

Global Collaboration in Artificial Intelligence: Bibliometrics and Network Analysis from 1985 to 2019

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Abstract

Purpose: This study aims to explore the trend and status of international collaboration in the field of artificial intelligence (AI) and to understand the hot topics, core groups, and major collaboration patterns in global AI research.

Design/methodology/approach: We selected 38,224 papers in the field of AI from 1985 to 2019 in the core collection database of Web of Science (WoS) and studied international collaboration from the perspectives of authors, institutions, and countries through bibliometric analysis and social network analysis.

Findings: The bibliometric results show that in the field of AI, the number of published papers is increasing every year, and 84.8% of them are cooperative papers. Collaboration with more than three authors, collaboration between two countries and collaboration within institutions are the three main levels of collaboration patterns. Through social network analysis, this study found that the US, the UK, France, and Spain led global collaboration research in the field of AI at the country level, while Vietnam, Saudi Arabia, and United Arab Emirates had a high degree of international participation. Collaboration at the institution level reflects obvious regional and economic characteristics. There are the Developing Countries Institution Collaboration Group led by Iran, China, and Vietnam, as well as the Developed Countries Institution Collaboration Group led by the US, Canada, the UK. Also, the Chinese Academy of Sciences (China) plays an important, pivotal role in connecting the these institutional collaboration groups.

Research limitations: First, participant contributions in international collaboration may have varied, but in our research they are viewed equally when building collaboration networks. Second, although the edge weight in the collaboration network is considered, it is only used to help reduce the network and does not reflect the strength of collaboration.

Practical implications: The findings fill the current shortage of research on international collaboration in AI. They will help inform scientists and policy makers about the future of AI research.

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Originality/value: This work is the longest to date regarding international collaboration in the field of AI. This research explores the evolution, future trends, and major collaboration patterns of international collaboration in the field of AI over the past 35 years. It also reveals the leading countries, core groups, and characteristics of collaboration in the field of AI.

Keywords Artificial intelligence; International collaboration; Collaboration pattern; Bibliometric analysis; Social network analysis

1 Introduction

With the rapid development of big data, computer science, cloud computing, the internet of things, and other technologies, the term “Artificial Intelligence” (AI) has appeared more and more frequently and has gradually integrated into every aspect of life. Autopiloted cars, tickets purchased via face recognition, AI speakers, and autonomous poetry-writing robots can be seen everywhere in our daily lives. Research on collaboration in the field of AI can reveal the subject nature of AI. It can help us to understand the development trends in the field of AI, and it can help us to explore leading countries and major participating institutions with regards to cutting-edge research in the field of AI, while finding the core collaboration groups and the main collaboration patterns. Our findings will help scientists and policy makers to identify the current status of global AI technology, predict the future collaboration trends of the AI discipline and promote deeper scientific collaborative research in the field of AI. In addition, due to the uneven allocation of global resources and technological development, our research can better promote the rational allocation of resources, give full play to the technical advantages of various regions, reduce the cost of scientific research, and improve efficiency, thereby accelerating the spread and sharing of knowledge, making AI technology spread to all parts of the world faster, and bringing happiness to all mankind.

Through this research, we hope to solve the following problems:

- (1) What is the evolving trend of international collaboration in the field of AI? What are the main patterns of collaboration in the field of AI? What kind of collaboration trend will this discipline follow in the future?
- (2) What level of maturity has international collaboration in the field of AI reached? What is the internal structure of its cooperative network? Which countries and institutions are leading and promoting the development of AI? Which countries and institutions are major participants in international collaboration? At the national and institutional level, are there mature core collaboration groups?

Bibliometric analysis methods are widely used in literature growth trend analysis and theme analysis in information science (Koehler, 2001; Pan, Jian, & Liu, 2019;



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Tsay, 2011), computer science (Chen et al., 2018; Godoy, Zunino, & Mateos, 2015), medicine (Sohn et al., 2018; Tarazona-Alvarez et al., 2019), psychology (Dinić & Jevremov, 2019). Social network analysis methods transform entities and relationships in the real world into nodes and edges in a network, thus visualizing co-occurrence. It is often used in keyword co-occurrence analysis, cited analysis, collaboration network analysis, and other research. Pajek (Tarazona-Alvarez et al., 2019), Ucinet (Gao et al., 2019), CiteSpace (Pan, Jian, & Liu, 2019), VOSviewer (Dinić & Jevremov, 2019; Peng & Dai, 2018), and other software are usually used to construct social networks and to analyze internal structures, central nodes, and core groups of networks.

At present, there are relatively few studies on AI collaboration. Our previous study (Hu, Wang, & Huang, 2019) selected 26,808 papers in the field of AI from the Web of Science core collection database. Using bibliometric analysis and social network analysis methods, we found that 84% of the papers between 1985 and 2017 were joint publications. Two-country papers were the main pattern of international collaboration at the country level, and country collaboration networks have reached a certain maturity. This study had a large granularity, however, and only analyzed collaboration at the country level, having failed to conduct a more detailed exploration. Niu et al. (2016) selected 20,715 papers included in the Science Citation Index Expanded (SCI-Expanded) and Conference Proceedings Citation Index-Science (CPCI-S) from 1990 to 2014. By using bibliometric analysis, spatial analysis, and social network analysis, they discovered the major journals and hot topics in the field of AI and probed into the regional distribution and development trends of international collaboration. This study only considered publications in the natural sciences, however, even though there are also many studies on AI in the social sciences (Cai et al., 2019; Miller, 2019; Pee, Pan, & Cui, 2019). Therefore, the conclusion is one-sided and cannot fully reflect global collaboration in the field of AI. Gao et al. (2019) conducted a bibliometric analysis of 12,301 papers in the WoS core collection database from 2008 to 2018. Through frequency analysis, correlation analysis, and trend analysis, they explored the changing trends of hot research in the field of AI, and they summarized five research topics. The study also conducted a social network analysis of country collaboration over the past 10 years. The papers it used for analysis, however, cover a short time range and cannot fully reflect collaboration between countries. In addition, it only calculated simple statistics on productive institutions and did not reveal the characteristics of institutional collaboration. Shukla et al. (2019) conducted a collaboration network analysis of publications published in the journal *Engineering Applications of Artificial Intelligence* (EAAI) from both the national and institutional levels and explored the coupling between institutions and countries. The data in this study was limited to only one journal, EAAI, and only institutions and countries with high



outputs were considered in the network construction process, so it did not reflect the general phenomenon of collaboration in the field of AI.

To solve the shortage of research on international collaboration in artificial intelligence, we choose papers in the field of AI in the WoS core collection database across a total of 35 years from 1985 to 2019. Using bibliometric analysis and social network analysis methods, from macro and micro perspectives, we explore the trends and hot topics of international collaboration in the field of AI at the author, country, and institutional levels. Compared with previous studies, our research makes the following innovations. (1) It conducts a comprehensive survey for all disciplines. Our research is not limited to a certain discipline or a certain level, and its dataset is a comprehensive selection of literature in the natural sciences, humanities, and social sciences, so its results reflect real global AI collaboration more comprehensively and precisely. (2) It covers a long time span in the dataset. Based on a comparative analysis of the literature over the past 35 years, we fully consider factors of timeliness to accurately present the mainstream collaboration patterns of different periods and their overall evolution. (3) It conducts a multi-dimensional in-depth exploration. We summarize the main collaboration patterns and future collaboration trends at various levels of granularity. We visualize the collaboration networks at different scales, gain insight into the internal structural characteristics of the networks and explore core groups and central nodes.

2 Methods

2.1 Data collection and processing

The AI data set used in this research are publications collected from Clarivate Analytics' Web of Science (WoS) core collection database using "Artificial Intelligence" as a search term. This database not only has a high impact but also contains journals and conference proceedings such as "Expert Systems With Applications," "IEEE Access," "AI Magazine," and "Proceedings of the IEEE," which have a high impact in the field of AI. Generally speaking, in other research fields, only articles studied (AleixandreTudó et al., 2019; Tang, Chou, & Tsai, 2019; Tarazona-Alvarez et al., 2019; Wu & Duan 2015), but a considerable part of the papers in the field of AI are collected in the form of conference papers, and the number of conference papers is generally on the rise. Therefore, the AI dataset used in this study is collected from articles and conference proceedings included in SCI-Expanded, SSCI, A&HCI, CPCI-S, and CPCI-SSH. Figure 1 shows the annual distribution of articles and proceeding papers spanning 1985–2019. The data used in Figure 1 has not been cleaned.

