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A Ten-year Review and Visual Analysis of Global Artificial Intelligence Research—A Bibliometric Analysis in CiteSpace Based on Highly Cited Literature

Hongbo Lai[1], Zhang Han[1], Yiwei Zhao[1], Yunxi Zhang[2]*

[1]School of Management, University of Shanghai for Science and Technology, China
[2]School of Economics and Management, Shanghai University of Political Science and Law, China

**Author to whom correspondence should be addressed.*

Abstract: Taking the highly cited literature related to artificial intelligence over the ten-year span between 2009 and 2019 from the Web of Science database as the data sample, this paper has analyzed the distribution of literature, hot topics of research, frontier research and evolution of artificial intelligence by using CiteSpace and applying dual-map overlay, co-word and co-citation analysis, among other bibliometric approaches. The research findings indicate full-fledged multidisciplinary features of artificial intelligence, but interdisciplinary integration is still at a nascent stage; most of the existing researches are focused on fundamental technologies, while applications are quite limited, with more applications of the computer vision technologies; deep learning is garnering the most interest, while a cutting-edge research theme could be the combination of quantum physics and machine learning.

Keywords: Artificial intelligence; CiteSpace; Co-citation analysis; Deep learning

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1. Introduction

Researches on artificial intelligence (AI) can date back to the 1940s and 1950s. The Dartmouth Conference held in 1956 is widely considered as the beginning of this field. A standard and consistent definition of artificial intelligence is absent. In the Webster's Dictionary, artificial intelligence is defined as "the capability of a machine to imitate intelligent human behavior"..

Over recent years, more and more government and business organizations have realized the importance of artificial intelligence. All countries around the world, especially the advanced ones, are implementing strategic realignment and targeting artificial intelligence. The United States, China, Europe and Japan, among other countries and regions, have made some tremendous headway in artificial intelligence. Unlike the business world in which a mass fervour for artificial intelligence didn't occur until recently, the academic world's interest in artificial intelligence started much earlier. In the All Databases of the Web of Science (WoS), the literature under the subject line of artificial intelligence first appeared in 1952, began to grow in the late 1980s and has been exploding in recent years, driven by the booming industry.

In this context, there is an abundance of artificial intelligence-related studies in the academic world, and the industry and the academia are increasingly interconnected. In order to portray the whole picture of artificial intelligence, sum up previous studies, and assess the available findings, we need to carry out an elaborate review and analysis of the literature that was produced globally over the last decade and then provide forecasts of future research trends.

1.1. A Review of Global Artificial Intelligence Literature

Artificial intelligence literature published in the Web of Science database over the last 60 years as of June 2019 was retrieved, and the returned results are shown in **Figure 1**. It is apparent that the literature related to AI has kept building up since the beginning of this century, and registered explosive growth after 2015. In this boom, many scholars have made a general overview of this subject, but there are some problems. First, the amount of literature has expanded at an exponential rate, making it difficult to review the literature on a subjective and qualitative basis in a chronological order or by topic[1]. Second, in these massive literature, some scholars pull out different main lines and choose to conduct reviews or researches from a certain perspective or focus on a specific field, including neuroscience study [2], deep learning [3], and economics [4]. These reviews have academic depth, but fail to present the whole picture of AI related research. Third, most reviews are more about a subjective analysis and collation of the literature, including the authors' personal opinions. As a result, the reviews are subjective, and cannot objectively reflect the facts on which the analysis and study should be based.

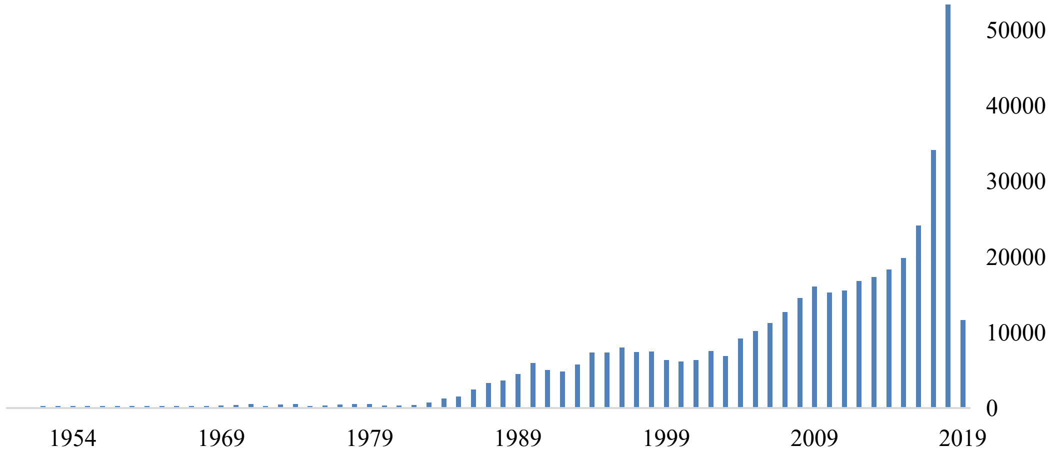

Figure 1. Annual distribution statistics of artificial intelligence literature (as of June 2019)

