Princeton University has the highest proportion of industry co-authored articles, more than twice the proportion of Tsinghua University's industry articles. Table 1 shows the numbers of the industry-cooperation articles of the sample universities from 2000 to 2020.

Table 1. The numbes of Industry-Cooperation Articles of the Sample Universities (2000-2020).

Country	University	Industry Collaboration Articles Count	Industry Collaboration Proportion
China	Tsinghua University	5571	2.79%
	Shanghai Jiao Tong University	4390	2.28%
	Peking University	3541	1.97%
	Zhejiang University	3296	1.71%
	Fudan University	2373	1.90%
	Xi'an Jiaotong University	2296	2.13%
	University of Science and Technology of China	2029	1.73%
	Harbin Institute of Technology	1480	1.31%
	Nanjing University	1257	1.34%
Germany	Technical University of Munich	6177	5.03%
	RWTH Aachen University	4436	5.70%
	Dresden University of Technology	3921	4.05%
	Karlsruhe Institute of Technology	2369	5.08%
	Technical University of Berlin	996	4.08%

	University of Stuttgart	906	4.20%
	Darmstadt University of Technology	874	3.85%
	University of Hanover	664	3.71%
	Brunswick Technical University	619	4.35%
United States	Harvard University	16874	4.87%
	University of Pennsylvania	5792	4.49%
	Columbia University	5350	4.47%
	Cornell University	4134	3.92%
	Princeton University	3305	6.61%
	Yale University	3206	3.11%
	Brown University	1434	3.17%
	Dartmouth College	1153	4.18%

The data in the table indicates that the proportions of industryly co-authored articles from universities in Germany and the United States are generally higher. Seventeen universities have proportions exceeding 3.5%, suggesting that the top institutions in these countries are more active in collaborating with enterprises for co-authorship. In contrast, while the number of industryly co-authored articles from Chinese universities is comparable to that of Germany, the proportion remains low. Only Tsinghua University and Shanghai Jiao Tong University have proportions of industryly co-authored articles that exceed 2%. This highlights a significant opportunity for improvement in collaboration between Chinese universities and enterprises.

Figures 3 and 4 illustrate the trends in the number and proportion of industryly co-authored articles for different countries and universities, analyzed by time and university.

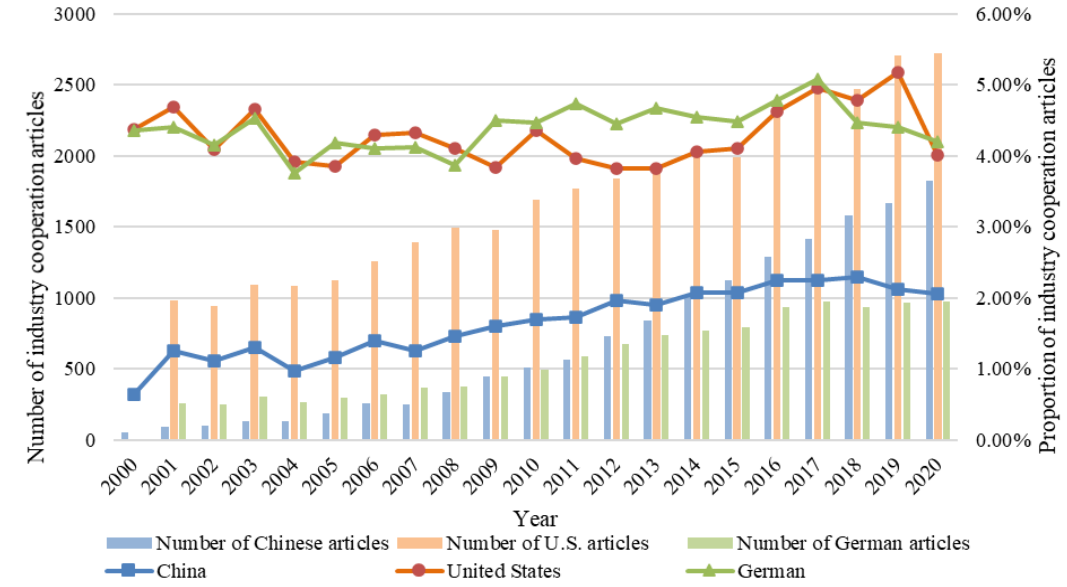


Figure 3. Temporal variation diagram of the quantity and proportion of industry co-authored articles of universities in China, Germany, and the United States from 2000 to 2020.