Through manual downloading, we obtained a total of 42,630 records. Data collection was completed on January 2, 2020. WoS provides more than 60 field



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identifiers. After analysis and screening, we finally reserved five field identifiers related to collaboration information for this study. The five fields are the author's full name (AF), corporate author (CA), source publication (SO), author's address information (C1), and publishing year (PY). Some of the older records missed one or more field of information. After processing, 38,224 papers were finally retained as valid data. After calculating the statistics of the SO field, Table 1 was compiled, listing the top 20 publications with the largest number of published papers and related information from 1985 to 2019.

Table 1. Top 20 AI publications and their paper amounts between 1985 and 2019.

Rank	Journals	Papers	Percent (%)
1	EXPERT SYSTEMS WITH APPLICATIONS	461	1.206%
2	IEEE ACCESS	290	0.759%
3	AI MAGAZINE	233	0.610%
4	ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE	220	0.576%
5	APPLIED SOFT COMPUTING	192	0.502%
6	ARTIFICIAL INTELLIGENCE	191	0.500%
7	SENSORS	152	0.398%
8	NEUROCOMPUTING	139	0.364%
9	ARTIFICIAL INTELLIGENCE REVIEW	122	0.319%
10	NEURAL COMPUTING & APPLICATIONS	122	0.319%
11	JOURNAL OF INTELLIGENT & FUZZY SYSTEMS	114	0.298%
12	MINDS AND MACHINES	111	0.290%
13	INFORMATION SCIENCES	105	0.275%
14	KNOWLEDGE-BASED SYSTEMS	104	0.272%
15	ENERGIES	103	0.269%
16	ARTIFICIAL INTELLIGENCE IN MEDICINE	99	0.259%
17	APPLIED ARTIFICIAL INTELLIGENCE	96	0.251%
18	EUROPEAN JOURNAL OF OPERATIONAL RESEARCH	96	0.251%
19	AGRO FOOD INDUSTRY HI-TECH	94	0.246%
20	KYBERNETES	93	0.243%

From the AF field of the WoS record, we can get all the author names of the papers. In this field, the names of different authors are separated by a semicolon, such as “Chen Yunqing; Zhou Guoqiang” and “Fong, Simon; Wong, Raymond; Pichappan, Pit.” Therefore, the number of authors of each paper can be obtained by writing a Python program to segment and count AF field information.

Data from the C1 field is needed for country-level analysis. Due to the long time range of the covered data, the data structure of the C1 field is more complex than that of the AF field. A total of 74% of the records (28,268 papers) are organized according to the rule “[Author(s)] institution, address,” such as “[Xu, Yang; Wang, Weijia; Yang, Jiabin; Li, Jiahong] Peking University, Department of Information Management, Beijing, People's Republic of China”. The remaining 26% of the records (9,956 papers) contain no author information in the C1 field, such as “Linkoping Univ, Dept Comp & Informat Sci, S-58183 Linkoping, Sweden.”



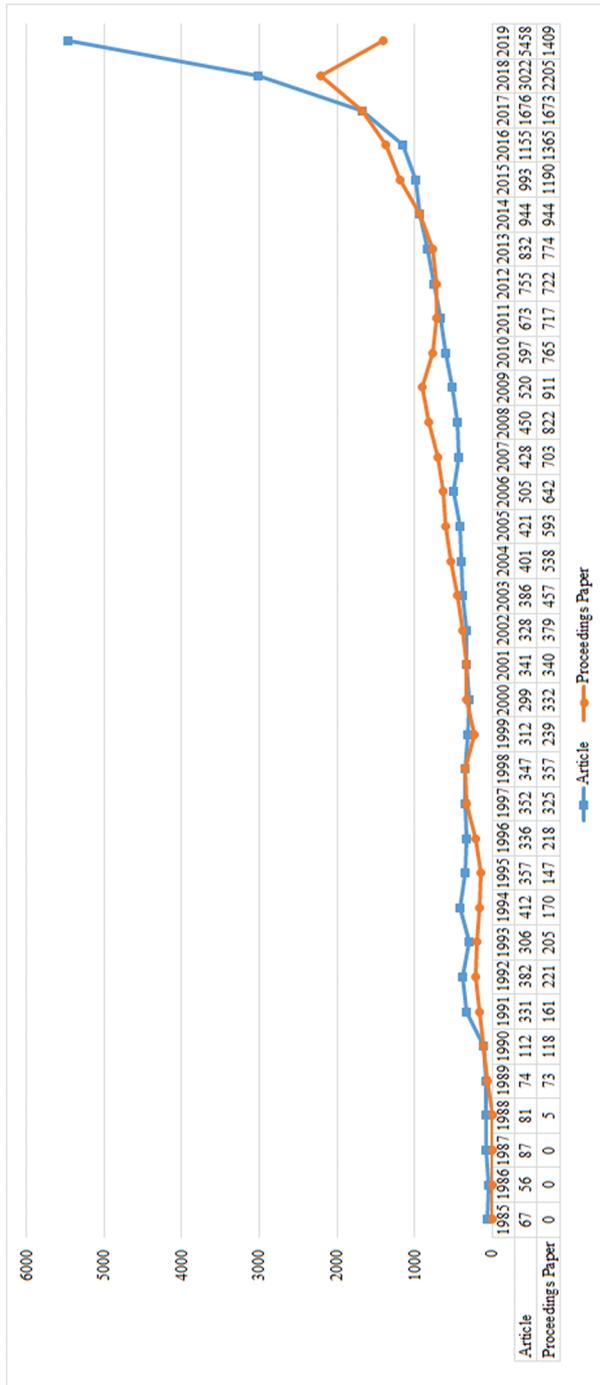


Figure 1. Comparison of the number of articles and proceedings papers 1985–2019.



Country information can be obtained by extracting the data in the last comma. Addresses in the United States, however, are organized differently. For example, in “[Du, Xiaojiang] Temple Univ, Dept Comp & Informat Sci, Philadelphia, PA 19122 USA,” the information after the last comma is “PA 19122 USA,” that is, state information is mixed with country information. To ensure data consistency, only the last country information is retained during the extraction process. In addition, country information can be missed in some of the records, such as in “AUBURN UNIV, DEPT ELECT ENGN, AUBURN, AL 36380.” At this point, we need to complete the country information through the agency information and the state name. Since the C1 field records before 1997 were all in uppercase, country information needs to be case uniform, such as by converting “CANADA” to “Canada.”

Collaboration information at the institutional level can be extracted before the first comma in the C1 record. Similar to the processing of country information, there is a need to unify the case of the institution names, such as converting “UNIV CALIF SAN FRANCISCO” to “Univ Calif San Francisco.” Some institutions have multiple naming methods, but the most common names are used for such cases. For example, “Univ Pennsylvania” and “Univ Penn UPENN” is merged into “Univ Penn,” and “NYU” is merged into “New York Univ.” In addition, during the 35 years from 1985 to 2019, some institutions changed their names and needed to convert their former names to their current names. For example, Castleton university, formerly known as “Castleton Coll,” is merged into its current name, “Castleton Univ.”

The extracted collaboration information is stored in SQL Server database for bibliometric analysis and social network analysis. The extraction process of country and institution information is shown in Figure 2 below.

2.2 Methods and tools

We extracted collaboration information from the WoS dataset and organized the data format using the Python programming language. With the help of Python3.6.2, Matlab 2011b, and Microsoft Excel 2016 for Windows, this paper conducted a bibliometric analysis on international collaboration in the field of AI at the author, country, and institutional levels, and it explored the trend and evolution of collaboration. Pajek5.01 was used to build collaboration networks at the country and institutional levels, to calculate the degrees of nodes, betweenness centralization (BC) and other indicators, and to explore the core groups and status of international collaboration.