The bibliometric approach based on mapping knowledge domain not only solves the problem of subjectiveness in the existing literature, allowing the scholars to intuitively investigate and analyze some fields, but also avoids the problem to a great extent where traditional reviews are too subjective because of pure data and its visual expression. This approach itself is an early application of artificial intelligence, so many scholars naturally use it as a tool for bibliometric and analytical research on the AI literature. Some scholars have analyzed the status quo from different angles, such as studies based on relevant authors, institutions, countries [5-8], as well as those based on the literature of AAAI (American Association for artificial Intelligence) Conference [9]. A number of tools of mapping knowledge domain are applied to bibliometric studies, including TDA [10], SciMAT [11], CiteSpace [12]. Among them, CiteSpace, developed by Professor Chen Chaomei, is one of the most widely used ones [13], owing to its unique features and excellent performance. Lv Wenjing et al. [12] used this program to analyze the knowledge map of artificial intelligence literature in CNKI(China National Knowledge Infrastructure) and CSSCI(Chinese Social Sciences Citation Index) databases, and to visually analyze the distribution from various levels and angles, but they did not analyze the co-citation network of this field. Co-words and co-citation network analysis can extract the topic words that are used frequently, and dig out the relationship among the literature, which helps us get a deeper understanding of the research field. Therefore, the method of mapping knowledge domain is used to further analyze the co-word network and co-citation network in the field of artificial intelligence.

Based on the foregoing work, this paper will use CiteSpace as a bibliometric tool to conduct scientific measurement and visualization of the literature of artificial intelligence. The "co-word network", "co-citation network" and the seldom used "dual-map overlay" functions are applied to identify the inherent connections in the artificial intelligence discipline and to analyze the hotspots and frontiers in this field, and also to shed light on the evolution and trends of popular sub-fields. We hope to provide more valuable reference from the academic perspective in this boom of artificial intelligence, and contribute to the construction and development of AI at a deeper level.

2. Materials and Methodology

To make sure the sample data feeding into the visual analysis in this paper represents a subjective and comprehensive picture of the status quo of artificial intelligence, this paper selects the WoS Core Collection as data sources. It contains the vast majority of high-level international academic achievements, including journal articles, conference proceedings and research reports. And it is a database widely recognized as a global reservoir of knowledge. By drawing upon the search terms used in the "*China AI Development Report*" released by the Science and Technology Policy Research Center of Tsinghua University in July 2018 and combining experts' opinions, we use the following search words: *artificial intelligence, machine learning, recognition image, computer vision, facial recognition, speech recognition, natural language processing, semantic search, semantic web, text analytics, virtual assistant, visual search, predictive analytics, intelligent system*. The OR logic is adopted among the search words to conduct topic search. At the same time, the search is confined to ESI highly cited literature. This retrieval method not only ensures completeness of the data but also helps sift out noisy data and minimize its effect on the analysis results. As the highly cited literature search applies only to the literature published after 2009, the retrieval interval is set to 2009 to 2019.

By following the said search strategy, the literature search was completed on June 19, 2019. A total of 2,178 entries were returned, including 1,746 articles, 432 reviews, 31 conference proceedings and 14 monographs. After these were imported into CiteSpace and duplicate entries were eliminated, 2,171 entries were left, constituting the data sample for the study.

3. Results and Discussion

3.1. Discipline Distribution

Firstly, the function for analyzing the retrieval results in WoS is used to make a preliminary analysis of the subject distribution of the literature in the retrieval results. In the WoS database, the literature is classified into one or more disciplines depending on what it involves. Discipline distribution is a macro-analysis which can reflect the scope it involves, the foundation it requires and the direction it applies. In order to better reflect the disciplines, we classified the disciplines as per the WoS categories which are more detailed than research areas. The results are partially shown in **Table 1**. In general, the research field of artificial intelligence shows multidisciplinary characteristics.