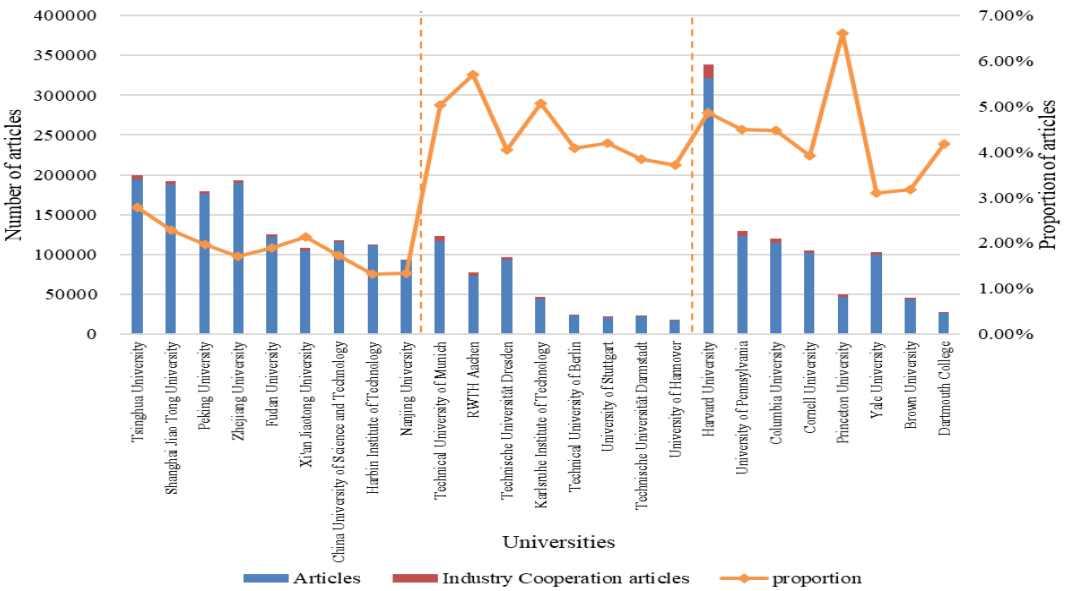


Figure 4. Diagram of the Quantity and Proportion of Industry Cooperation Articles of Chinese, German, and American Universities.

Figure 3 illustrates that the number of industryly co-authored articles in China, Germany, and the United States has generally increased each year. Notably, the

growth rate of industryly co-authored articles among Chinese universities has significantly accelerated since 2007, with the overall growth rate being the highest among the three countries.

A closer look reveals that the Chinese government implemented several policies to promote scientific and technological innovation around 2007. In 2006, China released the "Outline of the National Medium- and Long-Term Science and Technology Development Plan (2006-2020)")(P. s. R. o. China, 2006), which set forth objectives for advancing scientific and technological innovation. Subsequently, in 2010, the "Outline of the National Medium- and Long-Term Education Reform and Development Plan (2010-2020)" (P. s. R. o. China, 2010)explicitly stated the goals of enhancing higher education and strengthening scientific and technological innovation. This plan urged universities to enhance cooperation with all sectors of society and promote the transformation and application of research achievements.

It is evident that the combination of policy support and a conducive academic environment has fostered a collaborative relationship between Chinese universities and enterprises. In contrast, Germany has seen a stable trend in the number of industryly co-authored articles over the past five years. The number of co-authored articles between American universities and enterprises has fluctuated occasionally but generally exhibits an upward trend. This indicates that the cooperation between universities and enterprises in scientific and technological innovation in all three countries has become increasingly dynamic over the past two decades.

It can be observed from Figure 4 that while the number of industryly co-authored articles from Chinese universities has increased rapidly, its overall proportion remains relatively low compared to Germany and the United States. Over a span of 21 years, the average proportion of industryly co-authored articles from Chinese universities stands at only 1.91%, whereas both Germany and the United States exceed 4%. This suggests that, in terms of article co-authorship output, universities in Germany and the U.S. demonstrate stronger collaboration with enterprises.

Specifically, when examining the impact of the talent cultivation models of the United States and Germany on joint academic research between universities and enterprises, a notable example from the U.S. is the "I/UCRC" Industry-University Cooperative Research Center model (X. Wu, 2012). This model is supported by the National Science Foundation (NSF) and facilitates funding for general and fundamental research projects relevant to industry, thus encouraging collaborative research between industry and academia. In Germany, the prominent University Science Park model (Chen, Chu, & Hou, 2018) has been adopted. This approach creates an integrated cooperation system that links scientific research, education, and the economy, fostering active collaboration between scientific talent from universities and technical talent from enterprises, ultimately leading to the generation of numerous practical research outcomes.

Quantity and Temporal Variation in Cooperative Patents

Between 2000 and 2020, the total number of patents authorized by the C9 League universities in China exceeded 110,000. Tsinghua University alone had over 5,000 patents resulting from university-enterprise cooperation, significantly surpassing the numbers from Germany and the United States. However, the proportion of these collaborative patents was considerably lower than in Germany, accounting for less than one-third of the total. Additionally, the efficiency of patent conversion was relatively low. Table 2 provides an overview of the patent data for the sampled universities.

Table 2 Overall Situation of Patent Data of Sample Universities.

Country	University	University-Enterprise Cooperation Patents count	University-Enterprise Cooperation Patents Proportion
China	Tsinghua University	5960	22.79%
	Zhejiang University	1966	6.93%
	Peking University	1925	16.31%
	Shanghai Jiao Tong University	1510	8.41%
	Xi'an Jiaotong University	1094	7.65%
	Harbin Institute of Technology	535	3.04%
	Fudan University	321	5.68%
	Nanjing University	313	5.27%
	University of Science and Technology of China	219	4.99%
Germany	Dresden University of Technology	347	36.11%
	Technical University of Berlin	190	57.58%
	Technical University of Munich	158	43.89%
	University of Stuttgart	76	26.30%
	Darmstadt University of Technology	55	36.42%
	Brunswick Technical University	29	29.59%
	Karlsruhe Institute of Technology	9	23.08%
	RWTH Aachen University	4	33.33%
	University of Hanover	2	9.09%
	Harvard University	362	21.00%

United States	University of Pennsylvania	205	14.42%
	Yale University	173	23.60%
	Cornell University	169	17.16%
	Princeton University	107	14.60%
	Columbia University	106	7.28%
	Dartmouth College	35	9.54%
	Brown University	22	11.17%

Annual variation diagrams of the number and proportion of university-enterprise cooperation patents of different countries and universities were drawn with time and university as dimensions, as shown in Figures 5 and 6.