In the process of constructing the collaboration network, since the author order is not considered in this study, the contribution of each author in the cooperative



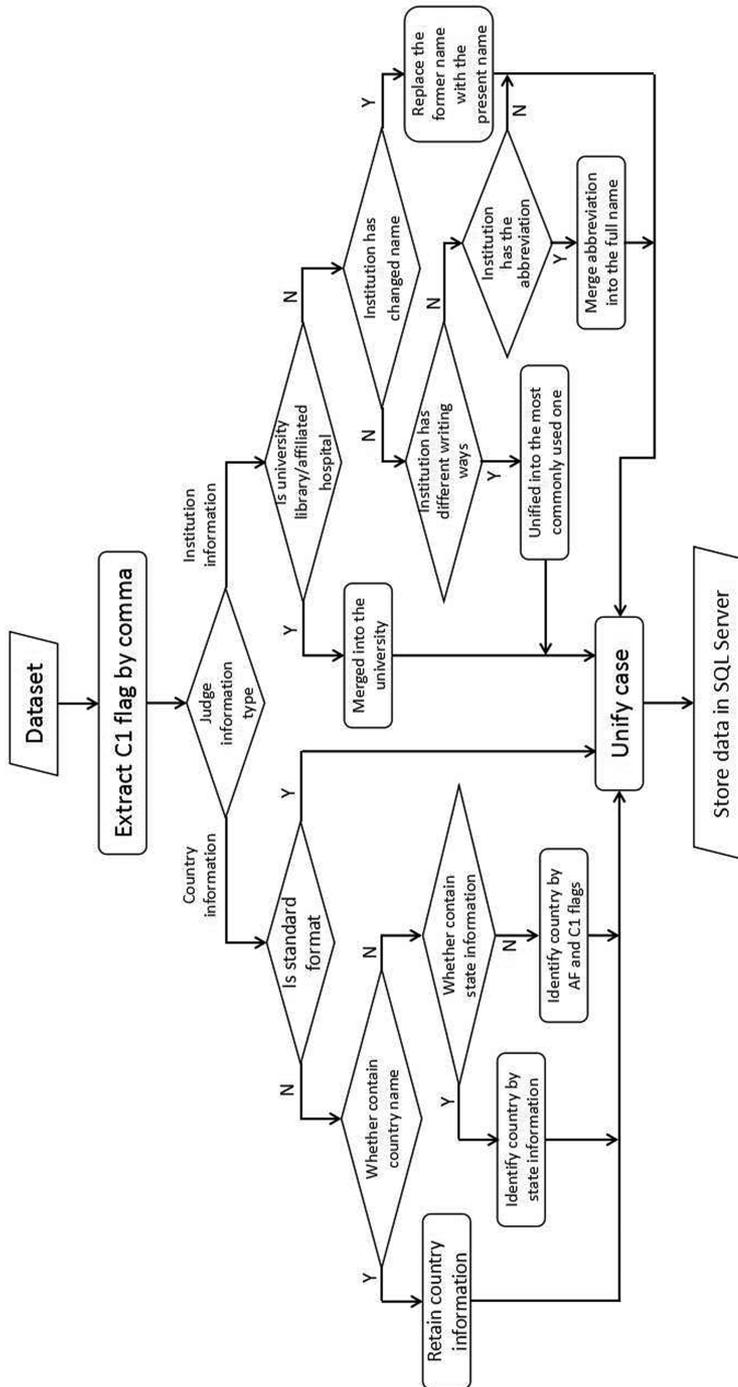


Figure 2. Extraction process for country and institution information.



relationship is considered as the same, and the collaboration networks constructed are undirected graph networks. Taking the country collaboration network as an example, each country/region is represented as a node in the network. If two countries/regions appear together in the C1 field, the two countries/regions are considered to have a cooperative relationship, and the two nodes are connected by a single edge. The closeness of the partnership is expressed using edge weights. The weight of the edge is defined as the number of times the countries/regions appear together in the C1 field.

For bibliometrics, the number of different types of papers and their percentage of total papers are calculated respectively. For social network analysis, the degree of nodes and betweenness centralization (BC) are used to measure the location and importance of nodes in the network.

The degree of a node refers to the number of nodes associated with that node in the network. For collaboration networks, the degree k_i of node v_i can be calculated by the following formula (1):

$$k_i = \sum_j a_{ij} = \sum_i a_{ij} \quad (1)$$

Betweenness centralization (BC) measures the degree to which a node is located between other nodes and reflects the degree to which the node controls resources in the network. For a given node v_i in a network, its BC can be calculated by formula (2):

$$C_B(i) = \sum_{j < k} g_{jk}(i) / g_{jk} \quad (2)$$

3 Results and discussion

In this section, we use bibliometrics analysis and social network analysis to analyze and discuss the international collaboration in the field of AI.

3.1 Bibliometric analysis of international collaboration

In this section, bibliometric analysis is conducted to capture the changes and development trends of international collaboration in the field of artificial intelligence over a total period of 35 years from 1985 to 2019 from the perspectives of authors, countries/regions, and institutions.

3.1.1 Collaboration at the author level

The collaboration between authors can intuitively reflect the degree of collaboration in the paper. Papers written by only one author are called single-author papers; papers written by two or more authors are called collaborative papers.



Collaboration at the author level was measured by the number of authors of the paper. Figure 3 shows the total number of papers, single-author papers, two-author papers, three-author papers, and four-or-more author papers in the filed of AI from 1985 to 2019. The trend line chart shows the percentage of each type in the total number of papers.

During these 35 years, 84.8% (32,412 papers) of papers in AI were collaborative, while only 15.2% (5,812 papers) were created by a single author. Two-author papers, three-author papers and four-or-more author papers accounted for 24.9% (9,509 papers), 23.4% (8,960 papers) and 36.5% (13,943 papers), respectively. This indicates that the collaboration in the field of AI has reached a certain level of maturity. The percentage of single-author papers showed a declining trend. The percentage of single-author papers in 1986 was the highest of all paper types, at 46.2% (18 papers). In 2019, the share of single-author papers fell to 11.4% (607 papers), the lowest of any paper type. In fact, since 2003, the percentage of single-author papers and its absolute number have been the lowest of all paper types, reflecting the increasing degree of scientific collaboration in the field of artificial intelligence. The proportion of two-author papers rose rapidly from 1985 to 1991 and was the dominant pattern of collaboration papers from 1989 to 2008. After 1991, it showed a downward trend year by year. Especially after 2012, two-author papers have become the one with the lowest proportion of all collaborative papers. Similarly, before 2013, the proportion of papers of three authors generally showed a slow rise, after which the proportion of papers of this type of collaboration began to decline, with the post-2016 timeline showing a steep decline (26.5%, or 617 papers). The proportion of papers with four or more authors in 2016 also showed a significant shift. From 2013 to 2016, the proportion of papers of this type decreased slightly, while from 2016 to 2019, the proportion of this type increased strongly. In 2019, the proportion of papers of four or more authors even exceeded half of all papers, reaching 54.4% (2,894 papers). Moreover, since 2009, in both proportion and absolute number of papers, papers with four or more authors were the most of all paper types, and in this period this paper type was the only one to show an increase over time.

Scientific research in the field of AI is mainly carried out in the form of collaboration, and as time goes by, the number of authors and degree of collaboration have been increasing. From 1989 to 2008, the two-author paper was the main pattern for the collaborative paper, while after 2008, the four-or-more author paper became the mainstream form of the international collaborative paper in the filed of AI. During the past 35 years, the proportion of papers with single authors gradually decreased. And although the proportion and number of papers jointly written by two



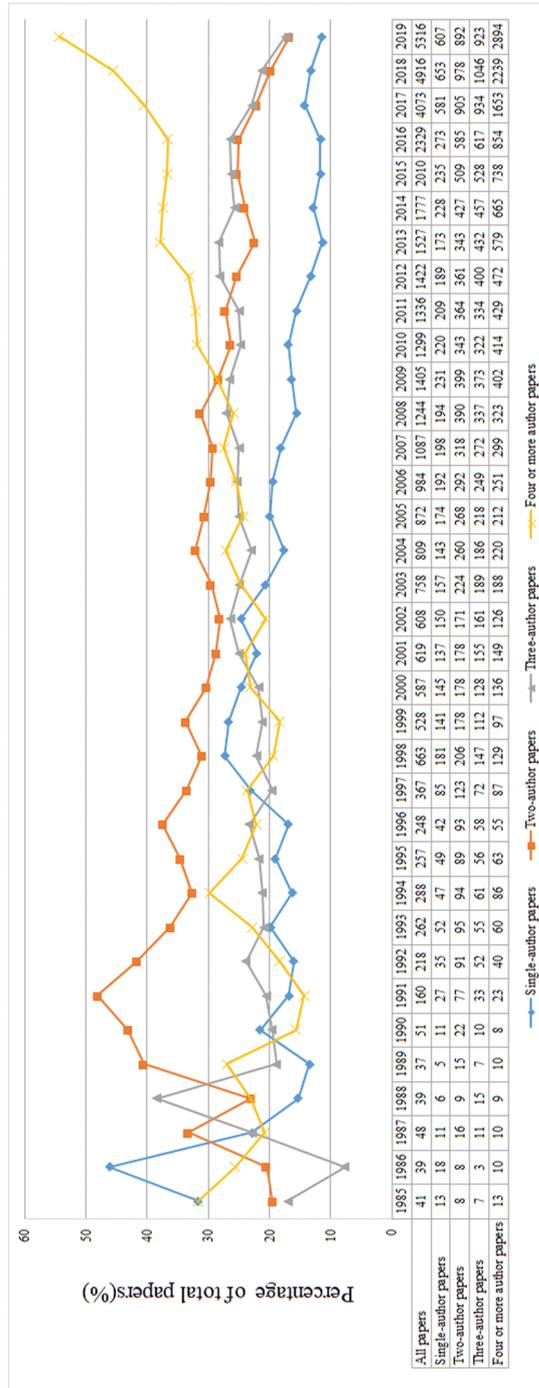


Figure 3. The temporal trend lines of collaboration at the author level in artificial intelligence field.

or three authors were more than that of single-author papers, the timeline also showed a declining trend. It can be inferred that the proportion of papers with fewer than four co-authors will continue to decrease, while those with more than three co-authors will continue to increase. Papers with four or more authors were the only type of collaborative papers which showed an increase, and papers with four or more authors accounted for more than 50% in 2019. Therefore, it can be judged that the form of collaboration with more than three authors is the main pattern of collaboration in the field of AI, and the scientific collaboration in this field presents a trend of increasingly many authors.

