Technological Convergence: Connotation, Status Quo, and Measurement—With a Discussion on Its Relationship with Interdisciplinarity (Postprint)

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Abstract

[Purpose/Significance] Interdisciplinary cross-fertilization and technology convergence are important driving forces for the development of modern science and technology. By clarifying the connotation of technology convergence and exploring its research progress and measurement indicators, this study aims to provide references for interpreting the knowledge structure of technology convergence and conducting related research. [Method/Process] Employing literature review and bibliometric methods, and based on distinguishing the connotations of technology convergence and technology fusion, this paper conducts visual analysis of technology convergence-related content from the perspectives of discipline and topic distribution, and systematically reviews and interprets measurement indicators from the diversity and cohesion perspectives. Finally, it further analyzes the similarities and differences between technology convergence and interdisciplinary research. [Results/Conclusions] Technology convergence and technology fusion are largely consistent in meaning, with subtle differences reflected in their fusion patterns. The measurement of technology convergence is generally based on two perspectives: diversity and cohesion. The former measures from three dimensions of richness, evenness, and disparity, while the latter mainly measures the roles and relationships of nodes in technology networks. From the perspective of first-order and second-order theme research, scientific research activities of technology convergence and interdisciplinary research exhibit similarities. Interdisciplinary indicators from the same perspectives and dimensions also provide references for measuring the degree and diversity of technology convergence and assessing fusion relationships between different technologies.

Full Text

Technology Convergence: Connotation, Status, and Measurement—Also Discussing Its Relationship with Interdisciplinary Science

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Abstract: [Purpose/Significance] The intersection and infiltration between disciplines and the convergence and integration of technologies are essential forces promoting the development of modern science and technology. By clarifying the connotation of technology convergence, this paper explores its research progress and measurement indicators to provide a reference for understanding the knowledge structure of technology convergence and related research. [Method/Process] Based on distinguishing the connotation of technology convergence and technology fusion, we employed literature survey and bibliometric methods to conduct visual analysis of technology convergence from disciplinary and thematic distributions, systematically reviewed and interpreted measurement indicators from the perspectives of diversity and cohesion, and finally further distinguished the similarities and differences between technology convergence and interdisciplinary science. [Result/Conclusion] Technology convergence and technology fusion share the same meaning in most cases, with subtle differences reflected in their convergence patterns. Measurement of technology convergence is generally based on two perspectives: diversity and cohesion. The former measures from three dimensions—variety, balance, and disparity—while the latter mainly measures the role and relationship of nodes in technology networks. From the perspective of first-order and second-order theme research, the research activities of technology convergence and interdisciplinary science share similarities, and interdisciplinary indicators from the same perspective and dimension also provide references for measuring the degree of technology convergence, diversity, and integration relationships between different technologies.

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With the emergence of new technologies and the gradual blurring of technological boundaries, many major scientific and technological discoveries and creations can no longer rely solely on a single technology. Cross-fertilization and integration between technologies have gradually become an important force driving the development of modern science and technology. Based on the coordinated development of scientific discoveries and technological innovations across various fields, the emerging trend of technology convergence has further stimulated scientific and technological discoveries and innovations. As an important force driving future technological innovation, technology convergence has become a crucial strategy in actual R&D fields [1]. Technology convergence not only creates opportunities for developing new technologies and knowledge but also serves as a key driver for enterprises to adapt to new markets [2-3]. It also promotes technology and industrial clusters by integrating complementary knowledge bases, thereby guiding industrial convergence [4].

Along with high attention from the scientific community and society, scholars have conducted a series of exploratory studies on technology convergence from different perspectives. I. Park et al. used association rules and link prediction to forecast technological convergence and employed topic modeling to predict emerging fields where technology convergence might be discovered [5]; Luan Chunjuan et al. designed a series of convergence indices based on the 20 technology sections of the Derwent Classification system to measure the degree of convergence between technology sections [6]; Li Yaya et al. studied technology convergence in the biochip industry and found strong integration tightness among biochip technology elements [7]. Additionally, some scholars have focused on issues such as industrial convergence, ethics, social risks, and risk governance. For example, Y. Cho et al. used network centrality indices to measure the technological intensity of the electronic printing industry to explore the evolution of corporate strategic positions under convergence [8]; F. Erik et al. discussed the ethical and social issues of nano-convergence technology [9]; C. Kuei and L. Mihail et al. focused on the risks and governance of convergence technology [10-11].