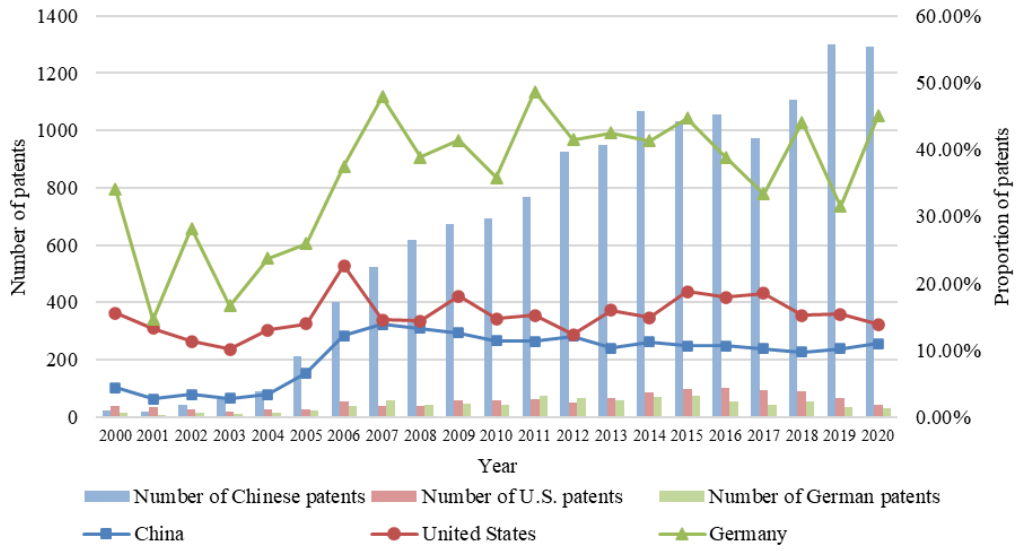


Figure 5. Annual Variation in the Quantity and Proportion of University-Enterprise Cooperation Patents among China, Germany, and the United States.

The figure shows that in Germany, the proportion of patents resulting from university-enterprise cooperation has been fluctuating at a relatively high level for the past 20 years. Since 2006, this proportion has consistently exceeded 30%. In contrast, the United States has maintained a more stable percentage, fluctuating between 10% and 25%. In China, the proportion of patents from university-enterprise cooperation increased steadily from 2004 to 2007. This rise can be attributed to the "Notice on the Establishment of National Technology Transfer Centers," issued in 2003 by the former State Economic and Trade Commission, the

Ministry of Education, and the Chinese Academy of Sciences (M. o. E. o. t. P. s. R. o. China, 2003). This initiative led to the establishment of multiple national-level technology transfer institutions, resulting in a brief surge in patent growth after 2004. However, the proportion of patents developed jointly by Chinese universities and enterprises remains relatively low. There is a pressing need for relevant policy guidance, incentive measures, and a robust protection mechanism to address this issue.

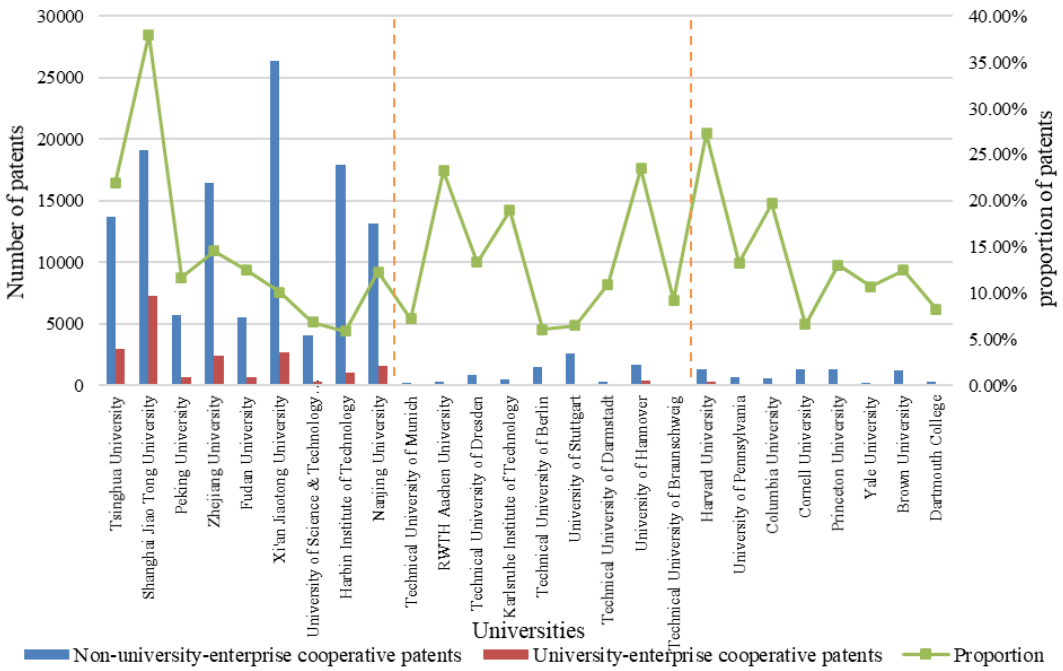


Figure 6. Quantity and Proportion of University-Enterprise Cooperation Patents of Chinese, German, and American Universities.