3.1.2 Collaboration at the country/regional level

Collaboration at the author level reflected the main collaboration patterns in the field of AI, as well as the evolution of the degree of collaboration based on the number of authors. Due to a lack of national information, however, international collaboration is not reflected. In this section, we explore collaboration trends and major patterns at the country/regional level. Similar to collaboration at the author level, we define papers with only one country/region name in the C1 field as single-country papers, and we define papers with two countries/regions as two-country papers, and so on. In addition, if the authors of the paper are all from the same country/region, differences between the collaboration paper and the single-author paper cannot be reflected. Therefore, we define the papers as domestic collaboration papers if their co-authors are all from the same country/region. In contrast, paper co-authors from two or more different countries are defined as international collaborative papers. Figure 4 is the trend line chart of international collaboration in the field of artificial intelligence at the country/regional level from 1985 to 2019.

Over these 35 years, the number of single-country papers (31,499 papers) and the percentage of them (82.4%) are significantly higher than that of any other types. In 1986 and 1988, the proportion of single-country papers even reached 100%, that is, all papers in the field of artificial intelligence were single-author papers or domestic collaborative papers. Moreover, the proportion of domestic collaborative papers (67.2%, or 25,687 papers) is 49.6% higher than that of international collaborative papers (17.6%, or 6,725 papers). This means in the field of AI, single-country papers and domestic collaborative papers are the main types of international collaborative papers, indicating that scientific collaboration between researchers from the same country is the main pattern of collaboration in the field of AI. Although the number of single-country papers and domestic collaborative papers accounted for the majority, with the passage of time, the proportion of such papers gradually decreased, showing a general downward trend. In 2019, the proportion of single-country papers dropped to 72.2%, and domestic collaboration papers accounted for 60.7%. The



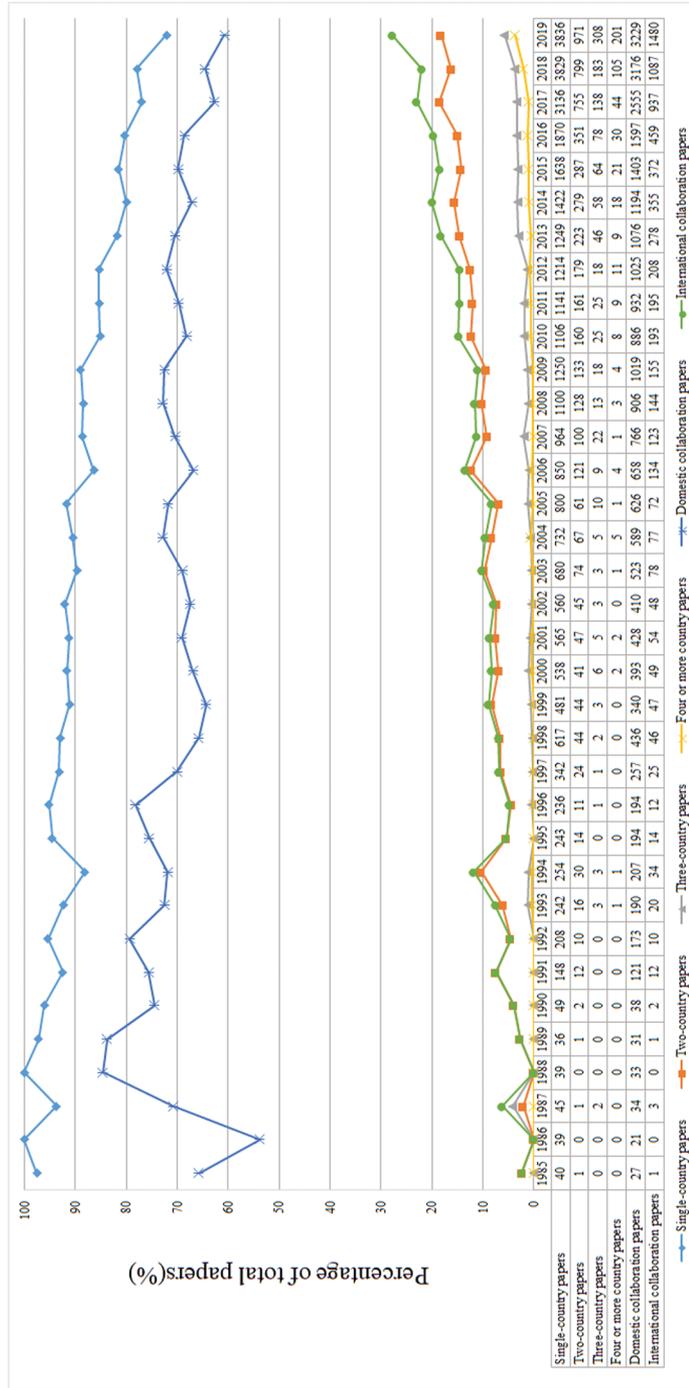


Figure 4. The temporal trend lines of collaboration at the country/region level in artificial intelligence field.

proportion of multi-country collaborative papers has been increasing, however, which shows the research in the field of AI is gradually shifting towards multinational collaboration.

For multi-country collaborative papers, the number of two-country papers remained in the lead except for in 1987. The proportion of two-country papers for all international collaborative papers from 1985 to 2019 is 77.2% (5,192 papers), indicating that two-country collaboration (Hu, Wang, & Huang, 2019) is still the main pattern in global artificial intelligence collaboration. In Figure 4, we notice that from 1985 to 2009, the trend lines for two-country papers and international collaborative papers basically overlap, which means that international collaboration was almost carried out in the form of cooperation between two countries before 2009. Although the proportion of international collaborative papers in 35 years is not high (17.6%, or 6,725 papers), it has increased from 0% in 1986 to 27.8% in 2019. This shows that scientific research collaboration in the field of artificial intelligence has developed towards internationalization.

3.1.3 Collaboration at the institutional level

Research in the field of AI at the country level revealed the main patterns and development trends of international collaboration from a macro perspective, but the granularity was not sufficiently fine. For example, for single-country papers, it is impossible to distinguish between single-author papers and multi-author papers from the same country. Also, international collaborative papers only showed the number of countries participating in collaboration, but no more detailed information can be obtained. Therefore, this section takes the institution as the minimum countable object and further investigates collaboration at the institutional level. In addition, country information was included in the statistical process to present a more granular picture of international collaboration. Figure 5 shows the time distribution of single-institution papers, two-institution papers, three-institution papers, and four-or-more institution papers, and it also shows the proportion of domestic-institution collaborative papers, international-institution collaborative papers, and international papers with two institutions, over time.