2 Connotation of Technology Convergence and Related Concepts

In 1963, N. Rosenberg first attempted to define the concept of technology convergence in his study of mechanical instrument technology convergence as "the process by which two hitherto distinct industrial sectors come to share a common knowledge and technological base" [14]. With the deepening of technology convergence research, scholars gradually reached a consensus on its definition. The concept proposed by C. Curran et al. has been widely recognized, stating that technology convergence refers to the process of transforming discrete or heterogeneous items into a unified whole, or integrating different technologies, equipment, and industries into a unified entity. They further divided convergence into four stages: scientific knowledge convergence, technology convergence, market convergence, and industrial convergence [8,15-16]. These four stages occur sequentially, with scientific knowledge convergence being the first step of technology convergence, ultimately leading to industrial convergence and achieving industrial innovation [17]. In other words, scientific knowledge convergence provides the theoretical foundation for technology convergence, while technology-level convergence concentrated in certain markets and industries ultimately leads to technological innovation across different markets and industries.

By integrating different scholars' understanding of technology convergence and citing descriptions by E. Kim and C. Curran et al., this paper interprets the connotation of technology convergence. Technology convergence involves the combination or recombination of existing technologies from different fields [15,18], emerging at the intersection of existing technologies. By integrating and reorganizing knowledge from existing technological fields, it obtains new functions that previous technologies did not possess, achieving technological transformation or developing into new technological branches—that is, new directions different from existing technological fields. It is important to note that this technological transformation does not generate entirely new technologies but rather achieves innovation based on the integration of existing technologies [19-21].

In technology convergence research, terms such as technology fusion, technology merging, technology cross-fertilization, technology hybridization, and multidisciplinary technology are used to describe related convergence phenomena. Among them, technology convergence and technology fusion are the most frequently used terms, with many scholars believing that they are interchangeable in most cases, as both can represent the convergence or fusion of existing technologies to derive new technological branches at a single point [19,22]. However, deeper analysis reveals that technology fusion essentially involves the substitution and complementation of existing technologies, representing innovative breakthroughs based on existing technologies. In contrast, technology convergence is defined as the innovative integration of two or more core technologies, emphasizing the development into new directions different from existing technologies [2,23-25].

To more clearly describe how technologies converge and fuse, as well as the subtle differences between technology convergence and technology fusion in the integration process, this paper takes two unrelated fields A and B as examples to present the processes of technology convergence and technology fusion, thereby reflecting the differences between their integration patterns, as shown in Figure 1 [Figure 1: see original paper].

Figure 1 Process of Technology Convergence and Technology Fusion

For two completely different research fields A and B, the process of technology convergence involves continuous exploration through the innovative integration of technologies from both fields, directing them toward new directions different from existing ones. When fields A and B undergo technology fusion, it means substituting a technology from one field with a technology from another field, with the newly generated technology partially replacing the function of the original technology. For example, nanobiotechnology is a new research field formed based on the convergence of nanotechnology and biology, reflecting the characteristic of technology convergence in transforming toward new research directions. In contrast, biochip technology is an innovative product of the fusion of biotechnology and semiconductor industrial technology.

3 Disciplinary and Thematic Distribution of Technology Convergence Research

Disciplinary and thematic distribution involves extracting disciplinary classifications and representative feature words from literature to explore the characteristics of disciplinary and thematic distribution in technology convergence research, using relevant algorithms for topic clustering and identification. Using the Web of Science Core Collection's SCIE/SSCI database as the data source, with the search query "TS=((technolog* NEAR/0 converg*) OR ((technolog* fusion*) AND converg*))" and document types limited to "Article" and "Review" for the period 1989-2019, we retrieved 579 relevant documents on technology convergence/fusion as analytical data.