Certain scholars have delved into the factors contributing to the relatively low conversion efficiency of patents held by Chinese universities, and the main aspects are as follows. To begin with, the patents of Chinese universities generally exhibit deficiencies in both quality and practicality (JuJie Guo, He, & Huang, 2007; D. Liu, 2018). Chinese institutions of higher learning have indeed filed a substantial number of patents based on their scientific research endeavors. Nevertheless, these research projects frequently commence from academic topics and tend to overlook the actual market trends and the specific requirements of enterprises. As a consequence, the resultant patents face significant hurdles in terms of marketability. Most of these patents have not been subjected to production experiments and remain confined to

the laboratory stage, rendering it arduous for enterprises to integrate them into their actual business operations.

Secondly, Chinese universities notably lack professional patent management and conversion institutions (Zhang & Huang, 2011). The initiation of patent conversion activities in Chinese universities has been relatively tardy. The vast majority of university research management departments are primarily engaged in the routine tasks of patent application and daily patent management. These departments are bereft of the necessary capabilities for conducting application evaluations of the patent market, which impedes their ability to effectively facilitate the conversion of patent achievements. Concurrently, both Chinese universities and enterprises are found to be deficient in corresponding patent conversion incentive mechanisms(Nonaka, 1994). The majority of universities have not incorporated patent conversion into their strategic agendas. Moreover, the process of achievement conversion demands a substantial investment of energy and financial resources. University faculty members lack the requisite motivation, and enterprises are disinclined to assume risks and allocate significant amounts of capital.

In contrast, Germany and the United States have established increasingly sophisticated achievement conversion systems. In the United States, most universities are equipped with technology transfer offices, and there are specialized agencies dedicated to conducting commercial research and identifying suitable partners. In Germany, the technology transfer funds of research universities have garnered robust support from the government, enterprises, and public welfare organizations. The government has also established multiple science and technology centers to offer free consulting services to enterprises, thereby effectively promoting the conversion of scientific research achievements(Sun, Liu, & Xu, 2016).

The study further integrates science and technology indicators to comprehensively analyze university-industry collaboration. A comprehensive analysis of the data of co-authored articles and cooperation patents between universities and enterprises shows that there are certain differences among China, Germany, and the United States in the proportion of industry co-authored articles and the proportion of university-enterprise cooperation patents. German universities perform better in both indicators and are more active in innovation cooperation with enterprises. Figure 7 is a scatter plot of the data of co-authored articles and patents of different universities and enterprises. Different shapes and colors in the figure represent different countries, and two line segments are used to mark the mean values of the relevant proportions.

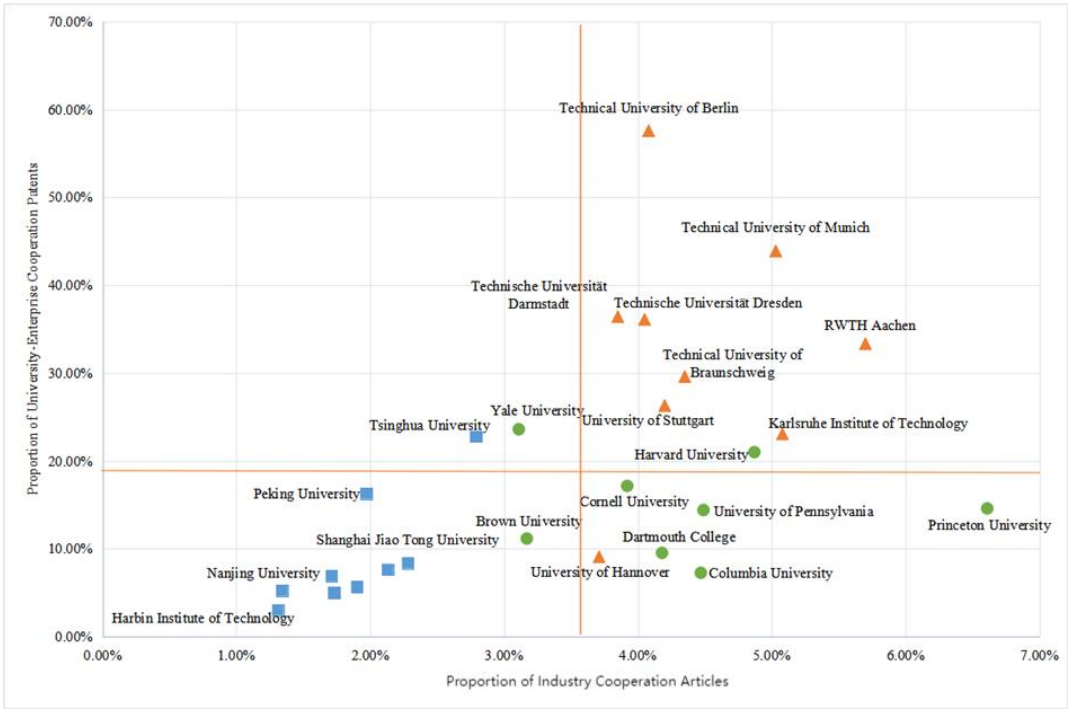


Figure 7. Scatter Plot of the Proportion of Industry Co-authored Articles and the Proportion of University-Enterprise Cooperation Patents.

