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Dynamics and characteristics of interdisciplinary research in scientific breakthroughs: case studies of Nobel-winning research in the past 120 years

Jingjing Ren[1] · **Fang Wang**[2] · **Minglu Li**[3]

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Abstract

This study explores the interdisciplinary dynamics and characteristics of major original scientific achievements. Based on the perspective of knowledge integration, it combines bibliometric and social network analysis to investigate key publications of Nobel-winning research in natural science and their reference data. The data cover 585 laureates in Chemistry, Physics, and Physiology or Medicine awarded between 1901 and 2020, as well as 835 key publications published between 1887 and 2012 and their 10,894 citation publications. The main findings are as follows: First, interdisciplinary knowledge integration is an essential feature of original scientific breakthroughs, although influential achievements typically result from a novel combination of a larger amount of distant knowledge but in fewer disciplines. Second, the development of various disciplines in natural science has followed different dynamics of interdisciplinary processes for more than 100 years. Chemistry and Physics have experienced a dynamic shift from centralization to decentralization in terms of the concentrated degree of integrated disciplines, while Physiology or Medicine has shown a more generally concentrated trend. Third, Nobel-winning research presents a trend of a greater degree of knowledge interconnection, and the migration of combined research methods, tools, and basic disciplines contributes to the increasingly intense structure of knowledge combination. Bridging disciplines that facilitate knowledge exchange have shifted in the knowledge network across three time periods (the 1900s–1940s, 1950s–1970s, and 1980s and beyond).

Keywords Interdisciplinary research · Knowledge integration · Nobel Prize · Dynamics

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✉ Fang Wang
fang.wang.jobs@gmail.com

[1] Canvard College, Beijing Technology and Business University, Beijing, People's Republic of China

[2] Institutes of Science and Development, Chinese Academy of Sciences, Zhongguancun Beiyitiao 15, Beijing 100190, People's Republic of China

[3] Bureau of Policy, National Natural Science Foundation of China, Beijing, People's Republic of China

Introduction

Scientific research demonstrates a trend of integrating multidisciplinary knowledge (Porter & Rafols, 2009; Zhou et al., 2022). The development of scientific research since the 1960s has led to an increase in interdisciplinary research and proved its effectiveness in solving critical issues in society (Schmidt, 2008). Interdisciplinary research produces successful scientific breakthroughs and influences economic and social needs (Rafols & Meyer, 2010). Theories of knowledge production, such as big science (Price et al., 1986), post-normal science, and 'Mode 2' (Hessels & van Lente, 2008), recognize the importance of interdisciplinarity in the development of science.

'Interdisciplinary' can be defined based on either knowledge linkage or team cooperation (Stokols et al., 2008; Wagner et al., 2011). The process of integrating different bodies of knowledge is the key aspect of interdisciplinary research (National Academy of Sciences, 2004). Hence, knowledge integration is considered the core feature of interdisciplinary research. Scientific research is a process of knowledge recombination resulting in new knowledge output. Studies on interdisciplinary research focus on the measures of interdisciplinarity and their impacts on scientific research (Leydesdorf, 2007; Leydesdorff & Rafols, 2011; Leydesdorff et al., 2019; Rafols & Meyer, 2010; Stirling, 2007; Uzzi et al., 2013; Wagner et al., 2011; Yegros-Yegros et al., 2015; Zhang et al., 2021; Zwanenburg et al., 2022), characteristics of knowledge exchange in a specific field or over a period of time (Barthel & Seidl, 2017; Chang & Huang, 2012; Larivière et al., 2012; Liu & Rousseau, 2012; Truc, 2022; Yan et al., 2013), and interdisciplinary research policies (Bromham et al., 2016; Petersen et al., 2021). However, an in-depth exploration of the dynamics and characteristics of knowledge integration in the development of science across different fields and in a long history remains underexplored, which limits our understanding of the trends and patterns in the development of science throughout history.

Herein, we investigated 2 research questions: first, 'what are the dynamics of interdisciplinarity of scientific breakthroughs?' and second, 'what are the characteristics of knowledge structure of the breakthrough achievements?' The investigation is based on analysis of the key publications of the Nobel Prize in natural science, namely, Chemistry, Physics, and Physiology or Medicine, and their reference data: Nobel Prize-winning research (hereinafter 'Nobel-winning research') is a noteworthy topic of investigation because it represents the most important original scientific research achievements (Shelton & Holdridge, 2004). Academia is increasingly interested in the analysis of Nobel Prizes, focusing on three aspects: the characteristics of laureates, including their achievements; the knowledge production process, including the generation and dissemination of revolutionary ideas; and the evaluation of research quality (Hansson & Schlich, 2015; Luttenberger, 1996). In-depth exploration of the disciplinary characteristics and dynamics of knowledge integration of Nobel-winning research can help us understand the laws of scientific research and discipline development and may lead to enlightened policy implications.

This study contributes to the related research in the following three aspects. First, by systematically examining the dynamics and characteristics of knowledge integration in Nobel-winning research pertaining to natural science in the long run, we demonstrate that scientific breakthroughs typically result from a novel combination of a larger amount of distant knowledge but in fewer disciplines, thus acquiring a better understanding of the development of natural science in the past 120 years.