Table 1. Discipline Distribution of Artificial Intelligence Research (TOP 21)

WoS Categories	Record Count	%
Computer Science Artificial Intelligence	538	24.702
Engineering Electrical Electronic	527	24.197
Computer Science Information Systems	149	6.841
Automation Control Systems	125	5.739
Computer Science Interdisciplinary Applications	123	5.647
Multidisciplinary Sciences	123	5.647
Neurosciences	122	5.601
Energy Fuels	100	4.591
Remote Sensing	94	4.316
Imaging Science Photographic Technology	91	4.178
Chemistry Multidisciplinary	89	4.086
Computer Science Theory Methods	85	3.903
Telecommunications	85	3.903
Biochemistry Molecular Biology	58	2.663
Computer Science Software Engineering	56	2.571
Geosciences Multidisciplinary	56	2.571
Engineering Civil	55	2.525
Materials Science Multidisciplinary	55	2.525
Computer Science Hardware Architecture	52	2.388
Environmental Sciences	52	2.388
Green Sustainable Science Technology	52	2.388

As shown in Table 1, most of the disciplines are conventionally perceived as "hard" subjects. Among them, computer science is the most prominent: this category represents a more than 42% share cumulatively. Artificial intelligence is a discipline derived from computer science. Though its development to date embodies the integration and diversification of disciplines, its fundamental nature is computer science. Electrical and electronics under the engineering discipline has a share almost equal to that of artificial intelligence under the computer science discipline. This suggests artificial intelligence technologies have been realized largely in physical reality, such as various electronic devices, robots as a typical example, which apply AI technologies. Multidisciplinary science and neuroscience come out on top in the table and stand out among all computer system and engineering disciplines, indicating an unfolding multidisciplinary trend in artificial intelligence.

This paper uses the dual-map overlay function of CiteSpace to make a deeper analysis of the discipline distribution. This function represents the entire dataset generated in WoS based on more than 10,000 journals in the context of the global science map. This is an approach to display the distribution of papers and citation trajectory in different disciplines[14], among other information. Compared with simple statistics on the distribution of disciplines, dual-map overlay incorporating citation data can better reflect the connections among various disciplines related to artificial intelligence. See **Figure 1**.

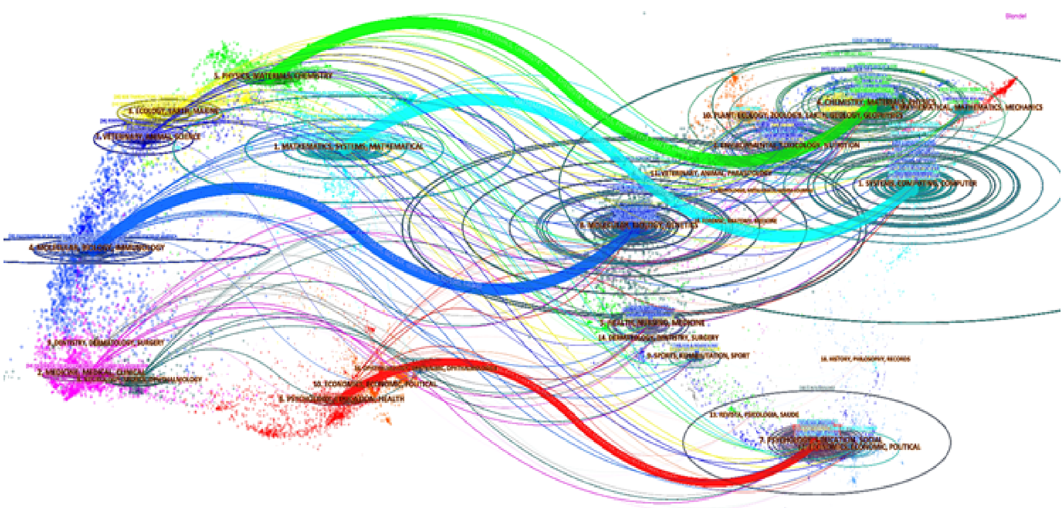

Figure 1. Dual-map overlay of the journal related to artificial intelligence

Figure 1 is the dual-map overlay of the journal discipline obtained by CiteSpace following some refinements and adjustments. In this figure, CiteSpace classifies numerous journals into clusters and names the clusters. The most important disciplines are shown on both sides of the map. The journals of cited literature are distributed on the right, regarded as the research foundation of artificial intelligence. The journals of citing literature are distributed on the left, as the application field of artificial intelligence. The ellipse on each cluster formed by the journals represents the number of papers and authors in the journal: the longer the horizontal axis of the ellipse, the more authors; the longer the vertical axis, the more papers.