Note: The squares represent Chinese universities, the triangles represent German universities and the circles represent American universities.

The proportion of industryly co-authored articles and university-enterprise cooperation patents at the Technical University of Munich and the Technical University of Berlin in Germany is significantly higher than that of other universities. This indicates that these two institutions have clear advantages in innovation collaboration with enterprises. In the United States, universities perform better in terms of industryly co-authored articles, with most institutions having a proportion that exceeds the average. However, their performance concerning university-enterprise cooperation patents is relatively mediocre, with only Yale University and Harvard University surpassing the average level.

In contrast, the level of innovation cooperation between Chinese universities and enterprises is lower compared to their counterparts in Germany and the United States. Only Tsinghua University displays a proportion of university-enterprise cooperation patents that exceeds the average, highlighting a stark contrast to the high number of authorized patent data from Chinese universities. This suggests that while Chinese universities possess strong capabilities in innovative research, many of their

innovative achievements and authorized patents remain unutilized and have not fully transitioned into practical applications.

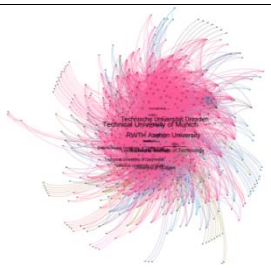
Despite their significant experience and accomplishments in scientific research, Chinese universities encounter substantial challenges in cooperation in scientific and technological innovation and in converting these achievements into applicable solutions. Thus, finding ways to enhance university-industry cooperation and improve the efficiency of converting innovative achievements has become an urgent issue that needs immediate attention.

This study analyzes the network structure characteristics of university-enterprise cooperation in China, Germany, and the United States from the perspective of cooperation networks, exploring the performance of indicators such as the scale, intensity, and average degree of university-enterprise cooperation across these different countries.

Network Analysis based on Co-authored articles

Upon examining the cooperation network diagram, it is evident that the university-enterprise collaboration in the field of published articles across the three countries generally exhibits a galaxy-like network structure. In this network, research institutions, large companies, and high-tech enterprises often serve as the core nodes alongside universities, with most nodes gathering around universities as central hubs. This indicates that the collaborative relationships among universities are generally closer than those between universities and enterprises. Additionally, the cooperation network diagrams for Germany and the United States show a greater diversity of nodes. Notably, the number of enterprises co-authoring articles with German universities is the highest, while there is a comparatively smaller number of enterprises collaborating with Chinese universities. The following table presents the cooperation network diagrams and relevant structural data pertaining to co-authored articles from universities and enterprises in China, Germany, and the United States.

Table 3. Cooperation Network Diagrams of Co-authored articles of Universities and Enterprises in China, Germany, and the United States.

	China	Germany	United States
Cooperation Network Diagram			
Network Node Scale	155	523	208
Network Edge Number	1476	4545	1950
Average Degree	19.05	17.38	18.75
Average Clustering Coefficient	0.662	0.793	0.797

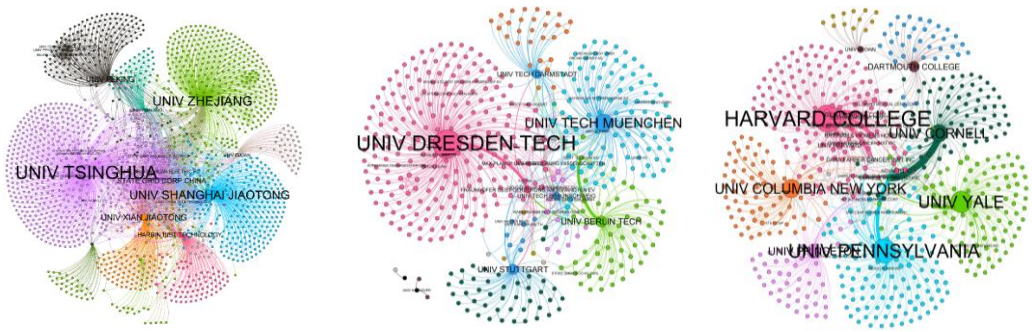
Note: Only nodes with a frequency greater than 10 are shown in the figure for the convenience of presentation.

In terms of the overall scale of cooperation networks, the collaboration between German universities and enterprises is the largest. Both the number of partnering enterprises and the frequency of cooperation are higher than in the other two countries. This trend is closely linked to Germany's long-standing emphasis on university-industry collaboration. The German government has implemented various policies to support and enhance this cooperation. For instance, the "Employee Invention Law" stipulates that 30% of the income generated from the patent conversion of employee inventions will be awarded to the inventors. Additionally, in 2014, the German government launched the "High-Tech Strategy 2025," which identifies university-industry cooperation as a key component aimed at improving Germany's innovation capacity and scientific and technological competitiveness (STIPCOMPASS, 2018).