For disciplinary distribution analysis, based on the Web of Science (WoS) disciplinary classification system, we used VOSviewer visualization software to construct a science overlay map of literature on technology convergence-related topics [26] (see Figure 2). In Figure 2 [Figure 2: see original paper], each node represents a WoS disciplinary classification, the distance between nodes indicates the degree of association between disciplinary classifications, and node size reflects the number of studies in that discipline. Nodes of the same category belong to a larger disciplinary classification, whose name is presented as a box label. The results show that technology convergence research involves all 18 major disciplines but is mainly concentrated in "Computer Science & Engineering," "Management," and "Social Science." At the sub-disciplinary level, "Multidisciplinary Sciences" accounts for a relatively large proportion, directly indicating that research across different disciplines plays an important role in technology convergence. Other disciplinary fields involved in technology convergence research include "Economics," "Engineering Electrical & Electronic," "Telecommunications," "Nanoscience & Nanotechnology," etc.

By extracting keywords from the literature, we constructed a keyword co-occurrence network for technology convergence (excluding terms like technology convergence/fusion) and used the Leiden clustering algorithm to cluster the topic network [27], with results shown in Figure 3. In Figure 3 [Figure 3: see original paper], each node represents a topic word, node size indicates the frequency of the topic word, and connections between nodes represent co-occurrence frequency. The analysis reveals that technology convergence research focuses on four main aspects: NBIC convergence technology (Cluster 1), with topic words including "Nanotechnology," "Biotechnology," "Cognition," "Information Technology," "Science Policy," etc. These topic words account for the largest proportion in the network, revealing the main research themes in current technology convergence, with the term "Interdisciplinary" reflecting the cross-disciplinary nature of this research theme. Technology convergence analysis methods (Cluster 2), with topic words including "Patents

Analysis," "Patent Citation Analysis," "Patent Citation," "Network Analysis," "Link Prediction," "Social Network Analysis," etc. These topic words reveal research methods primarily based on patent informetrics and network analysis.

Cross-cutting themes (Cluster 3), with main topic words including "Risk," "Governance," "Telecommunications," "Social Media," "Regulation," etc. These topic words reveal fields intersecting with technology convergence.

Other themes (Cluster 4): "Technology Adoption," "IPTV," "Security," "Technology Acceptance Model," "Robotics," etc. These themes include some technical methods, models, and other related fields in technology convergence.

Figure 2 Disciplinary Distribution of Technology Convergence Research (1989-2018)

Figure 3 Thematic Distribution of Technology Convergence Research (1989-2018)

4 Measurement of Technology Convergence

Quantitative measurement of technology convergence is crucial for detecting patterns of technology convergence and technological innovation development. Measuring the degree of convergence between different technologies based on measurement indicators can reveal development trends of technology convergence and provide guidance for formulating clear strategic deployments to promote technological innovation and development. In many studies, some measurement indicators for interdisciplinary science have also been applied to measure convergence between different technologies. Moreover, with the development of science and technology, the cross-fertilization and integration between disciplines and technologies have become increasingly complex, requiring consideration from multiple dimensions. Therefore, to more clearly interpret relevant measurement indicators of technology convergence, this paper systematically reviews and explains existing technology convergence indicators from the perspectives of diversity and cohesion, aiming to provide useful references for accurately understanding the concepts and application scopes of technology convergence measurement indicators. It should be noted that since most scholars do not distinguish between technology convergence and technology fusion in their research, and the two terms are often used interchangeably, this paper includes relevant fusion indicators when reviewing technology convergence measurement indicators.

4.1 Measurement of Technology Convergence: Diversity Perspective

The concept of diversity originated from ecological studies of biodiversity [28]. With the increasing complexity of science and technology, diversity has become an important research perspective for interdisciplinary science and technology convergence. Technology convergence diversity mainly refers to the fact that the methods, technical elements, and ideas of research objects come from different fields, and their combination gives research objects diverse characteristics.

When studying diversity in the economic field, A. Stirling proposed a three-dimensional measurement framework for diversity attributes, namely variety (the number of disciplines), balance (the evenness of disciplinary distribution), and disparity (the degree of difference in disciplinary nature) [29]. When introduced to the measurement of technology convergence, it can describe the diversity of technologies from the technical level. Therefore, this paper reviews relevant indicators of technology convergence from three dimensions based on the diversity perspective.