This picture shows that artificial intelligence papers have cited from or been cited by almost all major disciplines. Among them, four citation curves are very significant, detailed in **Table 2**. The citation relationship represented by the second citation curve has the highest strength. Both ends of this relationship are disciplines that are most closely related to artificial intelligence, again proving that AI is fundamentally a branch of computer science. Biomedicine is the second in citation strength. Aided by AI technologies, new drug research and development, gene sequencing and other tremendous workloads can be handed over to AI and robots for endless repetitions, simulations and trials and errors. Artificial intelligence could even learn and assist developers in innovative activities. Likewise, AI can considerably shorten the process of lots of experimental work in physics, materials and chemistry. At the same time, some people expect AI to discover natural laws men are yet to uncover through other methods like deep learning, and thereby to drive the advancement of physics and chemistry, cornerstones of modern sciences. Digging into social sciences is a dominant tendency of research in the latest developments of AI over the last decade. It can be seen on the map that the curve of psychology and education ranks the fourth in the strength of citation. This also shows the multidisciplinary nature of artificial intelligence and is expected to become more salient in the future.

Table 2. Journal citation relationships in the research of artificial intelligence (in descending order of strength of citation relationship)

Citing Discipline	Cited Discipline
mathematics, systems, mathematical	systems, computing, computer
molecular, biology, immunology	molecular, biology, genetics
physics, materials, chemistry	chemistry, materials, physics
psychology, education, health	psychology, education, social

Note: The names of disciplines are clustered by CiteSpace according to the journal by LLR algorithm.

The two ends of the four significant citation curves are all connected to the same disciplines. This indicates the research foundation and application of AI studies are still concentrated in the same or akin disciplines (compared to Chen Chaomei's research on the scientific map, which clearly reveals that some disciplines of application have more than one foundation [15]), and the characteristics of interdisciplinary citations are yet to show up. Perhaps in the future, on the basis of the apparent multi-disciplinary trends, more interdisciplinary citations will emerge, and the characteristics and trends of interdisciplinary integration will become manifest.

Compared to the left side, it is evident that the ellipse of cited literature on the right is more concentrated in several disciplines, including computer science, biomedicine, physical and chemical materials. The top four of most cited journals are IEEE Transactions on Pattern Analysis and Machine Intelligence, Science, Nature and Lecture Notes in Computer Science.

3.2. Hotspots

Comparatively speaking, discipline analysis is from a macro perspective, while research hotspots and evolution analysis based on keywords and references stand for a micro perspective. Compared with co-citation analysis, the results presented by subject-term co-word analysis are simpler, more intuitive and easier to interpret; while co-citation analysis requires specific literature searches. Therefore, the co-word analysis of subject terms can be carried out first, followed by the analysis of literature co-citation.

In CiteSpace, terminologies are extracted and generated from the titles, keywords, abstracts and supplementary keywords of the literature. Therefore, this paper uses terminologies in the co-word analysis, which can better reflect the topics of the literature. Node type is selected as Term. See **Table 3** below.

Table 3. Co-word analysis of artificial intelligence research (Top 10 by frequency)

Frequency	Terminologies	Centrality
168	machine learning	0.04
101	deep learning	0.06
96	computer vision	0.03
95	support vector machine	0.05
84	neural network	0.06
75	artificial intelligence	0.03
73	learning algorithm	0.03
57	convolutional neural network	0.01
56	learning technique	0.04
52	the-art method	0.08

Table 3 outlines the results of co-word network. Many terminologies, such as artificial intelligence, deep learning and machine learning, are widely known by and accessible to the masses in their everyday life. Machine learning is the primary approach to realizing AI. It has long been the core of AI and a hot topic in related fields. Firstly introduced as a concept originating in artificial neural network in 2006, deep learning is now the most popular among machine learning methods. Convolutional network, another high-frequency word, is a typical algorithm in deep learning. To be more precise, deep learning is a special type of machine learning. As it way outperforms most traditional machine learning methods, it is often studied separately.

Algorithms account for the vast majority of the top 10 subject words by frequency. Algorithms form the most crucial foundation of AI, or even function as the "soul" thereof. While computer vision is a universal technique and a basic application, it still represents, in our view, the rise of research on the application of AI. Apparently, AI research is still concentrated on the level of foundational technologies, which deep learning has garnered the greatest interest in recent years. The research on its applications is also booming, and the hottest field is computer vision. Compared with foundational technologies, however, its applications are underanalyzed.

