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Interdisciplinarity and Artificial Intelligence: A Two-Dimensional Analysis of Diversity and Cohesion

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Abstract

Nowadays Artificial Intelligence (AI) has increasingly become the core technology leading a new round of scientific and technological revolution and industrial transformation. AI is reaching out to all disciplines and breaking the border of disciplines. Hence many universities are using AI as a strategic tool to empower traditional disciplines. Tongji University in Shanghai is one of these universities. We use Tongji University's publications on AI as a case to study the interdisciplinarity that led by AI studies. We collect the AI publications which have Tongji University in the address. The publications are sliced into five four-year slices and classified according to the categories of their published journals. We then calculate the categories' diversity and cohesion based on the categories of the references of these AI publications. We plot the categories in a Cartesian coordinate system with diversity as one coordinate and cohesion as the other. The results indicate that categories involved in AI studies have gradually evolved towards high diversity and high cohesion. Initially, the categories "Computer Science, Artificial Intelligence" were in the Quadrant Ⅲ in the period of 2004-2007, then directly settled in the Quadrant Ⅰ in the period of 2008-2012, maintaining high cohesion and high diversity ever since. This trend is closely tied to the development of computational science and deep learning technologies. Additionally, categories such as "Computer Science, Interdisciplinary Applications", "Engineering, Electrical & Electronic", "Biochemical Research Methods", "Biotechnology & Applied Microbiology", "Mathematics & Computational Biology" and "Operations Research & Management Science" were already classified as high cohesion-high diversity categories in the early stages (before 2016), demonstrating strong interdisciplinary integration capabilities. "Neuroscience," show a significant increase in its academic influence after

2016. The history of these disciplines reveals the crucial role that AI has played in driving the advancement of the concerned categories.

Introduction

Currently, the fourth wave of the technological revolution, represented by artificial intelligence (AI), is rapidly evolving. As a comprehensive and interdisciplinary field, AI's innovations rely heavily on cross-disciplinary integration with various disciplines. Previous studies have shown that AI can discover new knowledge and generate new technologies through the transplantation of theories, method exchange, and object transfer, further breaking down disciplinary barriers and expanding disciplinary boundaries. This process leads to a higher-level, more integrated collaboration between AI and other disciplines, spawning emerging fields and producing disruptive, original breakthroughs (Wu, 2019). The advent of AI has promoted the convergence between different disciplines, bringing about profound transformations in the development of those fields (Cai, Wang, & Shen, 2019). Therefore, assessing the degree of disciplinary integration in AI-related interdisciplinary research fields, tracking the evolving trends of cross-disciplinary convergence driven by AI, are of paramount importance for understanding its transformative impact on a disciplinary system.

Interdisciplinary research is generally seen as a source of creativity and innovativeness (Dogan and Pahre, 1990). The citation relationships among scientific literature represent the integration and diffusion of knowledge, indicating the direction of knowledge flow (Liu & Rousseau, 2010). Liu, Rafols and Rousseau (2012) introduce a general framework for the analysis of knowledge integration and diffusion using bibliometric data. They proposed to capture the characteristic of interdisciplinarity by the calculation of diversity and coherence from bibliometrics data. Measuring how particular articles integrate research fields based on the assignation of the journals they cite to WoS Subject Categories, is one of the approaches for assessing interdisciplinary (Porter, 2006).

Rafols and Meyer (2010) state that diversity and coherence are the two basic notions for the study of interdisciplinarity. Diversity refers to the breadth in categories used and consists of three basic concepts: variety, balance and disparity (Stirling, 2007). Coherence refers to the extent to which different elements in the research (categories or topics) are interrelated. The notion of diversity puts the emphasis on how different the incorporated knowledge is, while the notion of coherence emphasizes how different bodies of research are consistently articulated and form a meaningful constellation. In this sense, an increase in diversity reflects the divergence of knowledge integration and diffusion, whereas an increase in coherence reflects their convergence (Rousseau et al., 2019). Measuring interdisciplinarity from the perspective of coherence helps to elucidate the distinct roles of each discipline within the overall network and to identify the dominant disciplines driving the interdisciplinary integration process.

The studies provide valuable insights for examining the diversity and cohesion of every discipline involved in AI-related interdisciplinary fields from a two-dimensional perspective.

In the face of the rapidly evolving field of AI, universities are actively exploring new models for interdisciplinary integration, such as the "AI+" model of discipline construction, to empower and transform the development of their academic fields through AI. In 2019, Tongji University became one of the first universities in the country to be authorized to establish an undergraduate program in AI, and it also took the lead in developing the discipline of "Smart Science and Technology". In 2021, Tongji University was approved to develop an interdisciplinary doctoral program in "Smart Science and Technology", initiating research in AI-driven interdisciplinary fields. On May 16, 2024, Tongji University released the "Action Plan for AI-Driven Discipline Innovation and Development (2024-2027)," launching eight core tasks to strengthen the development of AI-related disciplines. Taking Tongji University as an example, measuring the diversity and cohesion of discipline of AI-related interdisciplinary fields is crucial for understanding the evolution of AI-driven discipline integration.

Data

To study the trends and situation of disciplinary integration caused by AI, this paper selects Tongji University as a case study and collects all published AI papers by Tongji University. The Web of Science core collection database is used as the data source. We refer to the search terms employed in the 2018 China Artificial Intelligence Development Report published by the Tsinghua University Science and Technology Policy Research Center, combined with expert opinions. The search strategy is as follows: (TS=("artificial intelligence" OR "machine learning" OR "natural language processing" OR "computer vision" OR "facial recognition" OR "image recognition" OR "speech recognition" OR "semantic search" OR "semantic web" OR "text analytics" OR “virtual assistance" OR “visual search" OR" predictive analytics" OR" intelligent system" OR "Deep Learning" OR "Robotics" OR "Autonomous Systems" OR "Human-Computer Interaction" OR "ChatGPT")) AND AD=(Tongji), no time frame was set, and the "Affiliation" filter was applied to select "TONGJI UNIVERSITY". This search strategy resulted in the retrieval of 3,839 articles retrieved, conducted on October 3, 2024. After deduplication, 3,367 valid articles were retained for subsequent subject categories mapping.

Based on the Journal Citation Reports (JCR) from the WoS, which provides the subject category information of each journal (a total of 254 WoS categories), we mapped each reference's corresponding journal to one or more WoS categories. A total of 157,761 reference records were mapped to categories. After data cleaning and mapping the references' categories, references with fewer than three subject categories were removed (Diego, Puay, & Rafols, 2014). As a result, 2,783 papers were selected as the sample for this study (spanning the period from 2004 to 2023). Dataset Availability: https://zenodo.org/records/15220666.

The data were preprocessed illustrated in Figure 1. Each publication was mapped to its categories of the journal that the publication was published. Each publication’s references were also mapped onto the categories of the references’ journals. The publications with same category were conglomerated, together with their references and their categories, forming a map from the category of publications and its corresponding references' categories.

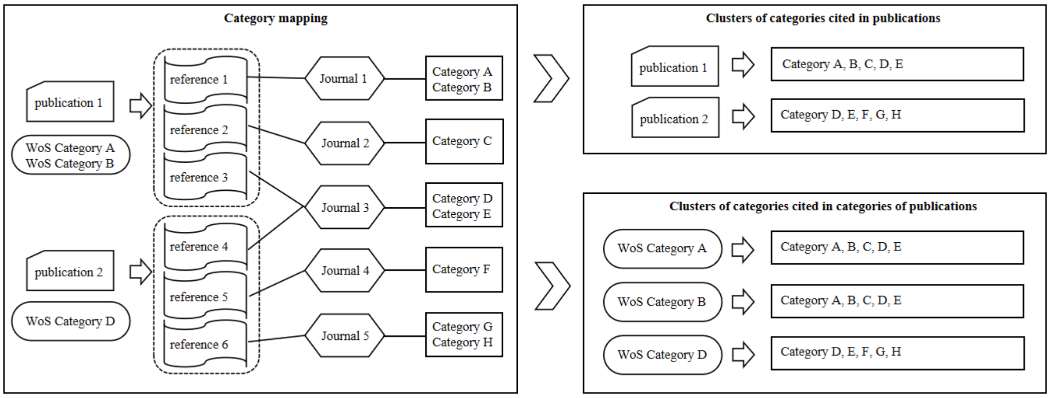

Figure 1. The mapping of the categories of publications and their references' categories.

The dataset was sliced into five four-year slices. Table 1 lists for every period the number of publications, the number of categories over which the publications are distributed, and the number of categories over which the references are distributed. The mapping in Figure 1 was also based on sliced dataset.

Table 1. Statistics of publications of Tongji University's artificial intelligence (AI) research field from 2004 to 2023.

Table	*Number of publications*	*Number of the categories the publications distributed*	*Number of the categories the references distributed*
2004-2007	17	21	45
2008-2011	47	35	98
2012-2015	103	42	140
2016-2019	450	102	205
2020-2023	2,166	171	237
2004-2023(total)	2,783	179	239

Methods

In this study, we adopt the conceptual framework proposed in (Rafols & Meyer, 2010) to measure the interdisciplinary of the categories related to AI research. Rafols and Meyer (2010) focused on measuring interdisciplinary of individual articles. Liu, Rafols & Rousseau (2012) enlarge this framework to a set of related articles. In this study, we measure the interdisciplinary of categories. the category is composed by a set of AI-related publications. So, we slightly modify the methods.