4.1.1 Single-Dimensional Indicators Single-dimensional integrated indicators for technology convergence are mostly used to measure the variety of technologies, including a series of convergence indices designed by Luan Chunjuan et al. based on the 20 technology sections of the Derwent Classification (DC) system to measure the degree of convergence between technology sections [6], and the convergence intensity listed in the research by Li Shuying and Fang Shu [30]. These two types of indicators mainly measure the degree of convergence between technologies based on the technology categories to which they belong, using the co-classification analysis method, as shown in Table 1 .

Table 1 Single-Dimensional Measurement Indicators for Technology Convergence

Indicator Name	Formula	Meaning	Application
Technology Convergence Index (TCI)	$TCI_{AB} = N_{AB} / N_A$	TCI_{AB} is the convergence index of technology A converging with technology B. N_A represents the number of patents in technology field A, and N_{AB} is the number of patents belonging to both technology field A and technology field B.	Used to measure the degree to which a certain technology converges with another specific technology.

Indicator Name	Formula	Meaning	Application
Average Convergence Index (AATCI)	AATCI_A = (TCI_{AB} + … + TCI_{AX}) / N	The first A represents "average," the second A represents technology section A. AATCI_A represents the average convergence index of section A, used to measure the convergence degree between section A and each technology section from B to X. N represents the number of sections other than section A.	Used to measure the convergence degree between section A and each technology section from B to X.

Indicator Name	Formula	Meaning	Application
Average Being-Converged Index (BAATCI)	BAATCI_A = (TCI_{BA} + … + TCI_{XA}) / N	B represents "being," TCI_{BA} represents the index of technology A being converged by section B, and so on. BAATCI_A represents the average being-converged index of section A, used to measure the degree to which section A is converged by each technology section from B to X.	Used to measure the degree to which section A is converged by each technology section from B to X.

Indicator Name	Formula	Meaning	Application
Convergence Intensity (CI)	CI_{AB} = N_{AB} / Min(N_A, N_B)	N_{AB} is the number of patents in the new field obtained through the convergence of technology A and technology B. N_A is the number of patents belonging to technology field A among the patents included in N_{AB}, and N_B is the number of patents belonging to technology field B among the patents included in N_{AB}.	Used to measure the convergence intensity of technology fields involved in the research subject.

Note: Compiled from references [6, 30]

4.1.2 Two-Dimensional Indicators Two-dimensional indicators for measuring technology convergence diversity mostly derive from two-dimensional measurement indicators for interdisciplinary science, as shown in Table 2 . Among them, the Shannon entropy index (SH) was originally used to measure information uncertainty [31] and was later introduced into technology convergence measurement. This indicator measures technology convergence from the dimensions of technological variety and balance. For example, M. Kim et al. used Shannon entropy to measure technological convergence and interdisciplinarity between different technology or industrial fields [21]; Liu Na et al. used Shannon entropy to identify core technology elements and potential important technology elements in the convergence process [32]. The absorption and diffusion indices originate from Simpson's diversity index (SI), which was proposed in 1949 and was initially mainly used to measure diversity in ecosystems [33]. It was later introduced into technology convergence research to measure knowledge flow in technology convergence. This indicator can comprehensively measure technology convergence from the dimensions of technological variety and balance, such as N. Ko et al. analyzing technology convergence in interdisciplinary fields based on knowledge flow between patented technologies [34].

Table 2 Two-Dimensional Measurement Indicators for Technology Convergence

Indicator Name	Formula	Meaning	Application
Shannon Entropy (Entropy)	SH_A = - *k* *P*{Ak} ln P_{Ak}	P_{Ak} is the proportion of patents belonging to technology field k in field A.	Used to measure the breadth of technology fusion between different technology or industrial fields.
Generality Index (GI)	GI_A = 1 - _i (P_i)^2	F represents the set of all technologies cited by technology A. P_i is the proportion of cited patents belonging to technology i among all cited patents.	Used to measure the diffusion degree of technology.

Indicator Name	Formula	Meaning	Application
Originality Index (OI)	OI_A = 1 - _i (P_i)^2	F represents the set of technology fields that cite technology A. P_i is the proportion of citing patents from technology field i among all patents citing technology A.	Used to measure the absorption degree of technology.