The average degree index indicates the overall connection status of all nodes in the network diagram, while the average clustering coefficient measures the degree of clustering among these nodes. The clustering coefficients for Germany and the United States are higher than that of China, and their average degree is slightly lower. This suggests that the collaboration between these two countries and their enterprises in terms of article co-authorship is more cohesive, and the partnerships between universities and enterprises are more balanced. In contrast, the cooperation network of Chinese universities shows a relatively high average degree but a low average clustering coefficient. This indicates that the collaboration among Chinese universities and research institutions in co-authorship is not well balanced. Analyzing specific co-authorship data reveals that some Chinese universities tend to cluster with other universities or research institutions. Prominent universities and research institutions hold significant positions in article co-authorship, leading to concentrated collaboration among them. Meanwhile, Chinese enterprises have a comparatively minor role in scientific research, with fewer connections to the core universities in the network diagram. This results in a cooperation pattern that predominantly features an aggregation of resources among universities and research institutes.

Network Analysis Based on Cooperative Patents

There are similarities in patent cooperation among sample universities in China, Germany, and the United States. Each university has a fixed group of cooperative enterprises, and these enterprises have established close cooperation relationships with specific universities to jointly promote scientific and technological innovation research. Figure 8 shows the cooperation network diagrams of patents of universities and enterprises in China, Germany, and the United States.



China Germany United States

Figure 8. Cooperation Network Diagrams of Patents of Universities and Enterprises in China, Germany, and the United States.

Note: Only nodes with a cooperation frequency greater than 1 are shown in the figure for the convenience of presentation.

The figure illustrates that the collaboration between universities and enterprises tends to cluster around individual universities. Each university has a specific group of partner enterprises with whom they have formed close cooperative relationships to advance scientific and technological innovation research. However, this collaboration often appears somewhat limited; most enterprises establish a partnership with only one university and do not reach out to others afterward.

One possible explanation for this is that universities, as knowledge producers, offer unique and diverse resources that many enterprises cannot replicate (Fukugawa, 2013). This creates a situation where multiple enterprises compete for collaboration with universities, but due to the distinct research areas and technical expertise of each institution, enterprises ultimately select the university that best aligns with their needs and capabilities. This results in a one-to-many cooperation model between universities and enterprises.

Additionally, the enterprises that closely collaborate with leading universities—whether domestically or internationally—are typically well-established and relatively large organizations. This suggests that such enterprises prioritize partnerships with top-tier universities, viewing them as vital for their technological innovation and research and development efforts. Furthermore, it has been observed that universities also engage in patent cooperation and joint research. This collaborative pattern fosters the sharing of resources and knowledge among universities, further enhancing technological innovation.

Table 4 The Top Two Enterprises with the Highest Cooperation Frequency of Each University.

Country	University	Enterprise
China	Tsinghua University	Shenzhen Foxconn Precision Group; Yida Technology Co., Ltd.
	Zhejiang University	State Grid Zhejiang Electric Power Co., Ltd.; Zhejiang Nanhu Co., Ltd.
	Peking University	Peking University Founder Group Co., Ltd.; Beijing Chuangshitong Technology Co., Ltd.
	Shanghai Jiao Tong University	State Grid Corporation; Huawei Technologies Co., Ltd.
	Xi'an Jiaotong University	State Grid Corporation; Xi'an Ruite Rapid Manufacturing Engineering Co., Ltd.
	Harbin Institute of Technology	State Grid Corporation; Harbin Institute of Technology Ruichi Technology Co., Ltd.

	Fudan University	Shanghai iQIYI Innovation Center Co., Ltd.; Huawei Technologies Co., Ltd.
	Nanjing University	Jiangsu Enju Environmental Protection Technology Co., Ltd.; Suzhou Nanzi Sensing Technology Co., Ltd.
	University of Science & Technology of China	Huawei Technologies Co., Ltd.; State Grid Corporation
Germany	Technical University of Dresden	Fraunhofer Institute for Applied Technology Promotion; Novald Company
	Technical University of Berlin	Deutsche Telekom AG; Fraunhofer Institute for Applied Technology Promotion
	Technical University of Munich	Bavarian Motor Works; Lanxess AG
	University of Stuttgart	Audi AG; Garnier Construction Machinery Company
	Technical University of Darmstadt	Fraunhofer Institute for Applied Technology Promotion; Deutsche Telekom AG
	Technical University of Braunschweig	Fraunhofer Institute for Applied Technology Promotion; Innovation Laboratory
	Karlsruhe Institute of Technology	Karlsruhe Research Center GmbH; Fraunhofer Institute for Applied Technology Promotion
	RWTH Aachen University	ASML Netherlands; ASML Company
	University of Hannover	BIOTRONIK SE & Co. KG; Braun Company
United States	Harvard University	Broad Institute; Dana-Farber Cancer Institute, Inc.
	University of Pennsylvania	Novartis Technologies Ltd.; INOVIO Biopharmaceuticals, Inc.
	Yale University	Yale University Corporation; Regeneron Pharmaceuticals, Inc.
	Cornell University	Cornell Research Foundation, Inc.; Nestlé Science and Technology Co., Ltd.
	Princeton University	Universal Display Corporation; Momentive Performance Materials, Inc.
	Columbia University	AT&T Inc.; Sony Corporation; Dana-Farber Cancer Institute, Inc.
	Dartmouth College	Maskoma Corporation; Immunex Corporation
	Brown University	Xerox Network Services; League for Sustainable Energy, LLC

By analyzing the top two enterprises with the highest frequency of cooperation from each university (as shown in Table 4), it is evident that there are distinct characteristics in patent collaboration between universities and enterprises across different countries. The cooperation network involving Chinese universities and enterprises is notably richer. Led by Tsinghua University, Zhejiang University, and Shanghai Jiao Tong University, each institution has established its own unique network of partnerships. A closer examination of the enterprises that collaborate most frequently with these Chinese universities indicates that each university tends to partner with companies located in the same region or those with which the university shares (Ding et al., 2010). For instance, the enterprises with the closest ties with Tsinghua University, Zhejiang University, and Peking University are the Shenzhen Foxconn Precision Group, State Grid Zhejiang Electric Power Co., Ltd., and Peking University Founder Group Co., Ltd.