We use the distribution of references' categories as analytical unit to calculate the diversity. However, we have to conglomerate all publications in the same category

together to form a map from the category of AI publications to its references' categories. We calculate the category' diversity based on the conglomerate of the publications in same category in each time slice. Each publication is categorized into one or more categories by Web of Science. When conglomerating a publication which has several categories, the publication and its references' categories are conglomerated into all the categories the publication belongs.
We use Rao-Stirling indicator to measure the diversity of categories. The specific formula for the Rao-Stirling indicator is as follows:

$$\text{Diversity} = \text{Rao} - \text{Stirling} = \sum_{i,j(i \neq j)} (d_{ij})^{\alpha} \cdot (p_i \cdot p_j)^{\beta}{}_{i}$$

Here, d_{ij} denotes the dissimilarity between category i and category j. The dissimilarity of categories is calculated based on the inter-category co-membership of the journals in Web of Science, which was proposed by Liu (2018) to construct global backbone of science. p_i and p_j denote the proportions of the total number of items under study in category i and category j, respectively. Finally, α and β are parameters that adjust the importance given to small distances (α) and weights (β). In case one lacks empirical reasons to adjust α and β, they are often taken as being equal to 1.
We also construct a categories co-occurrence network in each time slice. Figure 2 shows how we constructed the network.

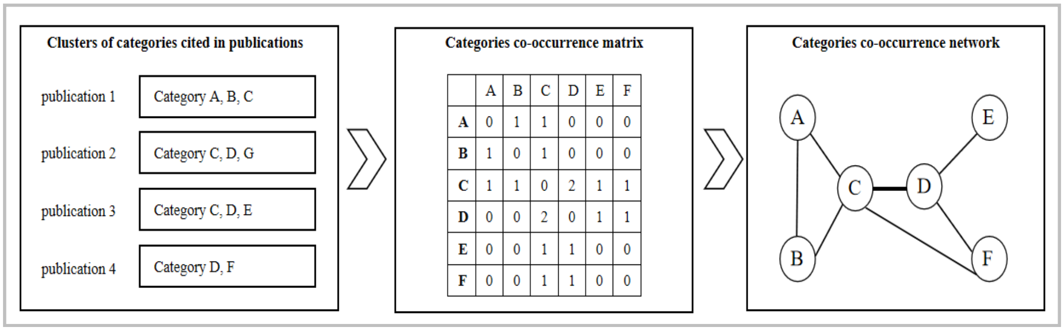

Figure 2. The process of constructing a categories co-occurrence network.

Since we focus on the role of a category in integrating different categories related to AI, we do not go to measure the whole structural consistency of the AI publications network. A category can be considered to reside in an important mediating position in a network if it is on a path between many other categories. Leydesdorff (2007) suggested that betweenness centrality can be used as a measure of interdisciplinarity at the journal level. Rafols et al.(2012) developed intermediation as a framework, complementary to the diversity-cohesion framework. Zhang et al (2020) review the measurement for the cohesion of interdisciplinary research. Betweenness was acknowledged as a valid indicator to measure the cohesion of a single-node in the network.

In this paper, we chose the betweenness centrality of nodes to represent the degree of cohesion of categories.
Betweenness centrality is used to measure the role of each category as a bridge in the flow of information between categories. The formula of betweenness centrality is as follows:

$$\text{Cohesion} = \text{Betweenness Centrality} = \frac{\sum_{jk(j\neq k)} g_{jk}(i)}{g_{jk}}$$

Here, g_{jk} denotes the total number of shortest paths between two nodes; $g_{jk}(i)$ indicates the number of shortest paths between two nodes that pass-through node i.

Principles of Cartesian Coordinate System Plotting

Cohesion and diversity are the two dimensions we used to describe the interdisciplinary of the AI related categories. We establish a Cartesian coordinate system with diversity as one coordinate and cohesion as the other and plot the categories in the system according to our calculation.
To ensure comparability, all the data are standardized. In this process, each data point–representing cohesion or diversity for a given stage–is transformed relative to the overall dataset's mean. After standardization, values above the average are represented by positive values, while values below the average are represented by negative values. Hence the origin in the coordinate system represents the mean value for both cohesion and diversity across the entire 20-year period.
The primary advantage of this standardization process is that it enables the comparison of different stages in a uniform manner, with all data transformed onto a common scale.

Classification of Fields of Categories

Leydesdorff (2016) distinguished all categories of WOS into 5 broad categories or 18 fields. The five broad categories include: Social Sciences & Psychology, Engineering & Mathematics, Medicine, Physics & Chemistry, and Biology. The eighteen fields include: Social Sciences, Computer Science and Engineering, Medicine, Psychology, Environmental Sciences, Chemistry & Applied Physics, Biomedicine, Health Care, Engineering, Agriculture and Food, Management, Biology, Chemistry, Infectious diseases, Physics, Pharmacology, Environmental Engineering, Medicine & Others.
Drawing on Leidesdorff's classification of 18 fields, we reorganize the 254 categories in WoS into more generalized and conceptually coherent domains. The specific steps are as follows:
(1) First, the correspondence between the 227 WoS subject categories and the 18 major domains, as organized by Leydesdorff (2016), was adopted;
(2) A new field "Literature, History, Arts, and Philosophy"—was added, resulting in a final total of 19 major fields of categories;

(3) For the remaining 27 subject categories not covered in Leidesdorff's classification system, we assigned them to appropriate field based on expert judgment.

Result

Base on the publications of AI research field of Tongji University from 2004 to 2023, we calculate the indicators of the categories' diversity and cohesion and plot these categories in a Cartesian coordinate system. Below, we will analyze the two-dimensional feature of categories' cohesion and diversity for the periods 2004-2007, 2008-2011, 2012-2015, 2016-2019, and 2020-2023.

The two-dimensional feature of AI research field during 2004-2007

Figure 3 shows the two-dimensional feature analysis chart of the categories in the AI research field at Tongji University during 2004-2007, and Table 2 displays the corresponding classification table of the categories' two-dimensional features. A total of 21 Web of Science categories of publications were involved during this stage. The study also statistically analysed the categories with betweenness centrality of 0. To avoid excessive redundancy of data points in the scatter plot, these categories were not presented in the two-dimensional feature analysis chart.

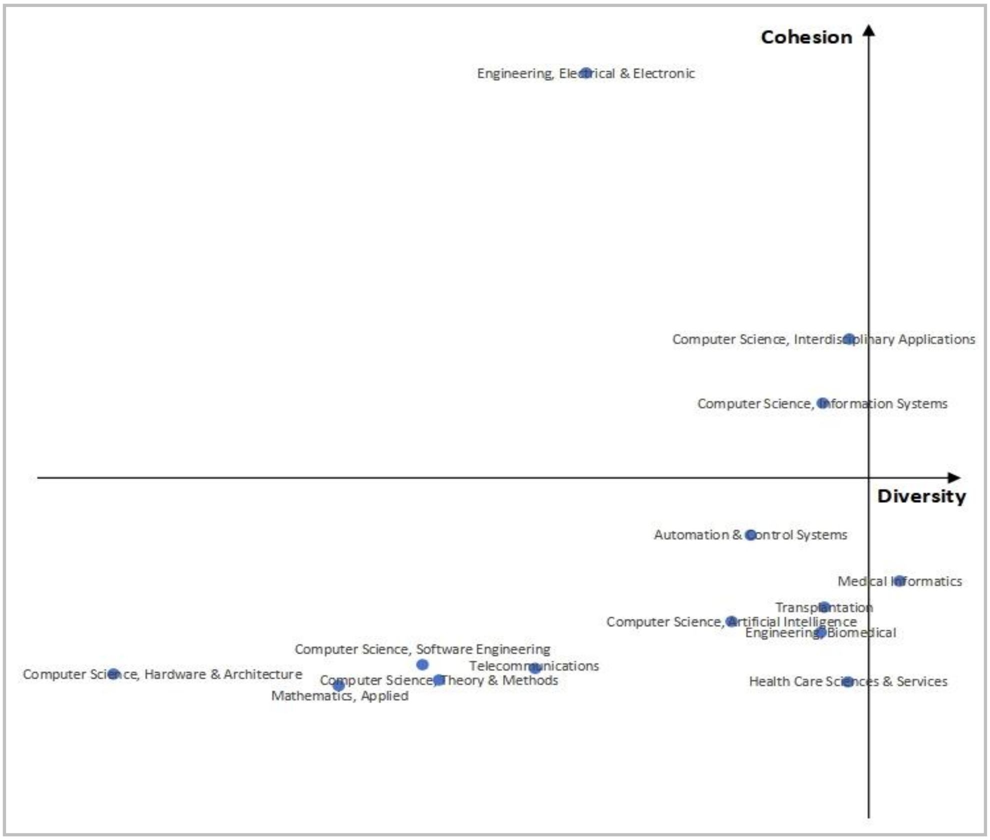

Figure 3. The two-dimensional feature analysis chart of the categories of publications (2004–2007).