Note: Compiled from references [21, 32-33, 35]

4.1.3 Three-Dimensional Indicators With the gradual deepening of technology convergence research, indicators integrating the three dimensions of variety, balance, and disparity have also been applied to the measurement of technology convergence. These include the diversity index (DI) proposed by W. Shim et al., which uses the diversity index size of technology A in time period t to measure the diversity degree of technology convergence [36]; and the specialization index proposed by A. Porter et al. in interdisciplinary research based on discipline and technology classification [37-38], which S. Kwon et al. used to measure the specialization degree of graphene and nanomedicine [39]. When the specialization index is higher, it indicates that the converged technology fields are relatively fewer and the correlation between technology fields is higher; when the specialization degree is lower, it indicates that the converged technology fields are relatively more and the correlation between technology fields is lower. The main three-dimensional measurement indicators for technology convergence and their meanings are shown in Table 3 .

Table 3 Three-Dimensional Measurement Indicators for Technology Convergence

Indicator Name	Formula	Meaning
Diversity Index (DI)	Diversity(D)*{At}* = i=1^n *j=1^n* *P*{iAt} ·P*{jAt}* · *d*{ij}	A is the citing technology (technology that cites technology i or j), and t is the time period. On the right side of the equation, n is the number of technologies cited by A, P_{iAt} is the proportion of technology A's citations to technology i in time period t among all citations of technology A, M_{iAt} is the number of times A cites technology i in time period t, and d_{ij} is the distance between technologies i and j.

Indicator Name	Formula	Meaning
Specialization Index (SI)	SI = [(f_i × f_j × cos(IPC_i - IPC_j))] / (f_i × f_j)	f_i and f_j represent the frequency of technology category i or j in the research subject, respectively. cos(IPC_i - IPC_j) represents the correlation degree between patent classifications IPC_i and IPC_j, which can be calculated based on citation and cited data between different technology field classifications.

Note: Compiled from references [29, 36, 39]

4.2 Measurement of Technology Convergence: Cohesion Perspective

In technology convergence measurement research, technology diversity describes the richness, distribution evenness, and disparity of converged technologies, while cohesion represents the relationship strength of these technologies in the technology network. Measuring technology convergence from the cohesion perspective helps understand the different roles of each technology in the overall network and identify dominant technologies in the technology convergence process. K. Kim measured corporate innovation capabilities and their impact on innovation using a series of centrality indicators based on patent networks [40]; C. Lee et al. used centrality indicators to obtain information about technology fusion, international cooperation, and knowledge flow from patent documents [41]. M. Kim et al. borrowed concepts from gravity to propose the binding force indicator (BF) to reflect the interaction between technology nodes [21], used to understand how closely each node is connected to other nodes, i.e., how tight the relationship is between each technology and other technologies. Based on a comprehensive review of relevant studies, this paper systematically summarizes the cohesion measurement indicators for technology convergence, as shown in Table 4 .

Table 4 Cohesion Measurement Indicators for Technology Convergence

Indicator Name	Formula	Meaning
Betweenness Centrality (BC)	BC = *{m≠v≠n V}* σ{mn}(v) / σ_{mn}	*σ{mn} is the number of shortest paths from m to n, and* σ{mn}(v) is the number of shortest paths from m to n that pass through v.
Degree Centrality (DC)	DC = deg(j_x)	deg(j_x) is the number of connections between technology node j_x and other technology nodes.
Closeness Centrality (CC)	CC(t) = 1 / _{t M(v)} d(m_x, n_x)	d(m_x, n_x) represents the distance between technology node m_x and other nodes.
Eigenvector Centrality (EC)	EC = λ _{i=1} M_A M_i C^2	Where M(v) is a group of neighboring nodes of v, and λ is a constant.

Indicator Name	Formula	Meaning
Binding Force (BF)	BF = C_A / n	C_A is the closeness centrality of technology A, M is the number of patents contained in each node (each node represents a technology), representing the size of the node. In technology network analysis, binding force can be used to explain the binding force of technology A among n technologies.