Each German university has formed its own unique cooperation cluster group. An analysis of specific patent cooperation data shows that the institutions that collaborate most frequently with the German Universities of Technology League are primarily off-campus public research institutions, as well as well-known enterprises both within Germany and internationally. For example, the top three institutions with the highest frequency of patent cooperation with German universities are Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V., Deutsche Telekom AG, and AUDI AG. This trend aligns with the structure of the German innovation system and government innovation policies. Germany has developed a scientific and technological innovation system with universities, public research institutions, and enterprises serving as its three pillars. The Fraunhofer Society is one of the most representative research institutions in this system. The German innovation framework clearly defines the roles and operational mechanisms of each entity and promotes collaborative efforts among these three innovation sectors based on local conditions. Germany has established a stable cooperation platform that fully mobilizes the scientific and technological innovation capabilities of universities and enterprises. This has improved the efficiency of converting scientific and technological achievements into practical applications, providing a strong foundation for fostering national development.

Institutions that frequently collaborate with American universities are primarily research funding organizations established by universities and various research enterprises. Examples include the Cornell Research Foundation, Inc., the Broad Institute, and the Dana-Farber Cancer Institute, Inc. In managing university-industry partnerships, many American universities set up dedicated technology management offices to facilitate the transformation of scientific and technological achievements (Yang, 2011). Additionally, some universities create separate management entities to handle technology transfer and intellectual property matters, thereby promoting

scientific research and technological innovation. These institutions operate independently from the university's main administration. By providing commercial services, they support university operations while maintaining greater authority and autonomy, which can lead to more efficient transformation of scientific research achievements.

Discussion

By conducting a bibliometric analysis of university-industry cooperation data from 26 top universities in China, Germany, and the United States, and constructing a cooperation network, we have uncovered the innovation cooperation patterns and characteristics of universities and enterprises in these three countries. The key conclusions are as follows: First, universities in Germany and the United States demonstrate better performance in terms of innovation achievements in collaboration with enterprises. While Chinese universities hold the largest number of authorized patents, the proportion of patents resulting from university-industry cooperation is relatively low, and the conversion rate of these innovation achievements is also not high. Second, universities and enterprises typically form a galaxy network structure when examining the cooperation network among the three countries. In addition to university nodes, research institutions, large enterprises, and high-tech enterprises often act as core nodes in the network, with all nodes gravitating toward the universities at the center.

These findings indicate that university-industry innovation cooperation in China has achieved notable success over the past two decades. However, compared to the cooperative frameworks in Germany and the United States, China still faces significant challenges in enhancing university-industry collaboration and the conversion of scientific and technological achievements, indicating ample room for improvement. Specifically, universities in Germany and the United States not only possess mature cooperation models and operational systems with enterprises but have also developed a relatively comprehensive ecosystem regarding achievement conversion mechanisms, policy support, and enterprise involvement. Although China has made some progress, it needs to exert further effort to deepen university-industry cooperation and improve the efficiency and quality of converting scientific and technological achievements.

In the case of the United States, while American universities excel in industry cooperation in research articles, they still exhibit weaknesses in university-industry cooperation patents. Moreover, compared to universities, the enterprises they collaborate with are relatively limited, with many enterprises maintaining stable and unchanging partnerships with a select few universities.

This study offers a comprehensive analysis of the university-industry collaboration status among C9, TU9, and Ivy League universities from a science and technology

perspective. Future research could delve deeper into the impact of national science and technology innovation policies. The policy directions, government support priorities, and strategic frameworks of different countries significantly shape the models of university-industry collaboration.

Additionally, future studies might employ more advanced research methods, such as deep learning and text mining, to identify hidden patterns and relationships. Incorporating dynamic network analysis could also be beneficial, as it would investigate how the collaboration networks between universities and industries evolve over time, providing a fresh perspective for assessing the long-term outcomes of these partnerships.

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References

Chen, H., Chu, G., & Hou, J. (2018). A Comparative Analysis on the Domestic and Foreign Modes of Cultivating Innovative Talents in Industry-University-Research Institute Cooperation. *Forum on Science and Technology in China*(01), 164-172.

China, M. o. E. o. t. P. s. R. o. (2003). Notice on the Establishment of National Technology Transfer Centers by the State Economic and Trade Commission, Ministry of Education, and Chinese Academy of Sciences. Retrieved December 30, 2024 from http://www.moe.gov.cn/jyb_xxgk/gk_gbgg/moe_0/moe_9/moe_35/tnull_427.html.

China, P. s. R. o. (2006). National Medium and Long-term Program for Science and Technology Development (2006-2020). Retrieved December 30, 2024, from http://www.gov.cn/gongbao/content/2006/content_240244.htm.