Table 2. Two-dimensional Features of the categories of AI publications (2004–2007).

Two-Dimensional Characteristics	*Field of Categories*	*Category Names*
Quadrant Ⅰ: High Cohesion - High Diversity (0 category)	None	None
Quadrant Ⅱ: High Cohesion - Low Diversity (3 categories)	Computer Science and Engineering	Computer Science, Interdisciplinary Applications; Computer Science, Information Systems; Engineering, Electrical & Electronic
Quadrant Ⅲ: Low Cohesion - Low Diversity (10 categories)	Computer Science and Engineering	Automation & Control Systems; Computer Science, Artificial Intelligence; Telecommunications; Computer Science, Theory & Methods; Computer Science, Software Engineering; Mathematics, Applied; Computer Science, Hardware & Architecture
	Health Care	Health Care Sciences & Services
	Medicine	Transplantation
	Chemistry & Applied Physics	Engineering, Biomedical
Quadrant Ⅳ: Low Cohesion - High Diversity (1 category)	Health Care	Medical Informatics
Categories with Betweenness Centrality of 0 (7 categories)	Computer Science and Engineering	Robotics; Engineering, Manufacturing; Transportation Science & Technology; Instruments & Instrumentation
	Pharmacology	Mathematical & Computational Biology
	Environmental Engineering	Energy & Fuels
	Chemistry & Applied Physics	Physics, Applied

From the two-dimensional feature analysis chart of the categories of publications, no categories were found in the high cohesion-high diversity quadrant (Quadrant Ⅰ) during this period. This indicates that Tongji University's interdisciplinary research in the field of artificial intelligence was still in infancy, and there was no widespread or close interconnection between disciplines at that time.

In the High cohesion-Low diversity quadrant (Quadrant Ⅱ), three categories were distributed: "Computer Science, Interdisciplinary Applications," "Computer Science, Information Systems," and "Engineering, Electrical & Electronic," all of which belong to the field of Computer Science and Engineering. These categories had relatively high cohesion, indicating a strong ability for disciplinary integration. However, their diversity was low, meaning their knowledge absorption scope was relatively limited and primarily concentrated within closely related sub-disciplines of the same broader field. It is noteworthy that the field of Computer Science and Engineering exhibited strong disciplinary cohesion during this period, making it the most important bridge for communication between other disciplines and the formation of academic networks. In the context of the rapid digital transformation and technological advancements in information technology at the time, these fields had significant potential for interdisciplinary applications.

The low cohesion-low diversity quadrant (Quadrant Ⅲ) included 10 categories, including "Computer Science, Artificial Intelligence," "Automation & Control Systems," "Health Care Sciences & Services," "Transplantation", etc. Spanning the fields of Computer Science and Engineering, Health Care, Medicine, Chemistry & Applied Physics. These categories were characterized by both low cohesion and low diversity, reflecting a narrower research citation range and insufficient interdisciplinary interaction. During this period, limited computational resources were a major bottleneck for the development of artificial intelligence. Compared to today's high-performance GPUs and distributed computing architectures, the computational capabilities of 2004-2007 were still limited, which restricted the training of complex models and the processing of large-scale data. As a result, the development of artificial intelligence was still in its early stages. The research focus of the "Computer Science, Artificial Intelligence" at this time was likely more concentrated on theoretical deepening within the discipline itself, rather than fostering interdisciplinary communication and applications. For instance, the most highly cited paper in the "Computer Science, Artificial Intelligence" field during this period was an article aimed to solve the of lack trust in P2P (Peer-to-Peer) Semantic Web (Wang, Zeng & Yuan, 2006). Despite not being directly related to artificial intelligence technologies or theories, solving this issue in P2P semantic networks not only enhances data reliability but also contributes to the development of distributed AI, knowledge graphs, and autonomous intelligent systems, thus providing a solid foundation for the innovation and popularization of artificial intelligence technologies.

In the low cohesion-high diversity quadrant (Quadrant Ⅳ), only the category of "Medical Informatics". "Medical Informatics" is the field that uses computers and related information technologies to handle tasks such as the storage, organization, retrieval, and optimal utilization of biomedical data, information, and knowledge, with the goal of supporting research and practice in the medical field and improving the accuracy, timeliness, and reliability of problem-solving and decision-making.

Between 2004 and 2007, the research in the "Medical Informatics" at Tongji University consisted of only two papers on the same topic, both published in 2005 (Xu et al.,2005; Xu et al.,2005). These studies used specific algorithms to train Artificial Neural Networks (ANNs) to identify the best treatment strategies for vascular tissue engineering based on experimental data. The results demonstrated the huge potential of artificial intelligence technology in decision-making within tissue engineering, enabling the analysis of large datasets and making more precise decisions to improve outcomes. These two papers cited 21 disciplines, spanning Computer Science and Engineering, Environmental Science, Biomedicine, Medicine, Biology, Agriculture and Food, Infectious Diseases, and Health Care. This wide span of disciplines explains the high measure of diversity for "Medical Informatics." However, due to the categories connected to "Medical Informatics" are themselves tightly interrelated, meaning these categories can communicate directly without needing "Medical Informatics" as an intermediary, resulting in a low measure of cohesion for "Medical Informatics".
statistically analysed the categories with betweenness centrality of 0, including "Robotics," "Mathematical & Computational Biology," "Energy & Fuels," and "Physics, Applied," indicating that they did not appear on the shortest connection path between any two categories. However, this does not entirely negate their potential intermediary value, as the flow of information between disciplines can also occur via non-shortest paths, and nodes along such paths can still facilitate knowledge exchange.
In summary, during 2004-2007, the level of interdisciplinarity in the fields of AI at Tongji University was weak. "Computer Science, Artificial Intelligence" during this period did not exhibit high diversity or cohesion. The number of categories in the Quadrant Ⅱ and Quadrant Ⅲ was high. The absence of categories in the Quadrant Ⅰ suggests that the interdisciplinary nature of the AI research field had not yet reached a highly converged level. However, as academic collaboration deepens and disciplines development, categories located in the Quadrant Ⅱ and Ⅳ may gradually evolve toward higher cohesion and diversity, thus driving the further development and evolution of the entire interdisciplinary research field in artificial intelligence.

The two-dimensional feature of AI research field during 2008-2011

The two-dimensional feature distribution of the categories in Tongji University's AI research field from 2008 to 2011 is presented in Figure 4 and Table 3. Compared to the situation from 2004 to 2007, the diversity and cohesion distribution of categories underwent significant changes, with the number of categories of publications increasing from 21 to 35. Among them, "Computer Science, Artificial Intelligence" achieved significant breakthroughs in diversity and cohesion, with the influence of AI in interdisciplinary research expanding continuously, gradually becoming a core driving force in the academic network.

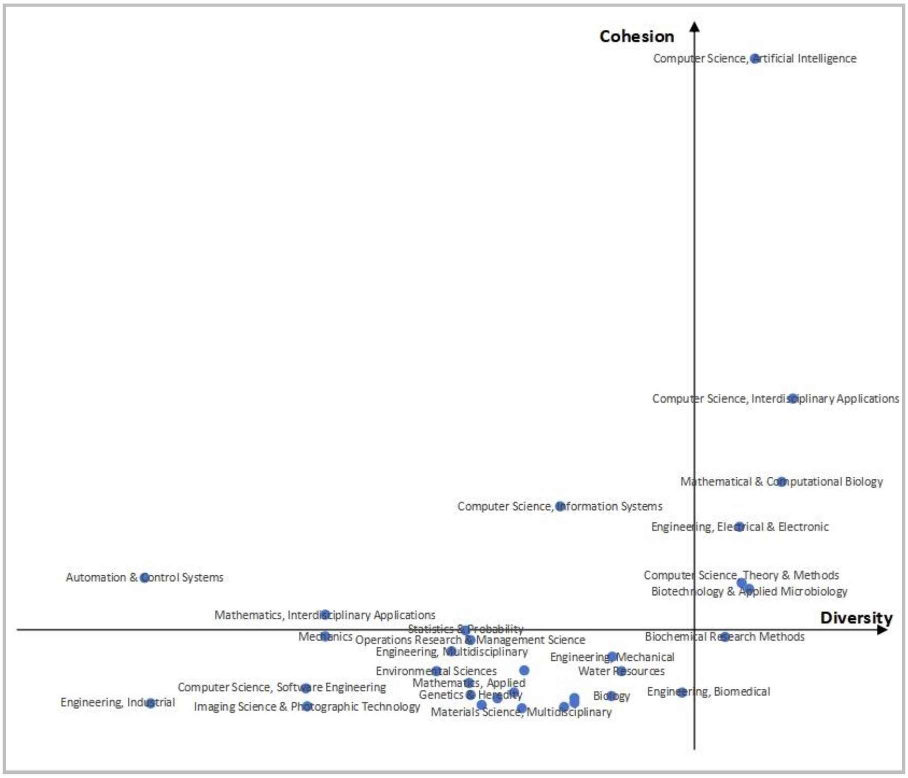

Figure 4. The two-dimensional feature analysis chart of the categories of publications (2008–2011).

Table 3. Two-dimensional Features of the categories of publications (2008–2011).