Note: Compiled from references [21, 40-41]

5 Relationship Between Technology Convergence and Interdisciplinary Science

Interdisciplinary science, while integrating existing disciplines, proposes new theories, methods, concepts, and research fields at the intersection of different disciplines. It is a comprehensive interdisciplinary product gradually formed and developed through the interaction and infiltration of different disciplines and represents the future direction of scientific development. Both technology convergence and interdisciplinary science are important products of today's scientific and technological development, with complex connections and many differences. Correctly understanding and distinguishing their relationship is an important prerequisite for in-depth research and promoting their development.

5.1 First-Order and Second-Order Themes of Technology Convergence and Interdisciplinary Science

From the perspective of science of science, interpreting the first-order and second-order themes of interdisciplinary science and technology convergence can cleverly connect the research activities of the two, which is of great significance for deeply understanding their research contexts. First-order theme research in interdisciplinary science is more positioned in the process of scientific research activities, i.e., when solving problems beyond the scope of a single discipline, experts and scholars from different disciplines integrate content from two or more disciplines or technologies at different levels (such as theories/concepts, information/data, tools/methods) to conduct practical activities [42], as shown in Figure 4 [Figure 4: see original paper]. For example, bioinformatics, a frontier interdisciplinary field between life science and computer science, introduces emerging computer technology and mathematical and statistical methods into biology to manage, integrate, analyze, and simulate massive biological data, solving important biological problems, elucidating new biological laws, and obtaining innovative discoveries unavailable through traditional biological methods. This is a typical example of first-order theme research in interdisciplinary science. Similarly, when solving problems beyond the scope of a single technology, researchers organically integrate different levels of technical knowledge (theories/concepts, information/data, tools/methods) from different fields. This practical activity is first-order theme research in technology convergence. For instance, the recently emerging nanobiotechnology integrates knowledge from nanotechnology and biology to apply nanotools to related medical/biological problems and improve these applications. The nanosheets used as new tools for medical and biological research are exemplary cases of first-order theme research in technology convergence.

Second-order theme research takes the scientific research results of first-order theme research as its object, attempting to understand and explore from a higher level the formation mechanisms and operational logic of interdisciplinary science and technology convergence research activities, as shown in Figure 4 [Figure 4: see original paper]. Liu Zeyuan, when discussing the first-order and second-order themes of interdisciplinary science, pointed out that the former is the foundation and prerequisite of the latter, or that first-order science is the research object of second-order science [42]. This theory also applies when analyzing the first-order and second-order themes of technology convergence. Taking the research results generated by technology convergence as the object to explore the fusion phenomena of different technologies/fields, attempting to analyze the trends of technology convergence, reveal its characteristics and patterns, and predict the trajectories and directions of technological development constitute the main content of second-order theme research in technology convergence.

When conducting corresponding scientific research activities for specific research problems, the consistent integration patterns from the research process to the similar forms of research output reveal the commonalities between first-order and second-order theme research in technology convergence and interdisciplinary science. The extension of second-order theme research is the academic, economic, and social impact brought by the research output of technology convergence and interdisciplinary science. The former's impact is mostly caused by technological-level innovation, while the latter can be traced back to multi-level cross-fertilization across different disciplines in technology, culture, economy, etc. As these scientific research results generate academic, economic, and social impacts, these impacts will in turn promote the proposal of new research problems, thereby pushing forward layer after layer of scientific fog in human social development (for example, major scientific issues such as how to prevent and block large-scale outbreaks of emerging infectious diseases, which new technologies can be used for early diagnosis and prognosis monitoring of cancer, and what impacts social changes have on people's physical and mental health).

5.2 Distinguishing Technology Convergence from Interdisciplinary Science

Since current basic scientific research on technology convergence and interdisciplinary science mostly focuses on second-order theme research, this section starts from the basic connotations of technology convergence and interdisciplinary science, exploring their connections and differences in second-order theme research from three aspects: formation path, research object, and measurement indicators.