3.3. Frontier and Evolution

In CiteSpace, research frontier refers to emerging theoretical researches and emergence of new topics, which is composed of the citation collection of co-citation references. Cluster naming in the co-citation network is determined by the terms extracted from the cited literature and can be regarded as the research frontier [16]. We use the co-citation network of the literature to further analyze the research frontier of artificial intelligence and its evolution trends since 2009. Meanwhile, the setting retrieves the top 50 most cited papers every year. As the retrieval of keywords contains keywords provided by the authors, plus additional keywords supplemented by WoS according to a given algorithm, there may be some deviation in the representation of the literature. Since the titles are carefully chosen by the authors to be pertinent to the contents, we choose to name the cluster by the title. After comparisons, the more representative and comprehensible naming results of the LSI algorithm are selected. The node type is selected as tree ring history. The size of the tree ring reflects the times the literature is cited, and the rings represent citations of the literature in different years. The minimum spanning tree pruning algorithm is selected to ensure that the co-citation network presented is not too cluttered without changing the network structure. Meanwhile, it is set to retrieve the top 50 most cited papers every year. Remaining clusters after the elimination of smaller clusters are shown in **Figure 3**. The Modularity index of clustering reaches 0.9, indicating a salient clustering structure of the co-citation network. The average silhouette value is low due to the presence of plenty of small-to-medium-sized clusters in the network. Therefore, the rationality of the clustering results can be established. The number of entries in each cluster is less than the total of 2,171 entries in the sample, indicating the existence of many subdivisions under the study of artificial intelligence.

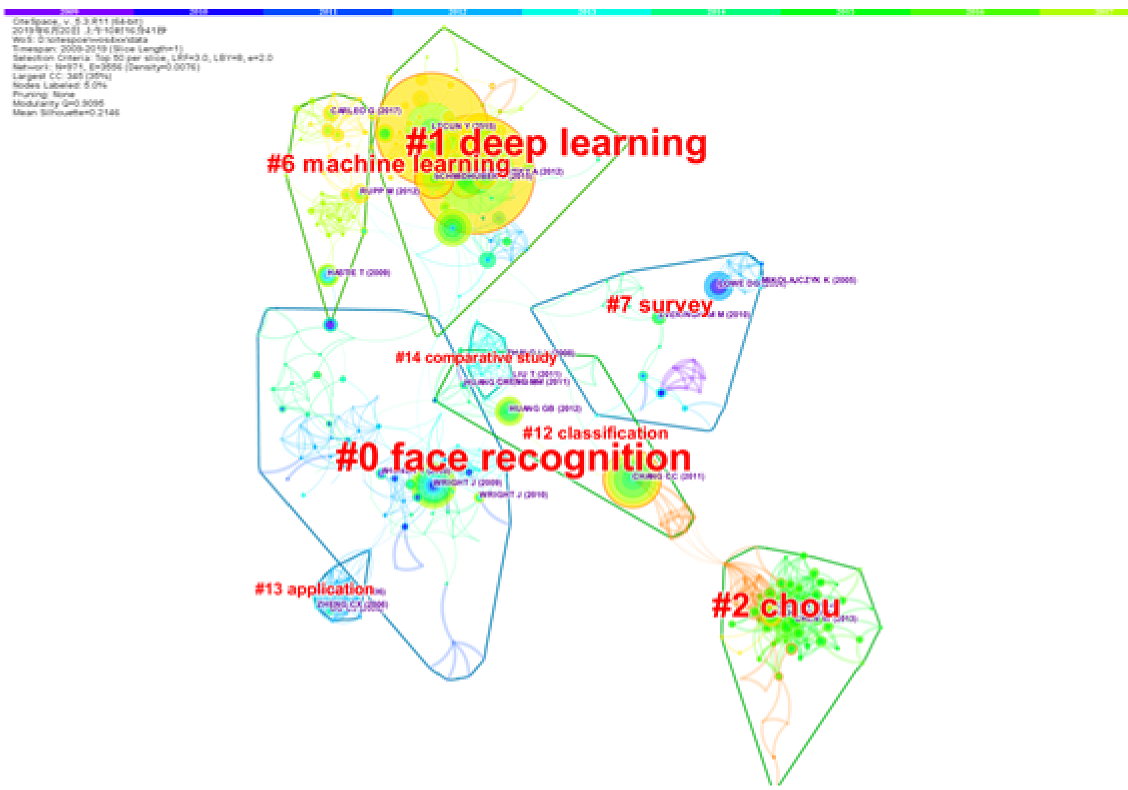

Figure 3. Co-citation network of artificial intelligence research

The results of analysis suggest face recognition, deep learning, Chou ‘s PseAAC and machine learning are the four largest clusters in terms of size. Next, there are classification, application and so on. Their cluster names denote the frontier research topics in the field over the time span of 2009-2019, and share some similarities with the hotspots identified based on the co-word of subject words in the previous section. In order to probe into these frontier research topics in more depth, the authors have produced a timeline view of the co-citation network based on the clustered co-citation network, as shown in **Figure 4** and **Table 4**.