Two-Dimensional Characteristics	*Field of Categories*	*Category Names*
Quadrant Ⅰ: High Cohesion - High Diversity (6 categories)	Computer Science and Engineering	Computer Science, Artificial Intelligence; Computer Science, Interdisciplinary Applications; Computer Science, Theory & Methods; Engineering, Electrical & Electronic
	Pharmacology	Mathematical & Computational Biology
	Agriculture and Food	Biotechnology & Applied Microbiology
Quadrant Ⅱ: High Cohesion - Low Diversity (3 categories)	Computer Science and Engineering	Computer Science, Information Systems; Mathematics, Interdisciplinary Applications; Automation & Control Systems

Quadrant Ⅲ : Low Cohesion - Low Diversity (22 categories)	Computer Science and Engineering	Computer Science, Hardware & Architecture; Telecommunications; Operations Research & Management Science; Mathematics, Applied; Statistics & Probability; Engineering, Multidisciplinary; Computer Science, Software Engineering; Engineering, Industrial
	Environmental Sciences	Water Resources; Remote Sensing; Environmental Sciences; Imaging Science & Photographic Technology
	Engineering	Engineering, Mechanical; Thermodynamics; Mechanics
	Chemistry & Applied Physics	Engineering, Biomedical; Materials Science, Multidisciplinary
	Chemistry	Chemistry, Multidisciplinary
	Biology	Biology
	Physics	Optics
	Pharmacology	Genetics & Heredity
	Medicine & Others	Medicine, Research & Experimental
Quadrant Ⅳ : Low Cohesion - High Diversity (1 category)	Chemistry	Biochemical Research Methods
Categories with Betweenness Centrality of 0 (3 categories)	Computer Science and Engineering	Robotics
	Engineering	Engineering, Aerospace
	Chemistry & Applied Physics	Physics, Applied

From the vector distribution of citing categories, the interdisciplinarity and cohesion levels of the artificial intelligence interdisciplinary field from 2008 to 2011 improved compared to 2004 to 2007. The number of categories in the Quadrant Ⅰ increased from a previous vacancy to 6. These categories span across the fields of Computer Science and Engineering, Pharmacology, Agriculture and Food. Among them, "Computer Science, Artificial Intelligence" exhibited a significant increase in cohesion and diversity, making it the category with the highest cohesion level among all the categories in this phase. This indicates that the influence of the AI field has substantially expanded, gradually establishing itself as a core hub in the academic network. "Computer Science, Interdisciplinary Applications" and "Engineering, Electrical & Electronic" made a significant leap from the Quadrant Ⅱ (High Cohesion -Low Diversity) in the previous phase to the Quadrant Ⅰ (High Cohesion -High Diversity). "Computer Science, Theory & Methods," which was in the Quadrant Ⅲ (low cohesion-low diversity) from 2004 to 2007, and "Mathematical & Computational Biology," which had betweenness centrality of 0, both made a remarkable leap to the Quadrant Ⅰ from 2008 and 2011, entering the realm of high cohesion–high diversity disciplines. "Biotechnology & Applied Microbiology" made its debut directly in the Quadrant Ⅰ, emerging as a new force in the interdisciplinary field of artificial intelligence.

"Mathematics and Computational Biology" is a discipline that uses statistical methods and computer algorithms to analyze genetic and genomic data. It emphasizes research in molecular evolution, molecular classification, molecular genetics, and population genetics using mathematical, statistical, and computational approaches based on biological data. Compared to traditional biological experiments, which are limited by the precision of operational levels, experimental tools, and observational accuracy, computational biology based on computers is faster, more cost-effective, and theoretically has unlimited computational precision and high reproducibility. This characteristic not only significantly enhances the efficiency of biological research but also drives the interdisciplinary integration of bioinformatics, genomics, computer science, operations research, and other fields, exhibiting strong cross-disciplinary integration and accelerating the collaborative development and innovation in related fields (Mao, Jiang and Yuan, 2024). One of the most-cited papers in the 2008-2011 period in the field of artificial intelligence and "Mathematical & Computational Biology" at Tongji University discussed the application of decision tree methods in machine learning to biology, such as cancer classification and genomics classification (Che et al., 2011).

"Biotechnology & Applied Microbiology" is a comprehensive discipline that covers both "Biotechnology" and "Applied Microbiology," with "Applied Microbiology" being an important component of the "Biotechnology" discipline system. "Biotechnology" includes many biological programs adjusted according to human needs, such as early animal domestication, plant cultivation, and the improvement of varieties through artificial selection and hybridization. Under the modern scientific paradigm, biotechnology has evolved into gene engineering, cell culture, tissue culture, and other technologies. At the same time, many pure life sciences fields, such as biochemistry, cell biology, embryology, microbiology, and molecular biology, are also related to biotechnology. One of the most-cited papers in the 2008-2011 period in Tongji University's artificial intelligence interdisciplinary field of "Biotechnology and Applied Microbiology" designed a novel transcriptome assembly algorithm called IsoLasso based on RNA-Seq. This algorithm can simultaneously reconstruct all full-length mRNA transcripts from millions of short-read sequencing data, achieving higher sensitivity and accuracy than the most advanced transcriptome assembly tools. The study found that although this research did not directly involve artificial intelligence-related technologies and methods, the breakthroughs made by the IsoLasso algorithm in short-read transcriptome assembly laid the groundwork for the later application of AI in gene sequencing (Li, Feng and Jiang, 2011).

In the Quadrant Ⅱ (High Cohesion -Low Diversity), 3 categories were distributed in 2008-2011, including "Computer Science, Information Systems," "Mathematics, Interdisciplinary Applications," and "Automation & Control Systems".

In the Quadrant Ⅲ (Low Cohesion -Low Diversity), the distribution of categories remains the most concentrated, with a total of 22 categories, an increase from the 2004-2007 period. This quadrant includes categories from nine fields: Computer Science and Engineering, Environmental Sciences, Engineering, Chemistry & Applied Physics, Chemistry, Biology, Physics, Pharmacology, Medicine & Others. This distribution suggests that although some disciplines have started to participate in interdisciplinary artificial intelligence research, their ability to integrate knowledge and their inclusivity remain at a relatively low level. They have yet to play a significant role in the cross-disciplinary knowledge flow network.

In the Quadrant Ⅳ (Low cohesion -High diversity), only "Biochemical Research Methods," was appeared during the 2008-2011 period. It is noteworthy that "Medical Informatics," which was in this quadrant in the previous phase, does not appear in any quadrant in this stage, indicating a significant disruption in the continuity of research in this field at Tongji University.

Furthermore, statistical results show that three categories with betweenness centrality of 0 during 2008-2011, including the newly added "Engineering, Aerospace" and the previously existing "Robotics" and "Physics, Applied." These disciplines are at the periphery of the academic network, contributing almost nothing to the overall network's connectivity and information flow. This phenomenon may be due to their low co-citation frequency with other disciplines, which has prevented the formation of effective knowledge transfer pathways. Additionally, related interdisciplinary research is still in its early stages and has yet to establish a stable network of academic interaction.

In summary, compared to the 2004-2007 period, the diversity and cohesion in the interdisciplinary field of artificial intelligence at Tongji University progress in 2008-2011. The Quadrant Ⅰ show a breakthrough from non-existence to presence, with "Mathematics and Computational Biology" and ""Biotechnology & Applied Microbiology" becoming significant interdisciplinary forces outside the field of Computer Science and Engineering, playing a central role in knowledge integration within the AI cross-disciplinary field. However, most disciplines remain concentrated in the low cohesion -low diversity region (Quadrant Ⅲ), with a relatively high number of peripheral disciplines, indicating that the level of communication between disciplines in the overall academic network has not yet fully matured. As interdisciplinary collaboration deepens, more disciplines are expected to transition from the Quadrant Ⅲ to the Quadrant Ⅱ or the Quadrant Ⅳ, and ultimately move toward the Quadrant Ⅰ (high cohesion -high diversity), thus further advancing research in the AI interdisciplinary field.

The two-dimensional feature of AI research field during 2012-2015

The two-dimensional feature distribution of categories for the period 2012-2015 is shown in Figure 5 and Table 4. Compared to 2008-2011, the number of categories increased by 7, and the two-dimensional distribution of categories exhibited new changes.