Similar to country-level collaboration, the proportion of single-institution papers in total papers was 51.8% (19,791 papers), the highest of any type of paper at the institutional level. This suggests that more than half of the research in the field of AI over the past 35 years has been done independently within a single institution. In the single-institution papers, 70.6% (13,979 papers) were co-authored, while only 29.4% (5,812 papers) were written by a single author. This further indicates that intra-institution collaboration has been the main pattern of collaboration research in the field of AI. The proportion of single-institution papers showed a downward



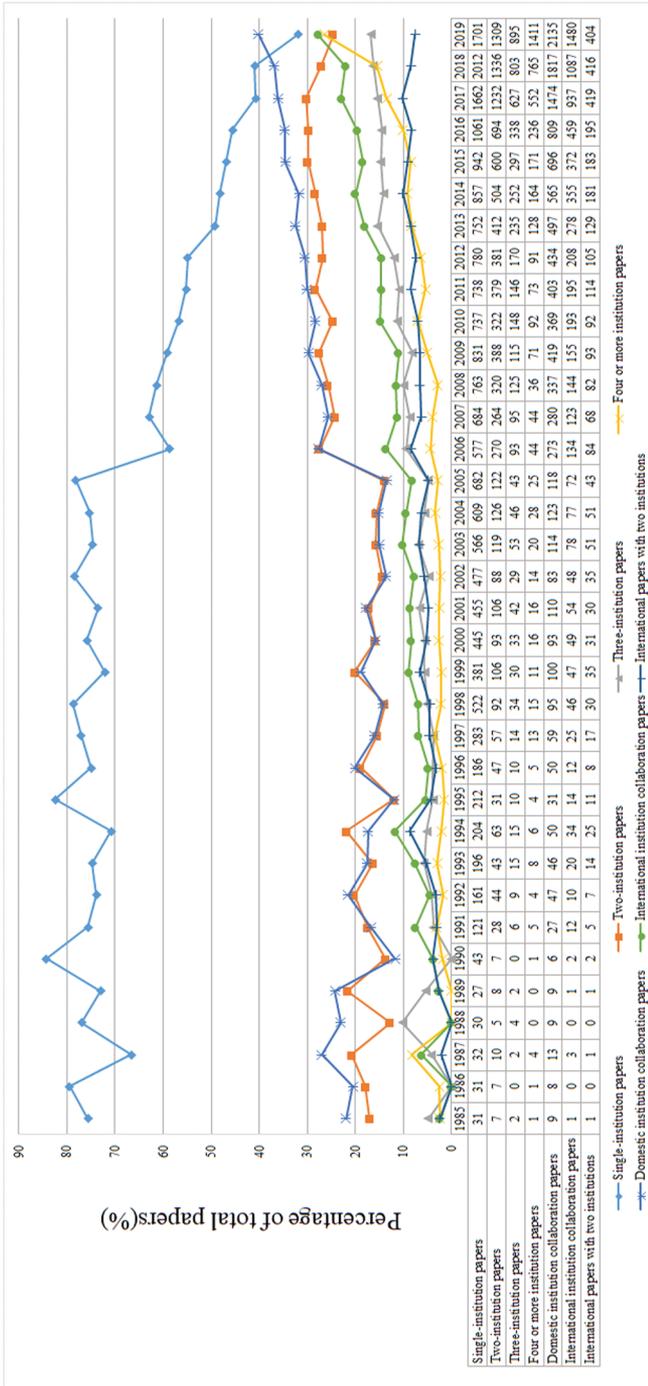


Figure 5. The temporal trend lines of collaboration at the institutional level in artificial intelligence.

trend, with the highest proportion (84.3%, or 43 papers) in 1990 and a drop of over 50% to 32.0% (1,701 papers) in 2019. This shows that multi-institution collaborative papers are gradually becoming the mainstream.

The share of two-institution papers was on the rise, from 17.1% (7 papers) in 1985 to a peak of 30.3% (1,232 papers) in 2017. But after 2017, the share of two-institution papers declined for two consecutive years to 24.6% (1,309 papers) in 2019. By contrast, though the proportions of three-institution papers and four-or-more institution papers were lower than that of two-institution papers before 2019, they maintained an upward trend over the past five years. The proportion of papers with four or more institutions showed a high growth rate in particular. In 2019, they exceeded the proportion of two-institution papers and three-institutions papers. And over the past 35 years, the number of two-institution papers (25.2%, or 9,620 papers) was 2.0 times that of three-institution papers (12.4%, or 4,738 papers) and 2.4 times that of four-or-more institution papers (10.7%, or 4,075 papers). This indicates that the two-institution paper has been the main pattern of collaboration in the field of AI at the institutional level. In addition, this shows a trend of multi-institution collaboration, and the proportion of papers with more than two institutions is increasing.

The proportion of domestic collaborative papers and international collaborative papers shows an increasing trend, indicating that the degree of collaboration in the field of AI is deepening. Between 1985 and 2019, 30.6% (11,708 papers) were domestic collaborative papers, and 17.6% (6,725 papers) were international collaborative papers. This result shows that domestic institution collaboration is the main pattern of international AI collaboration at the institutional level. Two-international-institution papers produced 44.1% (2,963 papers) of collaborative papers, while three-international-institution papers produced 21.8% (1,463 papers). This showed that international papers with two institutions have been the main pattern of collaborative papers between international institutions. In Figure 5, it can also be seen that the proportion of international papers with two institutions also began to decline from 2017, and the overall trend over time trend was similar to that of two-institution papers. This indicated that the proportion of collaborative papers with more than two institutions has also been increasing.

3.2 A network analysis of international collaboration

Through bibliometric analysis, this paper explores the evolution, main collaboration patterns and future development trends of international collaboration in the field of AI at the author, country and institutional levels from 1985 to 2019. In this chapter, with the help of social network analysis, we explore the central nodes, network structures and core groups in global AI collaboration over the past 35 years at the country/regional and institutional levels.



3.2.1 International collaboration at the country/region level

In this section, we analyzed international collaboration in the field of AI from a macro level. Figure 6 shows a country collaboration network built using Pajek software. Each node in the graph represents a country/region. The text next to the node is used to explain the name of the country/region represented by the node. The value in brackets is the degree of the node. The larger the degree of the node is, the larger the circle area of the node is, and the nodes of the same degree share the same color. An edge between nodes indicates collaboration between two countries/regions. Over the past 35 years, a total of 65.7 percent of countries (153 of 233 countries/regions) have participated in international collaboration in the field of AI. International participation, however, in neurosurgical (Frey et al., 2017) was 28.8% (67 country/region) and 33.0% (77 country/region) in brain death (Doğan & Kayır, 2019). This reflects that the international collaboration in the field of AI has been widely involved with other fields, with a high degree of collaboration. It should be noted that the country collaboration network contains 1,948 edges, but only 849 of them have a weight greater than two; that is, the two countries connected by such edges have only cooperated once or twice, and the collaboration between such countries is not close. To highlight the core and clearly show the network structure, we deleted all edges with weights less than five, and we deleted isolated nodes. Also we did not reflect the edge weight information in the image. The resulting network consists of 78 nodes and 586 edges. The nodes with large degrees are located in the central region of the network, while the nodes with small degrees are distributed in the edges of the network.

It can be clearly seen from Figure 6 that the countries/regions represented by the nodes with the largest degrees are the US, the UK, France, Spain, China, and Germany. The larger the degrees are, the more nodes are directly connected to this node in the network, indicating that the countries represented by this node have cooperative relations with more countries. The US and the UK were at the core of the network, conducting collaborative research in the field of AI with many countries/regions around the world. After calculation, the average degree of the whole network is 25.46, indicating that each country/region has an average of 25–26 partners. On the other hand, the average degree of the country collaboration network was 10.70 between 1985–2017 (Hu, Wang, & Huang, 2019). This shows that after 35 years of development, international collaboration in the field of AI has reached a high level of maturity and has been especially deepened in the last two years.

Betweenness centralization (BC) is another measure of a node's ability to control the network. In collaboration networks, a small node may play a key role in connecting the whole network. After calculation, the BC of the whole network is