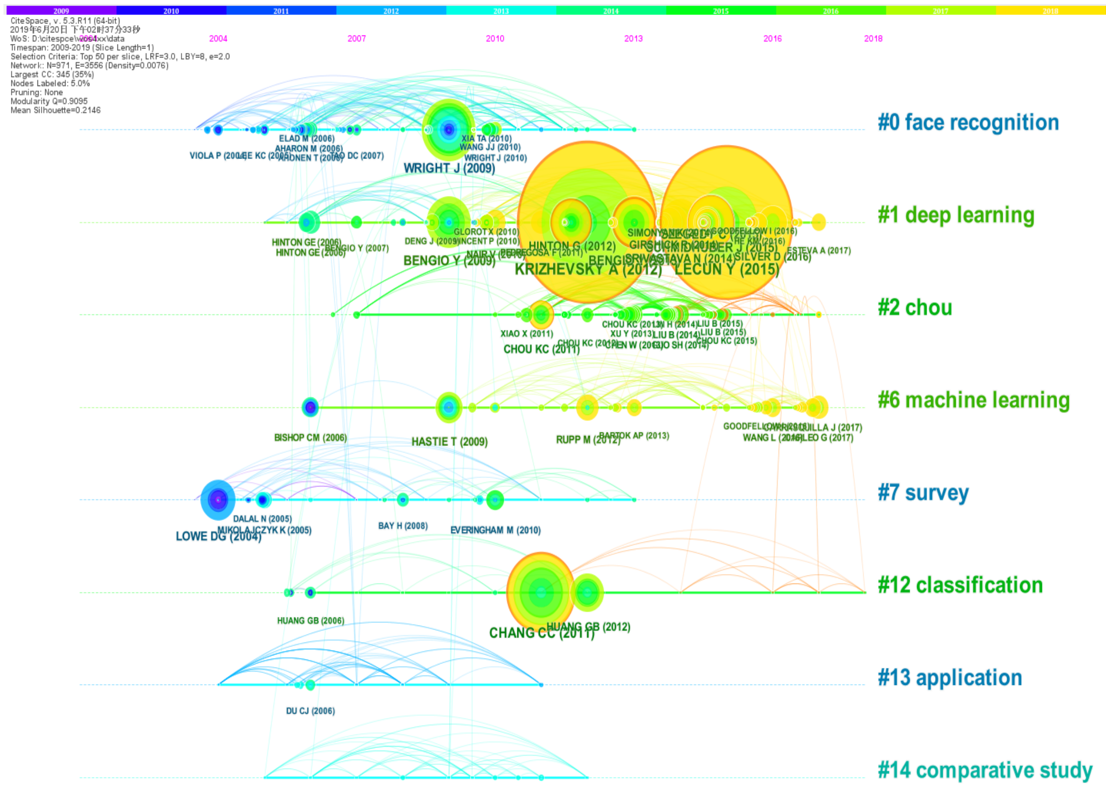

Figure 4. Timeline view of the co-citation network (partial)

Table 4. Details of main clusters

ClusterID	Label	Size	Silhouette	Begin	End	Last	Mean Year
0	face recognition	84	0.941	2004	2013	10	2008
1	deep learning	80	0.949	2005	2017	13	2012
2	chou	62	0.976	2007	2017	11	2014
6	machine learning	33	0.977	2006	2017	12	2014

The frontier represented by the largest #0 cluster is face recognition, which contains 84 co-citation entries and is an application of computer vision. One of the most important articles is authored by John Wright et al. and published in IEEE Transactions on Pattern Analysis and Machine Intelligence in 2009 [17]. This article is pioneering in incorporating sparse representation into face recognition, resulting in a giant step forward compared with the performance of existing face recognition methods: the recognition rate is much higher than that of traditional approaches, with superior effectiveness and stability.