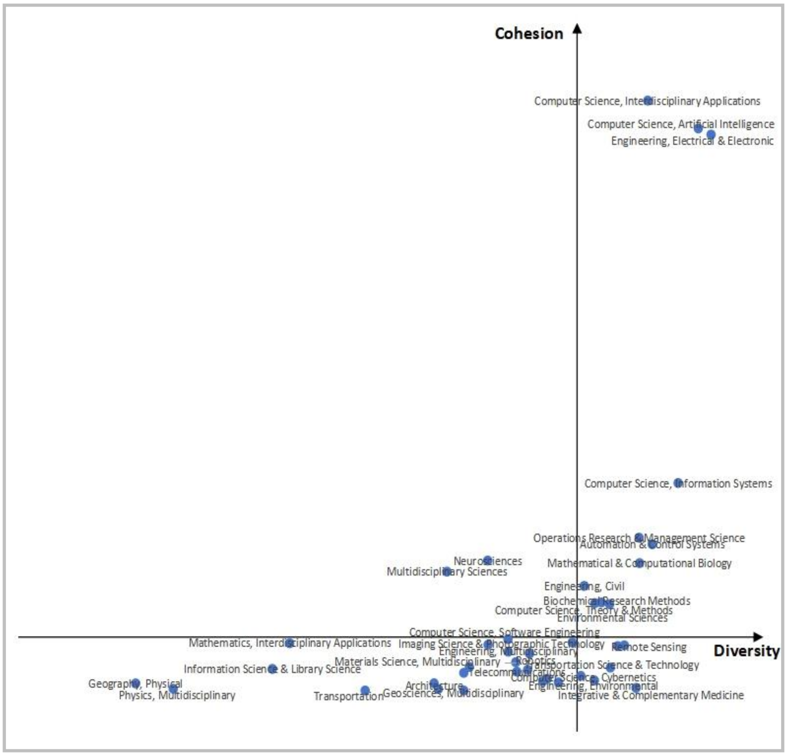

Figure 5. The two-dimensional feature analysis chart of the categories of publications (2012–2015).

Table 4. Two-dimensional Features of the categories of publications (2012–2015).

Two-Dimensional Characteristics	*Field of Categories*	*Category Names*
Quadrant Ⅰ: High Cohesion - High Diversity (11 categories)	Computer Science and Engineering	Engineering, Electrical & Electronic; Computer Science, Artificial Intelligence; Computer Science, Information Systems; Automation & Control Systems; Computer Science, Interdisciplinary Applications; Operations Research & Management Science; Computer Science, Theory & Methods
	Engineering	Engineering, Civil

	Chemistry	Biochemical Research Methods
	Environmental Sciences	Environmental Sciences
	Pharmacology	Mathematical & Computational Biology
Quadrant Ⅱ: High Cohesion - Low Diversity (2 categories)	Medicine & Others	Neurosciences; Multidisciplinary Sciences
Quadrant Ⅲ: Low Cohesion - Low Diversity (21 categories)	Computer Science and Engineering	Robotics; Telecommunications; Engineering, Multidisciplinary; Computer Science, Software Engineering; Computer Science, Hardware & Architecture; Mathematics, Interdisciplinary Applications
	Environmental Sciences	Water Resources; Imaging Science & Photographic Technology; Geosciences, Multidisciplinary; Geography, Physical
	Engineering	Engineering, Mechanical; Construction & Building Technology; Architecture
	Physics	Optics; Physics, Multidisciplinary
	Management	Information Science & Library Science
	Chemistry	Chemistry, Multidisciplinary
	Chemistry & Applied Physics	Materials Science, Multidisciplinary
	Social Sciences	Transportation
	Biomedicine	Biochemistry & Molecular Biology
	Pharmacology	Pharmacology & Pharmacy
Quadrant Ⅳ: Low Cohesion - High Diversity (6 categories)	Computer Science and Engineering	Transportation Science & Technology; Computer Science, Cybernetics
	Pharmacology	Integrative & Complementary Medicine
	Health Care	Health Care Sciences & Services
	Environmental Sciences	Remote Sensing
	Environmental Engineering	Engineering, Environmental
Categories with Betweenness Centrality of 0 (2 categories)	Environmental Sciences	Geology
	Physics	Astronomy & Astrophysics

From 2012 to 2015, 11 categories entered the Quadrant Ⅰ, including "Engineering, Electrical & Electronic," "Computer Science, Artificial Intelligence," "Engineering, Civil," "Biochemical Research Methods," "Environmental Sciences," "Mathematical & Computational Biology", etc. Compared to the 2008-2011 period, 6 additional categories were added. These categories span across five major fields: Computer Science and Engineering, Engineering, Chemistry, Environmental Sciences, Pharmacology.

We analyse some of the categories that entered the Quadrant Ⅰ. The development of "Computer Science, Artificial Intelligence" is closely related to the technological breakthroughs in deep learning after 2012. Deep learning, as an emerging field of machine learning, aims to automatically extract multi-layer feature representations from data. Its core idea is to use a data-driven approach with a series of nonlinear transformations to extract features from raw data, progressing from low-level to high-level, from specific to abstract, and from general to specialized semantics (Zhang, Wang, & Guo, 2018). The landmark event in the development of deep learning was the 2012 ImageNet Large-Scale Visual Recognition Challenge (Russakovsky et al., 2015), where Krizhevsky's deep convolutional neural network model reduced image classification error rates by nearly 50% (MIT Technology Review, 2013). Compared to the best traditional methods in 2011, the recognition error rate dropped by 41.1%. By 2015, image recognition error rates based on deep learning had surpassed human performance. Since then, deep learning has been widely applied in fields such as speech recognition, image processing, and natural language processing, profoundly influencing research directions in the interdisciplinary field of AI. It has gradually evolved into a core node in the interdisciplinary network, with strong interdisciplinarity and disciplinary cohesion. These qualities not only drive technological breakthroughs in related fields but also strengthen AI's critical position in the academic network of interdisciplinary fields. From 2012 to 2015, there were 27 publications of "Computer Science, Artificial Intelligence" at Tongji University, citing a total of 70 categories across 17 major categories fields (out of a total of 19, with Environmental Engineering and Infectious Diseases being excluded). During this period, the most cited paper in the "Computer Science, Artificial Intelligence" focused on improving the robustness of image recognition through deep learning techniques. Specifically, the paper involved training an autoencoder to extract shape and color features of objects from RGB images. These features were then passed into a Recurrent Neural Network (RNN) to extract multi-level features, resulting in hierarchical and robust feature representations. Finally, the features from each subset were combined and sent to a SoftMax classifier for object recognition.

"Engineering, Electrical & Electronic" also performed notably during this period. Electricity is an excellent carrier of both energy and information; it can be used to collect, store, process, transmit, and present information, as well as distribute, store, and convert energy in various forms. In simple terms, electrical and electronic engineering is the modern method of managing information and energy. Devices, circuits, and systems form the three foundational concepts of electrical and electronic engineering. Devices are the basic elements that construct circuits, circuits serve as carriers for specific functions, and systems are overarching architectures composed of multiple circuits to achieve complex objectives. This can be summarized as a transition from "hard" to "soft," where lower-level devices are closer to physics, while higher-level systems are more aligned with software and algorithms. As such, electrical and electronic engineering is a broad field that provides foundational technological support for numerous research and application areas. Examples include electronic systems widely used in aircraft and automobiles, precision instruments for medical diagnosis and surgery, wireless communication technologies enabling global connectivity, and semiconductor chip technologies supporting advancements in computing and AI. These applications illustrate the profound impact of electrical and electronic engineering on modern life and technological development.

"Operations Research & Management Science" also demonstrated high diversity and cohesion in the AI interdisciplinary field during 2012-2015, driven by its strong tool-based nature, broad application scenarios, and deep integration with AI and big data technologies. Operations research and management science focus on optimizing resource allocation and planning activities to maximize the utility of limited resources and achieve overall optimal objectives. To achieve this, mathematical methods are often employed to construct problem models, establish corresponding theories, and design and analyse solution algorithms. With advancements in computing and AI, computational capabilities have increased millions of times compared to traditional manual calculations, greatly expanding the application scenarios of operations research and management science. Its methods and theories are widely applied in fields such as engineering, economics, computer science, transportation, and supply chain management, significantly promoting interdisciplinary collaboration and knowledge integration.

Additionally, as a traditional strength of Tongji University, "Engineering, Civil" significantly enhanced its diversity and cohesion during this period by leveraging the rapid development of AI, a total of 4 papers was published, which collectively cited 25 different categories. Ji and Zhang (2012) utilized computer vision theory to establish the mathematical relationship between image planes and real-world space. This approach allowed for the capture of image sequences of planar targets mounted on vibrating structures, taken from digital cameras. By analyzing these images, the method could quantify structural dynamic displacements at the target positions, providing a precise measurement of complex object motion. This contributed significantly to structural displacement measurements in civil engineering projects. Computer vision is an important branch of artificial intelligence, focused on visual processing, which enables computers to "see" and understand visual content such as images and videos, mimicking human vision. The core capabilities of current computer vision systems are primarily based on deep learning models, which can process visual data from cameras, videos, or images. These capabilities include tasks such as image classification, object detection, pose estimation, image segmentation, and facial recognition. The deep integration of computer vision with machine learning has led to significant advancements in its applications across various fields.