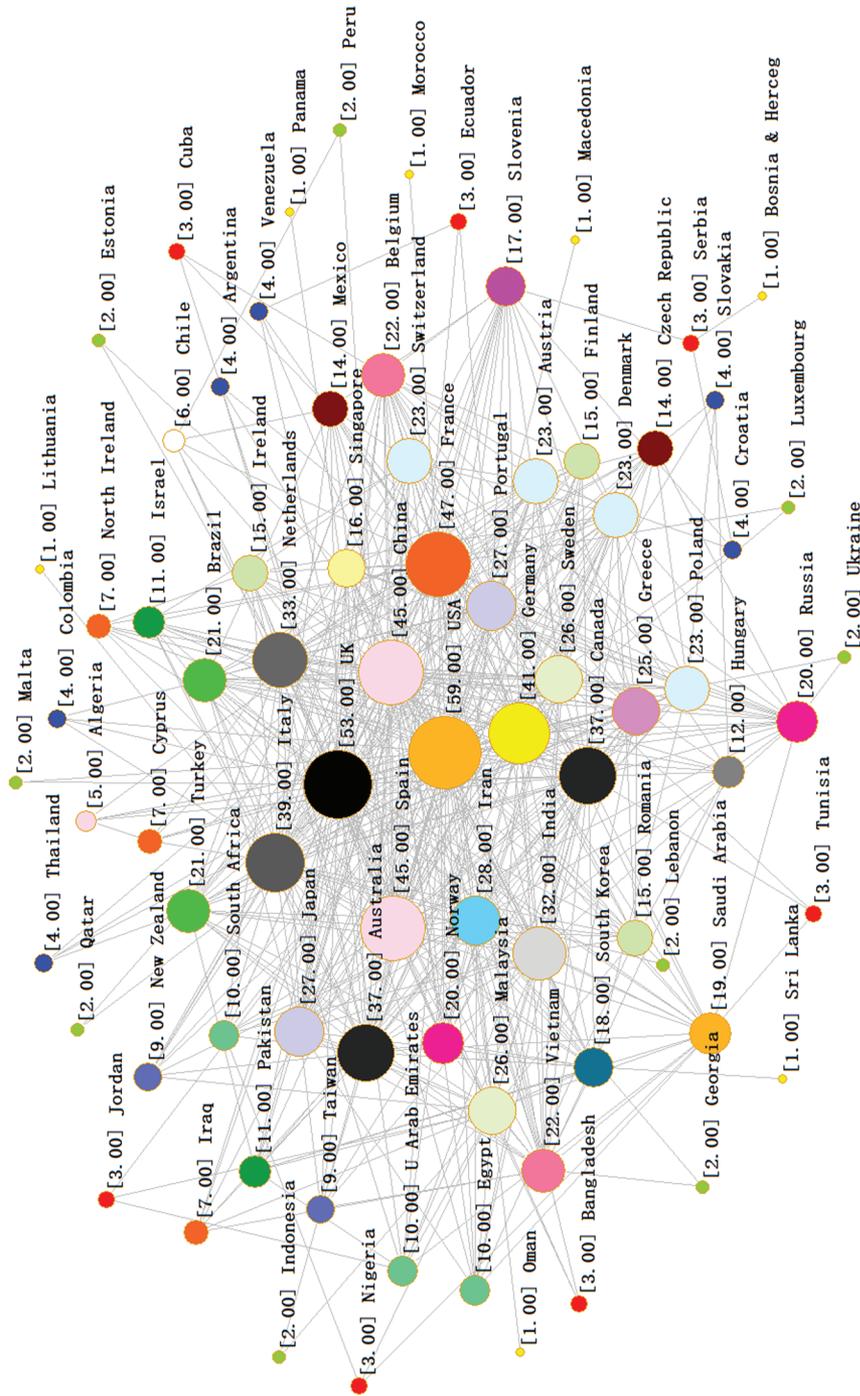


Figure 6. The country collaboration network in the global artificial intelligence field between 1985 and 2019.



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0.15665359, and the BC of the adjusted network is 0.18289824, as shown in Figure 6. Table 2 lists the top 20 countries/regions in terms of BC.

Table 2. Countries/regions with high BC in the collaborative network.

Rank	Country/region	BC	Degree
1	US	0.194044287	59
2	Spain	0.121497557	45
3	France	0.09336937	47
4	UK	0.08893566	53
5	Malaysia	0.066529876	26
6	Italy	0.049736817	39
7	Slovenia	0.046246703	17
8	China	0.044717068	45
9	Germany	0.044155013	41
10	Australia	0.041308894	37
11	Serbia	0.025974026	3
12	Canada	0.025611038	37
13	Iran	0.022606583	28
14	Poland	0.019977656	23
15	Netherlands	0.017546622	33
16	Saudi Arabia	0.014945119	19
17	Russia	0.013316129	20
18	Vietnam	0.01329915	22
19	Portugal	0.013039462	27
20	India	0.011128811	32

As can be seen from Table 2, the countries with high BC are the US, Spain, France, and the UK. In the country collaboration network (Figure 6), these countries also have high degree. This shows that they played a key role in international collaboration in the field of AI between 1985 and 2019. They did not only have a wide range of overseas partners, but also played a core and leading role in artificial intelligence research. We found that China and Germany, however, also had high degrees, but were slightly lower in the BC ranking. On the other hand, Malaysia, Slovenia and even Serbia with degree values of 3 had relatively high BC values. These countries also played an important role in connecting the entire network of international collaboration. This phenomenon indicates that more partners do not mean a stronger ability to control the collaboration network. It also reflects the problem that the degree to which a country/region participates in international collaboration cannot be fully reflected only by the degree and BC of nodes. Therefore, we adopt a normalization method to eliminate the dimensional differences of different countries' publications, to further analyze the degree of participation of countries in international collaboration. We calculate the ratio of the number of international collaborative papers to the total number of papers in each country, listing the countries/regions with a total publication volume of more than 100 papers from 1985 to 2019, as detailed in Table 3.



Table 3. Countries and regions with a high percentage of collaboration in the global field of AI between 1985 and 2019.

Rank	Country/region	Total papers	Collaborative papers	Percentage of collaborative papers
1	Vietnam	189	170	89.95%
2	Saudi Arabia	344	277	80.52%
3	U Arab Emirates	128	99	77.34%
4	Pakistan	301	229	76.08%
5	Sweden	332	251	75.60%
6	Switzerland	365	266	72.88%
7	Denmark	173	126	72.83%
8	Netherlands	578	402	69.55%
9	Tunisia	158	109	68.99%
10	Iran	1,279	880	68.80%
11	Slovenia	156	107	68.59%
12	Malaysia	737	499	67.71%
13	Portugal	461	310	67.25%
14	Belgium	310	206	66.45%
15	France	1,444	954	66.07%
16	Egypt	262	173	66.03%
17	Australia	1,180	773	65.51%
18	New Zealand	152	99	65.13%
19	Singapore	455	289	63.52%
20	Colombia	133	84	63.16%
21	Serbia	160	101	63.13%
22	Finland	234	146	62.39%
23	Israel	218	136	62.39%
24	Spain	1,960	1,218	62.14%
25	Italy	1,377	855	62.09%
26	Turkey	909	561	61.72%
27	Mexico	459	283	61.66%
28	Norway	191	117	61.26%
29	UK	3,070	1,863	60.68%
30	Canada	1,463	877	59.95%
31	Taiwan	888	532	59.91%
32	South Korea	869	516	59.38%
33	Brazil	1,077	638	59.24%
34	Greece	500	291	58.20%
35	Germany	1,538	892	58.00%
36	Austria	337	193	57.27%
37	USA	7,763	4,436	57.14%
38	Japan	1,239	697	56.26%
39	China	6,444	3,596	55.80%
40	Ireland	206	114	55.34%
41	Algeria	204	111	54.41%
42	Thailand	151	80	52.98%
43	Indonesia	180	95	52.78%
44	India	2,080	1,092	52.50%
45	South Africa	205	105	51.22%
46	Hungary	159	81	50.94%
47	Russia	540	267	49.44%
48	Czech Republic	379	164	43.27%
49	Slovakia	143	61	42.66%
50	Romania	627	263	41.95%
51	Poland	866	360	41.57%



In Table 3, the top five countries are Vietnam, Saudi Arabia, the United Arab Emirates, Pakistan, and Sweden. Although these countries are on the periphery of the country collaboration network, their international collaboration publications account for a considerable proportion of all publications. For Vietnam in particular, nearly 90% of the papers in the field of AI are international collaborative papers. This shows the high level of participation of these countries in international collaboration. The US, the UK, France, and Spain, however, which rank highly in terms of the degree of nodes and BC, had a relatively low proportion of international collaborative papers. In particular, the in US, which is at the center of the country collaboration network, only 57.14% of its papers are international collaborative papers.

3.2.2 International collaboration at the institutional level

In this section, we analyzed international collaboration in the filed of AI from the micro level. The smallest unit used to build the network is the institution. Similar to the bibliometrics analysis at the institutional level, we construct a collaboration network from the perspectives of all institutional collaboration and international institutional collaboration, respectively. The international institution collaboration network only considers institutional collaboration from different countries. On the basis of the former, the complete institutional collaboration network adds institutional collaboration from the same country/region.

3.2.2.1 Complete institutional collaboration network

Between 1985 and 2019, 15,351 institutions around the world participated in scientific collaboration in the filed of AI. There were 54,565 edges, however, with weights of only 1, while there were 7,306 edges with weights greater than 1. Similarly, edges with weights less than eight and isolated nodes were removed to facilitate the presentation of the network structure. In the end, the complete institutional collaboration network consists of 128 nodes, 121 edges and a total of 29 subnets. The largest subnet contains 48 nodes, while the other two large subnets contain 14 and six nodes, respectively. There is one subnet that contains four nodes, and there are six subnets that contain three nodes. The rest are composed of two nodes. The three subnets containing the largest number of nodes are shown in Figure 7 below. For convenience of distinction, these three networks are called sub-network 1 (SN-1), sub-network 2(SN-2) and sub-network 3(SN-3), respectively.