5.2.1 Formation Path Comparing technology convergence and interdisciplinary science from the perspective of formation path is an important way to analyze the differences in their formation mechanisms in second-order theme research. The formation path of technology convergence is the evolutionary trajectory in the process of technological development. From the perspective of analyzing the development process of technology convergence, C. Bores et al. believe that technology convergence is the process of combining two or more technology elements with different functions to form a technology with entirely new functions [23,32]. Some scholars point out that technology convergence is not a simple, one-way process but has a certain periodicity, further dividing technology convergence into four stages: creation, integration/fusion, innovation, and output. In the creation stage, knowledge from different previous fields achieves significant synergy while retaining some independence. In the integration stage, multidisciplinary knowledge and technology fuse into a new system. In the innovation stage, multiple collaborative technologies integrate to innovate knowledge, technology, and products. The output stage includes new applications and new inputs, while providing feedback to the innovation stage, thus forming a continuous cycle of convergence and divergence [20,43].

The development of disciplines shows a pattern of aggregation and dispersion. New disciplines generated in the process of interdisciplinary science will continue to form new synergistic effects in their development, aggregating on the basis of differentiation and continuing to differentiate under the premise of aggregation, thus forming a continuous cycle of aggregation and differentiation. Wang Haitao explored the different stages of interdisciplinary development from the perspective of overall formation path, believing that the development process of interdisciplinary science can be divided into three stages: convergence period, cross period, and fusion period [44]. The convergence period is the embryonic stage and the lowest level of interdisciplinary development. The cross period is the intermediate stage and the condition for interdisciplinary science to gradually mature. The fusion period is the final stage of interdisciplinary development, with the perfection and maturation of theoretical and technical systems being important markers of the fusion period and the highest level of interdisciplinary development.

Overall, both technology convergence and interdisciplinary science research have experienced several stages in their gradual formation process. Technology convergence goes through four stages—creation, integration/fusion, innovation, and output [20,43]—to ultimately generate new technologies, and the new technologies generated can also continue to undergo the above stages to integrate with other technologies and develop new technologies in different directions. Interdisciplinary science research goes through three stages—convergence period, cross period, and fusion period [44]—to finally produce new interdisciplinary fields. Therefore, whether technology convergence or interdisciplinary science, both are processes that gradually mature after experiencing different stages based on two or more different technologies and disciplines.

5.2.2 Research Object Clarifying the research object is a necessary prerequisite for any scientific research activity. Different research objects lead to differences in research methods, content, and results to varying degrees. From the perspective of second-order theme research, interdisciplinary science research focuses on cross-fertilization phenomena in disciplinary fields, conducting characteristic studies on research subjects at different levels (e.g., academic literature, journals, disciplines, institutions, etc.), measuring the interdisciplinarity of subjects, and finally revealing the internal patterns and issues of disciplinary cross-fertilization phenomena through research subjects. In contrast, technology convergence integrates and reorganizes knowledge from existing technology fields to analyze convergence phenomena of technologies/fields at different levels (e.g., patents, industries, institutions, etc.) and measure the degree of technology convergence. Therefore, there are significant differences in research objects between the two. The main research objects of interdisciplinary science are academic literature, journals, disciplines, etc., with measurement and analysis of the interdisciplinarity of these different-level research objects. In technology convergence research, patents, as the innovation carrier reflecting the technological development status of the field, constitute the main research object.

5.2.3 Measurement Indicators Distinguishing the measurement indicators of technology convergence and interdisciplinary science can reveal knowledge integration between the two in second-order theme research from a quantitative perspective. The results of reviewing existing indicators are shown in Table 5 . From the same perspective and dimension, some technology convergence-related measurement indicators are the same as interdisciplinary science-related measurement indicators. For example, the Shannon entropy indicator in interdisciplinary science can measure the degree of interdisciplinary science from the dimensions of disciplinary variety and balance, and it is also applicable in technology convergence measurement for measuring the variety and balance of technology elements.