"Mathematics & Computational Biology," as a typical representative of interdisciplinary research, continued to build on its advantages from the previous stage, further showcasing its critical role in the integration of bioinformatics and AI.
From the perspective of other quadrants, the number of categories in the Quadrant Ⅱ decreased from 4 in 2008-2011 to 2 in 2012-2015. Among the 4 categories in the Quadrant Ⅱ during 2008-2011, all except for "Mathematics, Interdisciplinary Applications" moved to the Quadrant Ⅰ, while "Mathematics, Interdisciplinary Applications" shifted to the Quadrant Ⅲ, reflecting a decline in its academic cohesion. In 2012-2015, the categories in the Quadrant Ⅱ, "Neuroscience" and "Multidisciplinary Sciences," both from the Medicine field, had not appeared in the previous two stages but emerged prominently in this phase. These disciplines exhibit a relatively high level of academic cohesion, indicating their significant role in connecting knowledge within the artificial intelligence interdisciplinary field. However, due to their higher degree of specialization or the fact that their application scenarios have not yet become widely generalized, their interdisciplinary diversity remains relatively low.
In the Quadrant Ⅳ, there are 6 categories, including "Transportation Science & Technology," "Computer Science, Cybernetics," "Integrative & Complementary Medicine," "Health Care Sciences & Services," "Remote Sensing," and "Engineering, Environmental." These disciplines involve a broad range of interdisciplinary content in their research areas, but their internal cohesion remains weak, preventing them from forming tight structural connections within the academic network.
The Quadrant Ⅲ remains the most populated quadrant, with 21 categories, similar to the number in 2008-2011. These categories include "Robotics," "Water Resources," "Engineering, Mechanical," "Optics", etc. Spanning across 10 major Categories Fields. Among these, "Robotics" published 6 papers in this phase, citing 24 different disciplines, but its academic influence remained concentrated in specific fields without deep collaboration with other disciplines in the AI interdisciplinary field. Consequently, its cohesion and diversity were relatively low.
In this phase, the disciplines "Astronomy & Astrophysics" and "Geology" with betweenness centrality of 0. However, it is important to note that these fields are increasingly influenced by AI, and their future potential for application and interdisciplinary collaboration is promising.
Overall, from 2012 to 2015, the cohesion and diversity of categories in the AI interdisciplinary field at Tongji University significantly increased. The number of disciplines in the Quadrant Ⅰ expanded from 6 in the previous phase to 11. "Computer Science, Artificial Intelligence," promoted the interdisciplinary research and application of disciplines closely related to AI, such as "Engineering, Electrical & Electronic," "Operations Research & Management Science," "Engineering, Civil". Additionally, the number of disciplines in the second and fourth quadrants increased significantly, suggesting strong potential for future growth toward the first quadrant. Although most disciplines still cluster in the low cohesion−low diversity region (Quadrant Ⅲ), this also provides new opportunities for academic development and innovation in the future.

The two-dimensional feature of AI research field during 2016-2019

The two-dimensional feature distribution of the categories in Tongji University's artificial intelligence interdisciplinary field from 2016 to 2019 is shown in Figure 6 and Table 5. During this period, artificial intelligence exhibited new characteristics, such as deep learning, cross-domain integration, human-machine collaboration, collective intelligence openness, and autonomous control, driven by new theories and technologies in mobile internet, big data, supercomputing, sensor networks, and brain science, as well as the strong demands of economic and social development. In 2017, China's State Council released the New Generation Artificial Intelligence Development Plan, explicitly emphasizing the need to seize major strategic opportunities in AI development. Subsequently, in 2018, the Ministry of Education issued the Artificial Intelligence Innovation Action Plan for Higher Education Institutions to further advance AI development. Against this policy backdrop, 2016-2019 became the initial phase of policy responses for AI development, and Tongji University's interdisciplinary AI research entered a new phase. The number of categories further increased to 102, and the AI interdisciplinary field gradually permeated more categories, showcasing a robust trend of interdisciplinary integration and development.

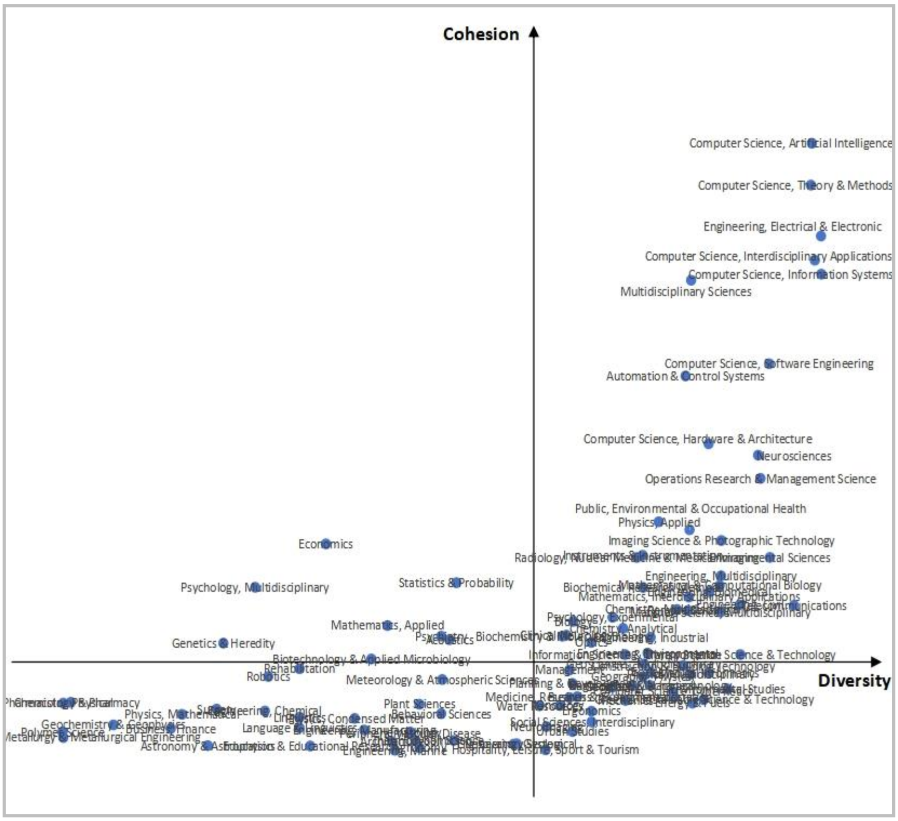

Figure 6. The two-dimensional feature analysis chart of the categories of publications (2016–2019). (To ensure clarity in the visualization given the high number of nodes, only the labels of key nodes are retained in the chart).

Table 5. Two-dimensional Features of the categories of publications (2016–2019).

Two-Dimensional Characteristics	*Field of Categories*	*Category Names*
Quadrant Ⅰ: High Cohesion - High Diversity (37 categories)	Medicine & Others	Neurosciences; Multidisciplinary Sciences
	Medicine	Radiology, Nuclear Medicine & Medical Imaging; Clinical Neurology
	Health Care	Public, Environmental & Occupational Health
	Pharmacology	Mathematical & Computational Biology
	Psychology	Psychology, Experimental
	Physics	Optics
	Biomedicine	Biochemistry & Molecular Biology
	Biology	Biology; Optics
	Computer Science and Engineering	Computer Science, Information Systems; Engineering, Electrical & Electronic; Computer Science, Interdisciplinary Applications; Computer Science, Artificial Intelligence; Computer Science, Theory & Methods; Telecommunications; Computer Science, Software Engineering; Operations Research & Management Science; Transportation Science & Technology; Engineering, Multidisciplinary; Computer Science, Hardware & Architecture; Mathematics, Interdisciplinary Applications; Automation & Control Systems; Engineering, Industrial; Instruments & Instrumentation
	Environmental Sciences	Environmental Sciences; Imaging Science & Photographic Technology; Remote Sensing

	Environmental Engineering	Engineering, Environmental
	Chemistry & Applied Physics	Materials Science, Multidisciplinary; Engineering, Biomedical; Physics, Applied
	Chemistry	Chemistry, Multidisciplinary; Biochemical Research Methods; Chemistry, Analytical
	Management	Information Science & Library Science
	Engineering	Engineering, Civil
Quadrant Ⅱ : High Cohesion - Low Diversity (8 categories)	Computer Science and Engineering	Statistics & Probability; Mathematics, Applied
	Engineering	Acoustics
	Psychology	Psychiatry; Psychology, Multidisciplinary
	Agriculture and Food	Biotechnology & Applied Microbiology
	Social Sciences	Economics
	Pharmacology	Genetics & Heredity
Quadrant Ⅲ : Low Cohesion - Low Diversity (29 categories)	Environmental Sciences	Engineering, Geological; Soil Science; Meteorology & Atmospheric Sciences; Geochemistry & Geophysics
	Medicine	Respiratory System; Behavioral Sciences; Peripheral Vascular Disease; Surgery
	Agriculture and Food	Agronomy; Plant Sciences
	Engineering	Thermodynamics; Engineering, Marine; Architecture
	Biomedicine	Hematology
	Computer Science and Engineering	Engineering, Manufacturing; Robotics
	Chemistry & Applied Physics	Physics, Condensed Matter; Chemistry, Physical; Metallurgy & Metallurgical Engineering
	Psychology	Education & Educational Research; Rehabilitation; Language & Linguistics; Linguistics
	Environmental Engineering	Engineering, Chemical

	Physics	Astronomy & Astrophysics; Physics, Mathematical
	Social Sciences	Business, Finance
	Pharmacology	Pharmacology & Pharmacy
	Chemistry	Polymer Science
Quadrant Ⅳ : Low Cohesion - High Diversity (26categories)	Social Sciences	Environmental Studies; Transportation; Geography; Urban Studies
	Health Care	Medical Informatics
	Environmental Engineering	Green & Sustainable Science & Technology; Energy & Fuels
	Physics	Physics, Multidisciplinary
	Engineering	Construction & Building Technology; Engineering, Mechanical; Mechanics; Planning & Development
	Computer Science and Engineering	Computer Science, Cybernetics
	Biology	Ecology
	Chemistry & Applied Physics	Nanoscience & Nanotechnology
	Environmental Sciences	Geosciences, Multidisciplinary; Geography, Physical; Water Resources
	Management	Ergonomics; Social Sciences, Interdisciplinary; Management; Business; Hospitality, Leisure, Sport & Tourism
	Medicine & Others	Medicine, Research & Experimental
	Biomedicine	Oncology
	Medicine	Neuroimaging
Categories with Betweenness Centrality of 0 (2 categories)	Computer Science and Engineering	Logic
	Social Sciences	Social Issues

From the perspective of the distribution in a two-dimensional quadrant, from 2016 to 2020, the number of categories located in the Quadrant Ⅰ increased significantly from 11 to 37 compared to the previous phase, includes 15 Fields of Categories. It is the first time, the Quadrant Ⅰ became the one with the most categories, breaking the longstanding dominance of the Quadrant Ⅲ in terms of category numbers.