The average degree of the complete institutional collaboration network is 8.06, indicating that over the past 35 years, on average, each institution cooperated with eight other institutions in the filed of AI. The network structure of the entire SN-1 is two closely related network groups connected by Xi'an University of Science & Technology (China). One of them takes Chinese Academy of Sciences (CAS)





Figure 7. Complete institutional collaboration network in the global artificial intelligence field between 1985 and 2019.

(China) as its center of scientific collaboration, and the other takes Islamic Azad University (Iran), Duy Tan University (Vietnam), the University of Kurdistan (Iran), and Ton Duc Thang University (Vietnam) as their collaboration center. We find that almost all the nodes that have cooperative relations with the CAS come from China. Similarly, seven of the 10 institutions that have worked with Islamic Azad Univ are from Iran. Four of the eight institutions in partnership with Duy Tan University are from Vietnam. In addition, in the other two subnets, almost all of the institutions that have partnerships with the central institutions are from the same country. The core institution of SN-2 is MIT, and most of the institutions are from the US. The core institution of SN-3 is Germany’s Cancer Research Center, and most of the institutions in that network are from Germany. Unlike the other two subnets, SN-3’s institutions are all medical.



The complete institutional collaboration network is not a fully connected network but consists, instead, of several sub-networks, indicating that inter-institution collaboration has not yet reached the maturity of country collaboration. Each sub-network reflects that collaboration at the institutional level is strongly featured by regional agglomeration. Collaboration is more likely to occur between geographically adjacent institutions. Collaboration between domestic institutions tends to be deeper, while collaboration between international institutions appears more fragile. At the institutional level, the core groups in the field of artificial intelligence research include the Chinese institution group led by the CAS, the Iran—Vietnam institution group with Islamic Azad University and Duy Tan University as the core, the US institution group with MIT as the core, and the German medical institution group with Germany's Cancer Research Center as the core.

3.2.2.2 International institution collaboration network

The international-institution collaboration network is a further refinement of the country collaboration network. It only considers inter-institution collaboration from different countries, so it better reflects the central institutions and core groups of international collaboration in the field of AI. A total of 7,730 institutions participated in international collaboration between 1985 and 2019. The collaboration network of these institutions contains 32,066 edges, but only 3,131 have weights greater than one. To visually show the situation of international collaboration at the institutional level, we removed the edges with weights less than five and isolated nodes. The resulting international-institution collaboration network has 122 nodes and 130 edges. Like complete institutional collaboration network, the international-institution collaboration network is not a fully connected network but consists of 27 subnets. The largest subnet, however, contains 65 nodes, accounting for 53.3% of the total network. The number of nodes contained in other subnets is less than five, and 22 subnetworks consist of only two nodes. Therefore, we only show the largest subnet in the international collaboration network in Figure 8 and call it the biggest sub-network of the international-institution collaboration network (BSIN).

From 1985 to 2019, the average degree of the international-institution collaboration network is 8.30, which is close to the average degree of complete institutional collaboration network in the previous section. This indicates that there are on average eight overseas partners for each institution and that international collaboration at the institution level also reached a certain level of maturity in the field of artificial intelligence. In Figure 8, the nodes with larger degrees are Ton Duc Thang University (Vietnam), the University of Kurdistan (Iran), Duy Tan University (Vietnam), and Islamic Azad University (Iran). These four institutions cooperate stably with more than 10 international institutions and are the main force for international collaboration



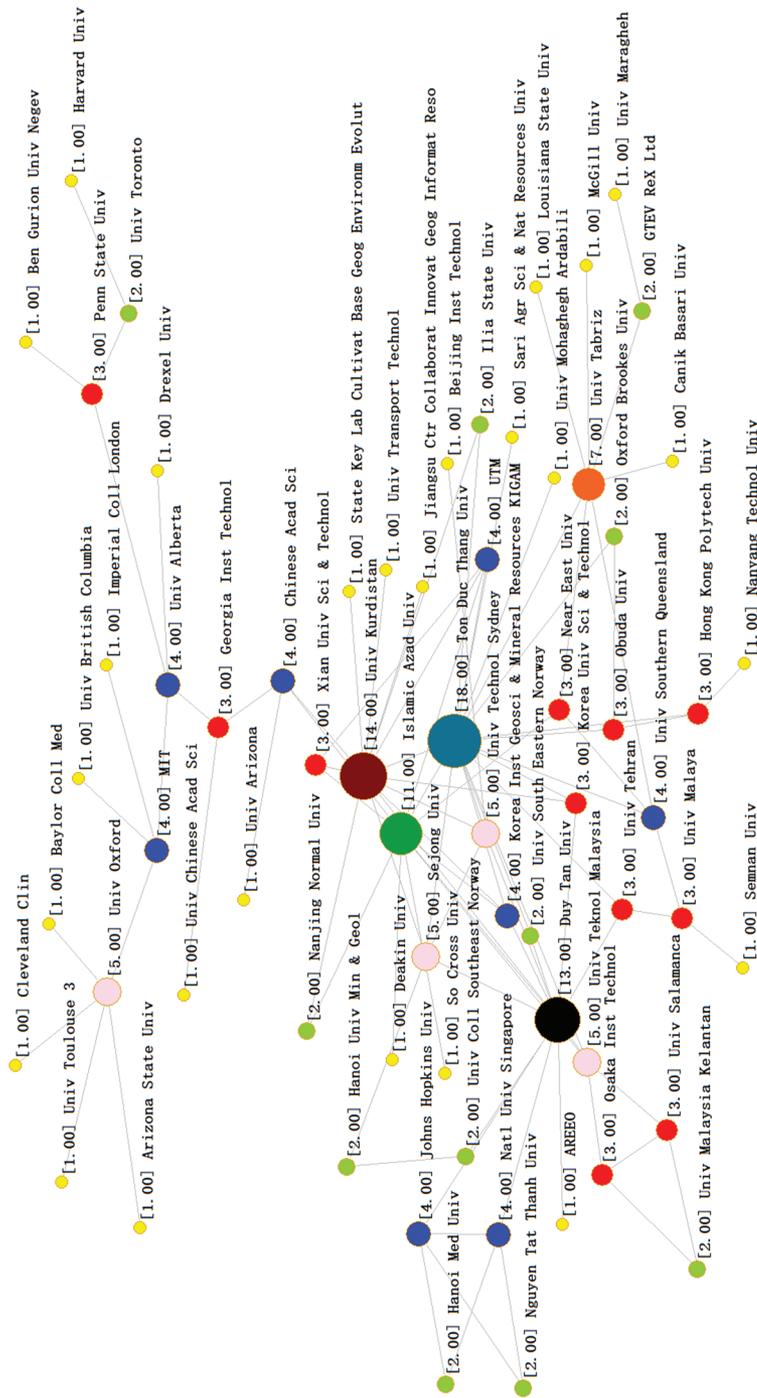


Figure 8. The biggest sub-network of the international-institution collaboration network (BSIN) in the global field of artificial intelligence between 1985 and 2019.



in the field of artificial intelligence. In addition, the institutions above-mentioned are all from Vietnam and Iran. Combined with Figure 7 and Table 3, it can be further concluded that Vietnam and Iran are important participants in international collaboration, which also confirms the conclusion of collaboration at the country level (Table 3); that is, the degree of international collaboration between these two countries is high. For countries such as the US, the UK, France, and Spain, which are at the core of the country collaboration network (Figure 6), their institutions are not at the core of the international-institution collaboration network. Moreover, the core institutions in the complete institutional collaboration network (Figure 7), such as the CAS (China) and MIT (US), also lie in a marginal position of the international-institution collaboration network. This finding shows that although countries that are at the center of the country collaboration network have produced a large number of papers, institutions from these countries are more inclined to establish broad and stable cooperative relationships with their own domestic institutions. Their cooperation is relatively scattered, and the degree of close cooperation is relatively low.

Figure 9 shows countries of 65 institutions in the BSIN network. The US, Iran, China, and Vietnam are among the top four institutions participating in international collaboration. Iran and Vietnam are not only at the center of the international-institution collaboration network, but they also have a large number of institutions in the network, which once again shows that they are indispensable to international collaboration in the field of AI. Although institutions from the US and China are not located in the center of the BSIN network, they still play a major role in international collaboration by virtue of their large number of institutions participating in international collaboration and their huge amount of publications (Table 3). The collaboration between international institutions also shows obvious regional characteristics, and countries located on the same continent are more inclined to carry out international collaboration. Also, international collaboration has economic characteristics, as it is easier for countries that are developed or developing to carry out collaboration. Based on the BSIN network and Figure 9, we can see two core groups in international collaboration in the field of artificial intelligence. The first is the Asian Institution Collaboration Group (Developing Countries Institution Collaboration Group) led by Iran (9), China (7) and Vietnam (6), and the other is the North American-UK Institution Collaboration Group (Developed Countries Institution Collaboration Group) led by the US (9), Canada (3), and the UK (2).