The co-citation literature in this cluster is distributed between 2004 to 2013, and the median year is 2008, indicating quite early time of the literature cited in this field. The timeline view shows clearly that the study of face recognition started very early and can be roughly divided into two periods. During the period from 2004 to 2007, the distribution of cited literature was relatively stable, and no works of cardinal significance appeared. After the publication of the article by John Wright et al. in 2009, which became a hit in this field, the literature distribution became stable again. Over these years, there were little research achievements worthy of mentioning, and the citation time of the article stopped at the year of 2017 or so. Face recognition is a frontier research that started early and evolved at a steady pace, but its development seemingly has stagnated over the recent years.

The frontier represented by cluster 1 is deep learning, which contains 80 cited works. Second in size, it contains plenty of masterpieces. In 2006, Geoffrey Hinton, the founder of deep learning, published two iconic articles on Neural Computation [18] and Science [19]. The one published in Science is widely recognized as a milestone in the history of deep learning, sparking off a deep learning boom in both the academic and business worlds[20]. In 2012, Hinton co-authored with the research teams at Microsoft, IBM and Google [21] an article on deep neural networks in speech recognition, published in the IEEE Signal Processing journal and hailed as the forerunner of deep learning in this direction. Yoshua and Bengio published two enlightening works in 2009 [22] and 2013 [23]. The former summarizes the motives and principles of learning algorithms in the deep learning framework and provides theoretical guidance for related studies. The latter is an overview of representation learning. Yann LeCun, together with Hinton and Bengio, known as the "troika" of deep learning, published a review about deep learning on Nature [2] in 2015. Along with an introduction of CNN, RNN, distributed feature representation and different applications thereof, they projected the future of deep learning.

Among other important works, Hinton's student Krizhevsky et al. applied deep learning to picture recognition in ILSVRC 2012[24] and beat the second-place SVM to win the crown, proving the capability of deep learning. Jürgen Schmidhuber presented a review of neural networks and deep learning in chronological order [25]. Christian Szegedy proposed a new deep convolutional neural network in the 2014 ILSVRC [26].

The co-citation literature in this frontier field is distributed between 2005 and 2017, and the median year is 2012. With the publication of two papers by Hinton in 2006 widely acknowledged as the starting point, deep learning was further developed by Bengio et al. In 2012, Hinton's team won the crown in ILSVRC-2012, which helped draw attention to the deep convolutional neural network and initiated a new phase of explosive development of deep learning. After that, some important works were published, and were widely cited in the last couple of years. Therefore, this paper concludes that deep learning is the most cutting-edge research field as a branch of AI, and relevant studies will continue at a high speed.

The label of cluster #2 is Chou, which refers to the pseudo-amino acid discrete model framework proposed by Chou. It may be deemed to represent the subdivision of protein structure prediction, and it is the only one named after biomedical terminology among all major clusters. It accords with the analysis of disciplines in the previous section of this paper. The core piece in this cluster is a review published by Kuo-Chen Chou in 2011 [27] in the Journal of Theoretical Biology, which comprehensively describes the steps of protein structure prediction. Another important paper has developed a set of genomic prediction methods for human, drosophila and nematodes [28]. Most of the authors in this cluster are ethnic Chinese, indicating this group of people have made some achievements in this field.

The co-citation literature in this field is distributed between 2007 and 2017, and the median year of publication is 2014. With the review published by Chou in 2011 as the watershed, co-citation was almost zero before that, and some influential works appeared after that. However, the citation duration of these works is short, and mostly concentrated in one or two years after their publication, indicating limited impact of these works.

The label of cluster # 6 is machine learning, which has long been a hot topic and the centerpiece of AI, and is the key method to realize AI. Given the long history of research in this field, its co-citation timeline view herein appears to be quite stable. The most important work in this field, authored by Trevor Hastie, provides statistical viewpoints on machine learning, inter alia. The Boosting method in this book is frequently cited [29]. Another consequential book by Christopher M. Bishop is a classic textbook in the field of machine learning [30], and has a preference for the Bayesian model. But it has been seldom cited in recent years as it was published long time ago (2006).

Obviously, in this cluster many works were published in top physics journals, including Science, Nature Physics and Physical Review. The same holds true in the discipline analysis. That suggests the combination of machine learning and physics. Juan Carrasquilla created a simple statistical physical model with supervised learning in 2016, demonstrating for the first time that machine learning can be applied to solve problems in physics[31]. After that, Lei Wang[32], Giuseppe Carleo[33] and other scholars did more work, mostly concentrated on quantum physics.

The citation in this field is distributed between 2006 and 2017, and the median year of publication is 2014, indicating that the literature cited in this field has come out of late and been replaced quite fast. From the perspective of timeline, the development of this field is quite flat. A couple of highly cited works came forth about every three years, but a span of explosive development as seen in deep learning did not occur. Around 2016, the combination of machine learning and physics began to take shape, and a series of important works came out. There are three main topics in this direction: the application of machine learning to physics, the interpretation of physical thoughts to machine learning, and quantum machine learning. We think these herald a new direction that has the potential to revolutionize physics, quantum physics and machine learning in particular.