During this phase, the influence of "Neuroscience" in the interdisciplinary field of artificial intelligence at Tongji University significantly increased. Neuroscience and artificial intelligence are closely related fields. In 1945, John von Neumann, in a paper outlining the architecture of modern digital computers, proposed that "the operation of the nervous system is", in fact, "digitally encoded on the surface," thus suggesting that the brain could inspire the development of computers. For example, in artificial intelligence, some principles used in Artificial Neural Networks (ANNs) are inspired by neuroscience. These include Convolutional Neural Networks (corresponding to the visual cortex), Regularization (corresponding to steady-state plasticity), Max Pooling (corresponding to lateral inhibition), Dropout (corresponding to synaptic failure), and Reinforcement Learning, which reflect the synergistic interaction between artificial intelligence and neuroscience. From 2016 to 2019, "Neuroscience" published a total of 7 papers at Tongji University, which cited 61 categories across 15 categories fields. The most cited paper during this period was an article published in 2018, it based on brain CT data from patients and healthy individuals, designed a novel 14-layer Convolutional Neural Network (CNN) for the early detection and identification of multiple science (MS), achieving an overall accuracy of 98.23% in the detection results (Wang et al., 2018).

The number of categories in the high cohesion-low diversity quadrant (Quadrant II) increased from 2 in the previous phase to 8, including "Statistics & Probability," "Applied Mathematics," "Acoustics," "Psychiatry," "Psychology, Multidisciplinary," "Biotechnology & Applied Microbiology," "Economics," and "Genetics & Heredity." These disciplines did not appear in the previous phase but directly entered the high cohesion category in this phase, indicating that once these disciplines emerged, they played a crucial role in connecting the academic network. However, their disciplinary diversity in terms of citation range remains relatively weak.

The number of categories in the low cohesion-high diversity quadrant (Quadrant IV) also increased significantly, from 1 in the previous phase to 26. These include "Environmental Studies," "Medical Informatics," "Green & Sustainable Science & Technology," "Physics, Multidisciplinary," etc., covering 13 categories fields. Although these categories are not prominent in terms of their intermediary position in the academic network, they are characterized by a large number and wide span of cited disciplines in their research, making them representative of interdisciplinary integration in the field of AI.

The number of disciplines in the Quadrant Ⅲ (low cohesion -low diversity) ranks second to the Quadrant Ⅰ, with a total of 29 disciplines, an increase of 8 from the previous phase. These disciplines are mostly from traditional fields or applied research areas with more limited scope. They include Biomedicine fields such as "Respiratory System," "Haematology," "Pharmacology & Pharmacy," Science application field such as "Geotechnical Engineering," "Thermodynamics," "Manufacturing Engineering," "Chemical Engineering," as well as foundational fields such as physics, chemistry, and mathematics, and social sciences such as "Education & Educational Research," "Business, Finance," and "Linguistics." Many of these are new categories that were not addressed in previous phases, with weaker interdisciplinary integration and cohesion, resulting in limited synergistic effects in the cross-disciplinary field of artificial intelligence.

In this phase, only "Logic" and "Social Issues" had 0 betweenness centrality, and both are considered "new categories" in this study. These categories were included precisely because they have gradually been influenced by artificial intelligence-related fields. It is foreseeable that, with the further expansion and application of AI technologies, these disciplines may strengthen their interdisciplinary collaborations with other fields in the future, showcasing greater potential for integration.

Overall, from 2016 to 2019, driven by artificial intelligence-related policies in China, Tongji University' s interdisciplinary field of artificial intelligence also saw new developments. More exploratory interdisciplinary research was conducted, such as the integration of artificial intelligence and foundational fields like neuroscience. During this phase, the overall diversity and cohesion of disciplines in the artificial intelligence field at Tongji University were further enhanced. The number of disciplines in the Quadrant Ⅰ surpassed that in the Quadrant Ⅲ for the first time, and the number of categories in the Quadrant Ⅳ was much greater than in the Quadrant Ⅱ. This suggests that high cohesion disciplines usually have higher disciplinary diversity in their citations, but disciplines with high diversity in cited fields may not necessarily have strong connectivity within the citation network. The core interdisciplinary development of artificial intelligence disciplines also made significant progress, not only broadening the scope of disciplines but also enhancing the overall connectivity of the academic network, thereby laying a solid foundation for deeper interdisciplinary collaboration and application in the future.

The two-dimensional feature of AI research field during 2020-2023

Between 2020 and 2023, the interdisciplinary field of artificial intelligence (AI) experienced rapid growth under the combined influence of policy support, technological advancements, and social demand. The number of categories increased sharply, rising from 102 categories in the previous phase to 172 categories, with a more diverse range of categories. This reflects the significant impact of AI technology in driving development across related fields.

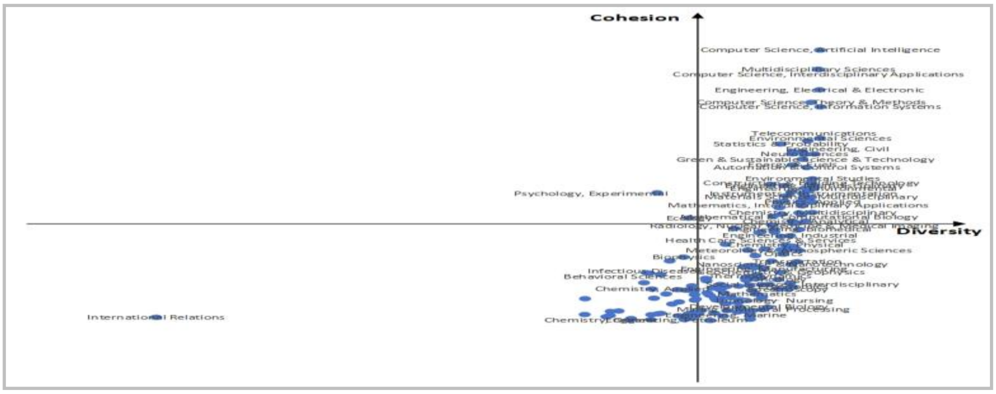

Figure 7. The two-dimensional feature analysis chart of the categories of publications (2020–2023).

First, the number of categories in the high cohesion-high diversity quadrant (Quadrant I) continued its growth, reaching 59 categories. These covered fields such as Computer Science and Engineering, Environmental Sciences, medicine, Engineering, and social sciences, encompassing nearly all of Tongji University's key development areas. During this phase, AI technologies demonstrated stronger disciplinary integration capabilities. Particularly with breakthroughs in deep learning, automation and control systems, and AI applications in the medical field, the ability of AI to drive interdisciplinary convergence significantly increased.

Second, compared to the previous phase, the overall distribution of disciplines in terms of the two-dimensional vector shows a clear shift to the right, indicating that the disciplines are accelerating their development towards higher diversity. At the same time, the number of disciplines in the Quadrant Ⅳwas significantly higher than in other quadrants, with 86 disciplines, whereas the Quadrant Ⅱ(high cohesion–low diversity) only had 2 disciplines. This further validates the asymmetry of the two-dimensional development of cohesion and diversity characteristics, namely that categories with high cohesion tend to have high diversity levels, while high diversity disciplines do not necessarily exhibit high cohesion.

Notably, it is worth noting that during this phase, no disciplines with betweenness centrality of 0. This indicates that all disciplines in the literature have, to varying degrees, connected with other disciplines within the interdisciplinary network of artificial intelligence, further emphasizing the overall improvement in the connectivity of Tongji University's AI cross-disciplinary field and the deepening of interdisciplinary collaboration.

In conclusion, from 2020 to 2023, driven by relevant policies, Tongji University’s interdisciplinary field of artificial intelligence entered a period of explosive development. During this phase, the number of disciplines increased significantly, and the overall disciplinary distribution shifted towards high diversity and high cohesion. The degree of interdisciplinary integration further deepened. From the two-dimensional distribution of disciplines in the literature, it is evident that artificial intelligence has had a broad and profound impact on multiple disciplinary fields. It not only holds a central position in computer science but has also deeply infiltrated fields such as computational biology, medicine, civil engineering, urban planning, transportation, environmental science, and agriculture in the natural sciences and engineering technologies. Additionally, AI has influenced social sciences, including psychology, education, sociology, and international relations, forming a pattern driven by artificial intelligence at its core, characterized by deep interdisciplinary integration. This underscores the key role of artificial intelligence in promoting disciplinary convergence and innovative development.