China, P. s. R. o. (2010). National Medium and Long-term Plan for Education Reform and Development (2010-2020) Retrieved December 26, 2024, from http://www.moe.gov.cn/srcsite/A01/s7048/201007/t20100729_171904.html.

China, P. s. R. o. (2021). Outline of the 14th Five-Year Plan for National Economic and Social Development and the Long-Range Objectives Through the Year 2035. Retrieved December 30, 2024, from http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm

China, P. s. R. o. (2022). Hold high the great banner of socialism with Chinese characteristics and strive in unity to build a modern socialist country in an all-round way - Report at the 20th National Congress of the Communist Party of China. Retrieved January 3, 2025

Dang, Q. T., Jasovska, P., Rammal, H. G., & Schlenker, K. (2019). Formal-informal channels of university-industry knowledge transfer: the case of Australian business schools. [Article]. *Knowledge Management Research & Practice, 17*(4), 384-395.

Ding, L., Huang, L., & Guo, K. (2010). Research on the Industry-Academia Cooperation Model in Vocational Colleges and Institutes. *West China Development*(4), 112-112.

Etzkowitz, H., & Leydesdorff, L. (1996). A triple helix of academic-industry-government relations: Development models beyond 'capitalism versus socialism'. [News Item]. *Current Science, 70*(8), 690-693.

Foundation, N. S. (2018). U.S. and International Research and Development: Founds and Alliances. Retrieved December 27, 2024, from http://www.nsf.gov/statistics/seind02/c4/c4s3.htm.

Fukugawa, N. (2013). University spillovers into small technology-based firms: channel, mechanism, and geography. [Article]. *Journal of Technology Transfer, 38*(4), 415-431.

Guo, J., He, M., & Huang, Y. (2007). The Analsis on the Transfomation of the Patent Technology in Universities & Colleges and It's Commercialized Countemm easures. *Technology and Innovation Management*(03), 80-83.

Guo, J., Xie, F., Wang, H., & Wang, M. (2019). Research on the Dynamic Evolution of Cooperative Networkbased on Industry-University Joint patent Data——An Analysis of" Double First-Class" Universities. *Science & Technology Progress and Policy, 36*(17), 1-10.

Hu, J., Zhu, G., & Ma, Y. (2011). System Dynamic Analysis on Influencing Factors of Industry-University-Research Cooperation in Open Innovation Context. *Science of Science and Management of S.& T, 32*(08), 49-57.

Kenney, M., & Patton, D. (2009). Reconsidering the Bayh-Dole Act and the current university invention ownership model. *Research Policy, 38*(9), 1407-1422.

Kwon, K. S., Park, H. W., So, M., & Leydesdorff, L. (2012). Has globalization strengthened South Korea's national research system? National and international dynamics of the Triple Helix of scientific co-authorship relationships in South Korea. [Article]. *Scientometrics, 90*(1), 163-176.

Liu, D. (2018). Transformation of University Patents in China： Problems and Strategies. *Tianjin Science & Technology, 45*(06), 1-5.

Liu, F., Ma, R., & Jiang, N. (2011). Research on Evolutionary Paths of Industry — University — Research Institute Networks of Patent Collaboration Based on the“985 Universities”. *China Soft Science*(07), 178-192.

Nonaka, I. (1994). A DYNAMIC THEORY OF ORGANIZATIONAL KNOWLEDGE CREATION. [Article]. *Organization Science, 5*(1), 14-37.

Rast, S., Khabiri, N., & Senin, A. A. (2012, Jan 13-15). *Evaluation Framework for Assessing University-Industry Collaborative Research and Technological Initiative.* Paper presented at the International Conference of the Asia-Pacific-Business-Innovation-and-Technology-Management-Society, Pattaya, THAILAND.

STIPCOMPASS. (2018). High-Tech Strategy 2025. Retrieved January 2, 2024, from https://stip.oecd.org/moip/case-studies/1.

Sun, Z., Liu, C., & Xu, R. (2016). Research University Technology Transfer Optimization Design Under The Perspective of System Comparison. *Science and Technology Management Research, 36*(20), 72-77.

Wang, S. (2020). Impact of university-industry collaboration on overall technology innovation performance of the university. *Journal of Innovation and Entrepreneurship Education, 11*(02), 1-6.

Wang, X., Wang, H., & Liu, L. (2005). Research on Industry-Academia-Research Alliance Models and Selection Strategies. *China University Science & Technology*(11), 64-67.

Wu, R., Liu, S., & Li, Z. (2021). Research on Knowledge Transfer Mechanisms in Industry-Academia-Research Collaborative Innovation. *Technology and Industry Across the Straits, 34*(06), 13-18.

Wu, X. (2012). Construction of Collaborative Innovation Alliance Involving Production，Teaching and Research and Experiences: I/UCRC Model. *China Higher Education Research*(04), 47-50.

Xiao, Y. (2016). Lessons and References for China from Typical Cases of Industry-Academia-Research Cooperation in Developed Countries: The Example of Germany's Dual System. *China University Science & Technology*(10), 43-45.

Yang, G. (2011). A Survey of the Transfer and Transformation of S&T Achievements in the United States. *Science & Technology for Development*(09), 87-93.

Zhang, P., & Huang, X. (2011). The Current Status, Issues, and Development of Patent Technology Transfer in Chinese Universities. *China Higher Education Research*(12), 34-37.