As with collaboration at the country/region level, in addition to judging the importance of institutions in international collaboration according to the degree of nodes, we also calculate the BC of the network. The total BC of the international institution collaboration network is 0.03549168, which indicates that most institutions do not have an intermediary function. The BC adjusted according to the



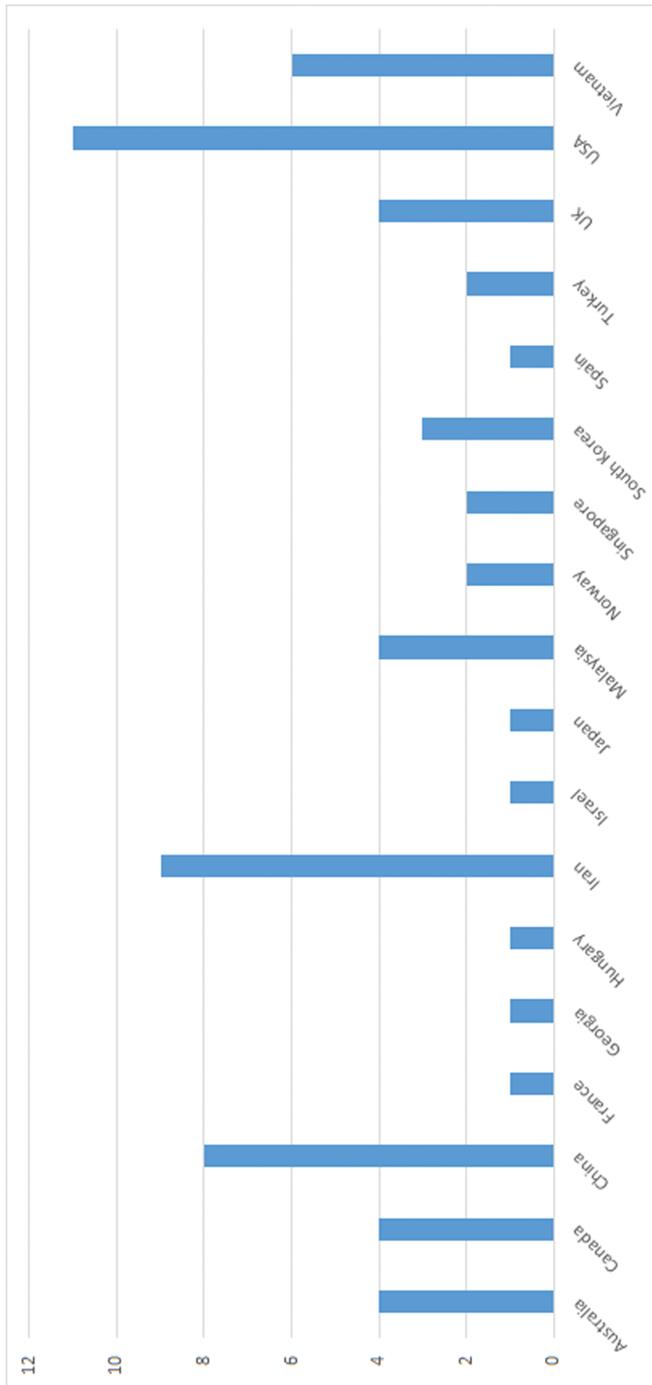


Figure 9. Country distribution of institutions in the BSIN.



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Table 4. Institutions with high BC in the biggest sub-network of international-institution collaboration network.

Rank	Institution	Country	BC	Degree
1	Chinese Academy of Sciences	China	0.405336672	4
2	Ton Duc Thang University	Vietnam	0.384635685	18
3	Georgia Institute of Technology	USA	0.371527778	3
4	University of Alberta	Canada	0.350694444	4
5	University of Kurdistan	Iran	0.295375309	14
6	Islamic Azad University	Iran	0.288076771	11
7	Duy Tan University	Vietnam	0.223353933	13
8	MIT	USA	0.203373016	4
9	University of Tabriz	Iran	0.153155313	7
10	Oxford	UK	0.12202381	5
11	University of Technology Malaysia	Malaysia	0.095804022	5
12	Penn State University	USA	0.091765873	3
13	University of Tehran	Iran	0.039564365	3
14	University of Technology Sydney	Australia	0.036280213	5
15	Near East University	Turkey	0.033982326	3
16	Sejong University	South Korea	0.032871873	5
17	University of Malaya	Malaysia	0.031909121	3
18	GTEV ReX Ltd	UK	0.03125	2
19	University of Toronto	Canada	0.03125	2
20	Hong Kong Polytechnic University	China	0.03125	3
21	National University of Singapore	Singapore	0.030505952	4
22	Johns Hopkins University	USA	0.030505952	4
23	University of Southern Queensland	Australia	0.028754488	4
24	University of Salamanca	Spain	0.015376984	3
25	Osaka Institute of Technology	Japan	0.015376984	3
26	Korea Institute of Geoscience & Mineral Resources KIGAM	South Korea	0.006101012	4
27	Korea University of Science & Technology	South Korea	0.005030213	3
28	University of South Eastern Norway	Norway	0.005030213	2
29	University College of Southeast Norway	Norway	0.003571429	2
30	UTM	Malaysia	0.003515133	4
31	Xi'an University of Science & Technology	China	0.001070799	3
32	Nanjing Normal University	China	0.001070799	2
33	Hanoi University	Vietnam	0.000907137	2
34	Obuda University	Hungary	0.000496032	3

principles above is 0.10567512. The BSIN shown in Figure 8 is 0.35853266. Although the degree of the CAS (China) node is only four, its BC is the largest in the BSIN network, and it is an important node connecting the collaboration groups of Asian institutions and the collaboration group of North American—UK, playing an important role as a bridge. Similarly, institutions such as the Georgia Institute of Technology (US) and the University of Alberta (Canada) also have low degrees and high BC values. Ton Duc Thang University (Vietnam) not only has the highest degree in the BSIN network, it also ranks second in BC, which indicates that this institution is not only at the core of international collaboration at the institutional level, but it also plays an important role in maintaining collaboration in the field of artificial intelligence in Asia and even the world.



4 Conclusions

Our study is the longest to date on international collaboration in the field of AI. We obtained 38,224 papers between 1985 to 2019 in the field of AI from the WoS core collection database, and we explored the evolution, future trends and major collaboration patterns of international collaboration in the field of artificial intelligence over the past 35 years from the perspectives of authors, countries/regions, and institutions through bibliometric analysis. In addition, we also used the social network analysis method to conduct an in-depth study of the country collaboration network and the institutional collaboration network from the macro and micro levels. We also discovered the leading countries, core groups and characteristics of collaboration in the field of AI.

After 35 years of development, 84.8% of papers in the field of AI are collaborative papers, and the degree of collaboration will continue to deepen. At the macro level, intra-country collaboration is the main pattern, and joint research between two countries is the most common form of international collaboration. A total of 153 countries/regions have participated in global AI collaboration, among which the US, the UK, France, and Spain are the leading countries. Vietnam, Saudi Arabia the United Arab Emirates, Pakistan and Sweden have a higher degree of participation in global AI collaboration. At the micro level, intra-institution collaboration and domestic-institution collaboration are the main patterns. Global institutional collaboration not only has regional characteristics, but it also reflects economic characteristics, and it has even produced a medical-oriented collaboration group.

Admittedly, there are still some deficiencies in our research. First, the country collaboration network and the institution collaboration network we have built are undirected graphs; that is, the contributions of participating countries/regions, as well as institutions, are viewed equally. In fact, the contribution of participants in international collaboration may not be the same. In a cooperative relationship, there could be a dominant object. Second, although we consider the weights of the edges in the collaboration network, the weight is only used as the criterion to reduce the network, which does not reflect the strength of collaboration. Therefore, in the future, on the one hand, we will try to use a directed graph to construct the collaboration network to thus reflect the primary and secondary relationships in collaboration. Also, the methods of quantitative analysis will be used to transform the weights of the edges into the strengths of these cooperative relationships. On the other hand, we will divide time periods and explore the evolution of international collaboration in the field of artificial intelligence in more detail from the perspective of dynamic changes.



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Author contributions

Haotian Hu (hhtdlam@126.com) designed the methods, collected the data, performed the data analysis and wrote the manuscript. Dongbo Wang (db.wang@njau.edu.cn) proposed the research question and revised the manuscript. Sanhong Deng (sanhong@nju.edu.cn) performed the research and revised the manuscript.

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