Table 5 Related Measurement Indicators for Technology Convergence and Interdisciplinary Science

Perspective	Dimension	Interdisciplinary Science Indicators (#)	Technology Convergence Indicators (*)	Shared Indicators (&)
Diversity	Single-dimensional	Gini coefficient (#); Citations outside category (#); etc.	TCI (*), *AATCI* (*), BAATCI (*); *CI* (*); etc.	Cosine similarity (&)
	Two-dimensional	Herfindahl index (#); Brillouin index (#); etc.	Shannon index (&); Simpson index (&)	
	Three-dimensional	Integration index (#); True Diversity index (#); etc.	Specialization index (&); Rao-Stirling index (&)	
Cohesion		Network Density (#), External-Internal (#), Coherence index (#); etc.	DC (&), CC (&), EC (&), BC (&) indicators	

Note: Interdisciplinary science indicators (#), Technology convergence indicators (*), Shared indicators (&)

Although some indicators for interdisciplinary science and technology convergence research differ, this does not mean that these indicators cannot be applied to both. For example, the Gini coefficient, which explores the evenness of distribution across disciplinary categories, is an internationally common indicator used to measure income gaps between countries or regions. In existing interdisciplinary science measurement indicator systems, it is used to measure the unevenness of interdisciplinary science [45]. This indicator is also applicable for quantifying differences between technologies and the evenness of technology category distribution in technology convergence when integrating multiple technologies to achieve innovation beyond single technology. The Herfindahl index and Simpson index are similar, originally mainly used in economics to measure industrial concentration. These indicators can also comprehensively measure the concentration degree of technology convergence from the dimensions of variety and balance. In three-dimensional diversity measurement, the True Diversity indicator is an improvement of the Rao-Stirling diversity indicator, making indicator values quantitatively comparable [46], and to some extent, this indicator can also be used to measure the diversity degree of technology convergence. Additionally, the integration index (Integration) used in interdisciplinary science to measure the integration degree of interdisciplinary science research results and authors' research content [38] can measure not only disciplinary distribution but also consider disciplinary similarity, making it applicable for measuring the integration degree of technology classifications. In network analysis, the network density indicator (Network Density, ND) used to measure the closeness of connections between nodes and the external-internal index (External-internal index, EI) used to analyze the cohesion degree or overall network faction degree of subgroups within the overall network [47-48] can all be constructed based on technology categories. Conversely, technology convergence indicators can also be applied to interdisciplinary science. For example, the convergence index designed by Luan Chunjuan for Derwent technology sections uses the ratio of the number of patents shared by two technology sections to the number of patents contained in one section to measure the convergence degree between the two sections. Based on the number of disciplines in literature, this indicator can also be used to measure the degree of interdisciplinarity between disciplines. In summary, the similarity between technology convergence and interdisciplinary science measurement indicators provides more possible directions for subsequent research expanding technology convergence-related measurement indicators.

6 Conclusion and Outlook

This paper first distinguishes technology convergence from technology fusion, revealing their differences in integration patterns. It then summarizes the current disciplinary distribution characteristics of technology convergence research, which are concentrated in computer science and engineering, management, and social sciences, along with corresponding research themes. In measuring technology convergence, this paper systematically reviews various current indicators from the perspectives of diversity and cohesion, revealing the role of indicators in measuring knowledge element flow, convergence degree, and trends between technologies. Among them, three-dimensional measurement of diversity and cohesion can be divided based on the characteristics and functions of indicators, providing references for constructing a measurement indicator system for technology convergence.

Existing technology convergence research mostly involves interdisciplinary or emerging technologies with complexity and diversity characteristics. This paper clarifies the connotations of first-order and second-order theme research in technology convergence and interdisciplinary science. When distinguishing between interdisciplinary science and technology convergence, it discovers some commonalities between the two in formation paths and measurement indicators, reveals differences in research objects between disciplinary cross-fertilization and technology convergence in basic scientific research, and points out that interdisciplinary indicators from the same perspective and dimension can provide references for expanding technology convergence-related measurement indicators.

With the rapid development of science and technology, the integration trend of science and technology has become increasingly obvious, and technology convergence has long exceeded the traditional sense of technology scope. Technology convergence is forward-looking and innovative. It can promote innovation-driven development, establish new economic models, solve increasingly complex social problems, and create disruptive industries that are currently unimaginable. The convergence of nanotechnology, biotechnology, information technology, and cognitive science has gradually formed a convergence model that has attracted much attention, demonstrating its unique advantages and potential. In this context, technology convergence will inevitably derive more new models and fields, leading continuous breakthroughs and leaps in technology and continuous iteration and upgrading of industries.

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Note: Figure translations are in progress. See original paper for figures.