By summing up the foregoing analysis of four clusters, we find that some reviews or some referential books are of cardinal significance, and these works are often written by the most accomplished and distinguished experts and scholars in this discipline. Some examples are the review of deep learning by LeCun, Hinto and Bengio [2], the interpretation of the steps of protein structure prediction by Chou [27] and the most classic machine learning textbook by Bishop [30]. The citation of these works by all highly cited works indicates the research in artificial intelligence attaches great importance to foundational studies. At the same time, we notice that many important cited works are the results of efforts on solving practical problems. The most obvious case is deep learning. The papers of Krizhevsky [24] and Szegedy[26] are both the results of their participation in the ILSVRC competition, and Wright [17] introduced sparse representation in order to reduce excessive data and noise in the process of image recognition.

4. Conclusion

4.1. Main Conclusions

This paper elaborates on and analyzes the status quo, hotspots, frontiers and trends of artificial intelligence research using CiteSpace based on the sample data of highly cited references from 2009 to 2019. The findings are summarized as follows.

1) Our research indicates full-fledged multidisciplinary features of artificial intelligence, but interdisciplinary integration is still at a nascent stage. This paper analyzes the fields involved in artificial intelligence research from the level of discipline by using the function of dual-map overlay. Research on AI is widely distributed in computer, biomedicine, physics, chemistry, social sciences and their related disciplines, a sign of its multidisciplinary nature. However, the citation curve does not tangibly reveal an interdisciplinary citation relationship, which indicates the integration of the disciplines under study is yet to take shape. In general, artificial intelligence, unlike traditional classical sciences, is not an independent discipline and is yet to develop a set of scientific principles of its own.

It is more like a craft or an experimental approach. Therefore, multidisciplinary and interdisciplinary integration is its inherent nature, and will reveal itself more and more in the future.

2) Research on artificial intelligence focus on foundational technologies, while application research is limited in quantity and focus on computer vision. In this paper, the hotspots of AI are analyzed through the terminology-based co-word network. Terms of foundational technologies, most being algorithms, dominate the list of top ten words by frequency, led by deep learning. Computer vision is a basic application, and face recognition is a typical application thereof. We think it heralds the beginning of application research, although generally speaking, artificial intelligence applications are underanalyzed.

3) Deep learning is currently the most popular and frontier research, and the combination of quantum physics and machine learning may be the most exciting one. We have generated a co-citation network of the sample literature and clustered it, followed by a detailed analysis of the important literature in the subdivisions under study, represented by four largest clusters. The aim is to study the frontier direction and its evolution process. The study of deep learning contains a number of papers which were highly cited and continue to be cited. Combining the results of co-word analysis, we may conclude that deep learning is the most popular research frontier. Some papers addressing the combination of physics, especially quantum physics and machine learning, came forth in the field of machine learning in 2016. The combination of these two fields may be the most current direction and is likely to be further combined with deep learning. We also notice in the analysis that artificial intelligence attaches importance to basic research, and its key theoretical research findings have derived from the process of solving practical problems.

4.2. Inspirations and Deficiencies

As a non-conventional and non-independent discipline, artificial intelligence will spread and penetrate into more fields like water flowing into everything in the future. It is set to promote the integration of more disciplines, and drive the advancement of disciplines. Meanwhile, continued efforts on basic research will enable AI to meet social needs better, giving a boost to application research. A trend of "AI+" in the academic world like in the industry will ensue.

Deep learning is a hotspot and frontier as expected, but the combination of quantum physics and machine learning is not. We find it interesting that AI may continue to penetrate other basic sciences and bring about substantial changes, as already foreshadowed in the discipline analysis section. We may expect artificial intelligence, mainly machine learning/deep learning, to bring about game-changing reforms as an "invention of invention methods" [34]. At the same time, this paper is intended to contribute to the development and construction of relevant disciplines, and facilitate the higher-level development of AI in broader aspects such as economy, institution and policy.

In order to improve data quality and ease the burden of data processing, the sample literature in this paper has been obtained by running a search using some keywords and picking out those highly-cited ESI papers. Some important works may have been excluded from the analysis because they do not meet the criteria. In addition, it is impossible for this paper to cover a longer timeline for all sorts of reasons, and thus the research and analysis of the earlier period of artificial intelligence is not available.

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