Conclusion

We used Tongji University's publications on artificial intelligence as a case to study AI's interdisciplinarity with the indicators of the diversity and cohesion of the references of these publications. We collected the AI publications of Tongji University and sliced them into five four-year periods, then calculated every period's

indicators of the categories' diversity and cohesion, and plotted these categories in a Cartesian coordinate system.
On the whole, from 2004 to 2023, the number of categories in the AI research field has significantly increased. The overall distribution of categories has shifted from low cohesion and low-diversity to high-cohesion and high-diversity. This phenomenon indicates that AI has had a broad and profound impact on multiple academic fields, and is deeply penetrated in the natural sciences and engineering disciplines such as computational biology, medicine, civil engineering, urban planning, transportation, environmental science, and agriculture. Additionally, AI has influenced social science fields including psychology, education, sociology, and international relations. This has led to a pattern where AI serves as the core driving force for the deep interdisciplinary convergence and integration of multiple disciplines, highlighting its critical role in promoting interdisciplinary convergence and innovative development.
From the perspective of key nodes, "Computer Science, Artificial Intelligence" initially resided in the Quadrant Ⅲ(low cohesion-low diversity), directly transitioned to the Quadrant Ⅰ(high cohesion-high diversity) during 2008-2011, where it has since maintained its high cohesion and high diversity characteristics. In addition, categories such as "Engineering, Electrical & Electronic," "Mathematics & Computational Biology," "Biotechnology & Applied Microbiology," "Operations Research & Management Science" and "Engineering, Civil" had already entered the high cohesion-high diversity category before 2016, demonstrating strong interdisciplinary integration capabilities. Examining the development history of these categories reveals the critical role AI technologies have played in driving their growth. "Neuroscience" and artificial intelligence are closely related fields., showed a significant increase in its academic influence after 2016, reflecting the synergistic interaction between artificial intelligence and neuroscience.
The research also found that the development of cohesion and diversity levels of disciplines exhibits asymmetry. Specifically, categories with high cohesion tend to have higher diversity, and are more likely to enter the high cohesion -high diversity quadrant. However, categories with higher diversity do not necessarily exhibit strong cohesion.
This study also counts the categories with a betweenness centrality of 0. Although these categories do not serve as "bridges" or "mediators" in connecting any two other categories, and contribute almost nothing to the overall network connectivity and information flow, the trend in their numbers indicates that they have gradually transitioned from isolation to integration in the field of AI. Furthermore, they have increasingly been influenced by artificial intelligence, suggesting significant potential for interdisciplinary applications and collaboration in the future.
Overall, this study demonstrates that artificial intelligence is not only a highly interdisciplinary field but also a comprehensive and leading catalytic force that can deeply merge with and permeate various disciplines. This power could be applied and validated within other disciplines. Therefore, in the development of disciplines at universities, it is essential to align with the trend of AI-enabled interdisciplinary integration and actively explore the fusion of AI with traditional disciplines. For

instance, civil engineering is evolving toward smart construction, mechanical engineering is advancing toward intelligent manufacturing, and transportation is progressing toward smart mobility. AI research should transcend disciplinary boundaries, opening new journeys within the intersection and fusion of disciplines, and moving toward broader frontiers.

Acknowledgments

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References

Bai, J., Wu, Y., Zhang, J., & Chen, F. (2015). Subset based deep learning for RGB-D object recognition. Neurocomputing, 165, 280-292.

Cai, S., Wang, Q., & Shen, Y. (2020). Artificial intelligence empowerment: Innovation and development of university discipline construction-An interview with Professor Chen Jie, Academician of the Chinese Academy of Engineering. E-Learning Research, 41(02), 5–9.

Che, D., Liu, Q., Rasheed, K., & Tao, X. (2011). Decision tree and ensemble learning algorithms with their applications in bioinformatics. Software tools and algorithms for biological systems, 191-199.

Chubin, D. E., Porter, A. L., & Rossini, F. A. (1984). "'Citation classics'" analysis: An approach to characterizing interdisciplinary research. Journal of the American Society for Information Science, 35(6), 360–368.

Diego, C., Puay, T., & Ismael, R. (2014). Interdisciplinarity and research on local issues: Evidence from a developing country. Research Evaluation, 23(3), 195–209.

Dogan, M., & Pahre, R. (1990). Creative marginality: Innovation at the intersections of social sciences. Westview Press.

Ji, Y. F., & Zhang, Q. W. (2012, July). A novel image-based approach for structural displacement measurement. In Proc. 6th Int. Conf. Bridge Maintenance, Safety Manage (pp. 407-414).

Leydesdorff, L. (2007). Betweenness centrality as an indicator of the interdisciplinarity of scientific journals. Journal of the American Society for Information Science and Technology, 58(9), 1303–1319.

Liang, D., Bo, W. H., & Jiang, L. B. (2017). Computational biology: An emerging frontier discipline in biology. Chinese Forestry Education, 35(S1), 139–142.

Liu, Y. (2018). Constructing global backbone of science based on inter-categories co-membership of journals. Journal of the China Society for Scientific and Technical Information. 37(06): 580-589.

Liu, Y., Rafols, I., & Rousseau, R. (2012). A framework for knowledge integration and diffusion. Journal of Documentation, 68(1), 31-44.

Liu, Y., Rousseau, R. (2010). Knowledge diffusion through publications and citations: a case study using ESI-Fields as unit of diffusion. Journal of the American Society for Information Science and Technology. 61(2): 340–351.

Li, W., Feng, J., & Jiang, T. (2011). IsoLasso: a LASSO regression approach to RNA-Seq based transcriptome assembly. Journal of computational biology: a journal of computational molecular cell biology, 18(11), 1693–1707.

Mao, K. Y., Jiang, Y., Yuan, Y. C., et al.. (2024). Development trends of computational biology in 2023. Life Sciences, 36(1), 11–20.

MIT Technology Review. (2013, April 23). The 10 breakthrough technologies of 2013 [EB/OL]. Retrieved from https://www.technologyreview.com/s/513981/the-10-breakthrough-technologies-of-2013/
Pan, L. B., Ge, L. Q., & Wang, S. (2022). The development of information systems: From network-driven to knowledge-driven. Journal of China Academy of Electronics and Information Technology, 17(9), 929–934.
Porter, A. (2006). Interdisciplinary research: Meaning, metrics and nurture. Research Evaluation, 15, 187–195.
Rafols, I., & Meyer, M. (2010). Diversity and network coherence as indicators of interdisciplinarity: Case studies in bionanoscience. Scientometrics, 82, 263–287.
Rafols, I., Leydesdorff, L., O'"Hare, A., et al. (2012). How journal rankings can suppress interdisciplinary research: A comparison between innovation studies and business & management. Research Policy, 41(7), 1262–1282.
Rousseau, R., Zhang, L., & Hu, X. (2019). Knowledge integration: Its meaning and measurement. In W. Glänzel, H. F. Moed, U. Schmoch, & M. Thelwall (Eds.), Springer Handbook of Science and Technology Indicators (pp. 69-94). Springer Verlag.
Russakovsky, O., Deng, J., Su, H., et al. (2015). ImageNet large-scale visual recognition challenge. International Journal of Computer Vision, 115(3), 211–252.
Stirling, A. (2007). A general framework for analysing diversity in science, technology and society. Journal of the Royal Society Interface, 4, 707–719.
Von Neumann, J. (1993). First draft of a report on the EDVAC. IEEE Annals of the History of Computing, 15(4), 27-75.
Wang, S. H., Tang, C., Sun, J., Yang, J., Huang, C., Phillips, P., & Zhang, Y. D. (2018). Multiple sclerosis identification by 14-layer convolutional neural network with batch normalization, dropout, and stochastic pooling. Frontiers in neuroscience, 12, 818.
Wang, W., Zeng, G., & Yuan, L. (2006, September). A semantic reputation mechanism in P2P semantic web. In Asian Semantic Web Conference (pp. 682-688). Berlin, Heidelberg: Springer Berlin Heidelberg.
Wu, Z. H. (2019). Promoting talent training and technological innovation in artificial intelligence through convergence. China University Teaching, No. 342(2), 4–8.
Xu, J., Ge, H., Zhou, X., Yan, J., Chi, Q., & Zhang, Z. (2005). Prediction of vascular tissue engineering results with artificial neural networks. Journal of Biomedical Informatics, 38(6), 417-421.
Xu, J., Zhou, X., Yang, D., Ge, H., Wang, Q., Tu, K., & Guo, T. (2005). Applying informatics in tissue engineering. Methods of Information in Medicine, 44(01), 38-43.
Zhang, J. Y., Wang, H. L., & Guo, Y. (2018). A review of deep learning research. Computer Applications Research, 35(7), 1921–1928+1936.
Zhang, L., Sun, B. B., & Huang, Y. (2020). Interdisciplinary scientific research: Connotation, measurement, and impact. Science Research Management, 41(7), 279–288.