Second, by distinguishing the three aspects of diversity in variety, balance, and disparity in Chemistry, Physics, and Physiology or Medicine over a long time, we are able to identify the different development trends across the three fields and provide new evidence on the dynamics between balance and scientific breakthroughs over a long time period, thus obtaining a more comprehensive understanding of the overall degree of integration between different knowledge components in scientific breakthroughs across different fields and of the relationship between distinct and comprehensive characteristics of interdisciplinarity and the quality of scientific research. These findings also demonstrate the need to analyse the three aspects of diversity separately to precisely understand the characteristics of interdisciplinarity.

Third, unlike most extant research on interdisciplinarity, this study addresses the feature of knowledge combination in a network and the interconnection of knowledge as an important perspective to understand the interdisciplinary nature, in addition to diversity analysis. By combining bibliometrics and social network analysis (SNA) approaches to simultaneously analyse the diversity and coherence dimensions of interdisciplinarity, we are able to better capture the large-scale breadth of the knowledge base of scientific breakthroughs and the novelty of their knowledge integration. We reveal that the interdisciplinary nature of scientific breakthroughs features a trend of increasing diversity and coherence concurrently, albeit to a different degree across the three fields, thus completing the understanding of the interdisciplinary characteristics of scientific breakthroughs.

The remainder of this paper is organized as follows. "Literature review" section reviews the literature on interdisciplinary research and the Nobel Prize. "Research design" section proposes the research design. "Empirical results" section presents the empirical results and discusses the research findings, and "Conclusions" section provides the conclusion and discussion.

Literature review

Dynamics of interdisciplinary research

Scientific research has undergone remarkable changes in the integration of interdisciplinary knowledge. Porter & Rafols (2009) documented a 50% increase in the number of disciplines and references per article and a 75% increase in the number of co-authors from 1975–2005 in natural science research. Similarly, the average number of disciplines of Nature publications increased from 1–2 to 9 from 1900–2017 (Gates et al., 2019). The number of references per article in Economics and Business, and Political Science have increased more than threefold from 1960–2009, while other social science disciplines have achieved more than 200% growth (Zhou et al., 2022). However, the degree of interdisciplinarity varies across disciplines. For example, interdisciplinarity in the field of biology is relatively high, while it is relatively low in physics and mathematics (Porter & Rafols, 2009; Yan et al., 2013).

A higher level of interdisciplinarity typically improves the originality or novelty of scientific research, resulting in the spread of interdisciplinary research. Highly cited papers in more than 90% of NSF (National Science Foundation)-supported disciplines have a higher level of interdisciplinarity than others (Chen et al., 2015). The increase in the effective number of disciplines was associated with an approximately 20% increase in the research impact (Okamura, 2019). Highly cited papers generally exhibit higher variety and disparity and lower balance. The effect of variety on citation impact is most significant, followed by disparity and balance (Chen et al., 2021a). Researchers conducting interdisciplinary studies demonstrate a high degree of cognition of complexity, internalize knowledge of multiple disciplines, and can observe and comprehensively understand the connections between phenomena involving multiple disciplines. This increases the possibility of major scientific discoveries (Alexander et al., 2013). Uzzi et al. (2013) reported that the most influential papers, measured by the top 5% citations, featured a combination of novel and well-established science. Balancing atypical knowledge with conventional knowledge is a crucial link between innovativeness and impact. However, cognitive and collaborative challenges associated with interdisciplinary research and/or hurdles in the review process might reduce scientists' productivity (Leahey et al., 2015).

Measures of interdisciplinary research

Two approaches are used to measure interdisciplinarity: bibliometric and SNA. Bibliometric analysis extracts data representing the disciplines in scientific literature, such as discipline classification and co-authors (Morillo et al., 2001; Wagner et al., 2011; Wang et al., 2015). Indicators are constructed from two recognized key attributes, namely, diversity and coherence. Diversity measures the differences in the bodies of integrated knowledge, typically divided into three dimensions: variety, balance, and disparity/similarity (Leydesdorff et al., 2019; Porter et al., 2007; Stirling, 2007); coherence measures the intensities of the relations between these bodies of knowledge (Nesta & Saviotti, 2005; Rafols & Meyer, 2010). Integrated indicators to measure comprehensive aspects of diversity have been proposed, including Simpson's diversity (Simpson, 1949), Shannon entropy (Shannon, 1948), Brillouin's diversity (Brillouin, 1956), Rao-Stirling (Rafols & Meyer, 2010), Hill index (Zhang et al., 2016), and DIV indices (Leydesdorff et al., 2019). Each measure has its advantages and disadvantages; however, none were able to uniformly measure the degree of interdisciplinarity (Zwanenburg et al., 2022).

Interdisciplinary research is considered a knowledge integration process characterized by high cognitive heterogeneity and intense relational structures. SNA is capable of analysing the magnitude of interdisciplinarity by assuming that the location of a subject category in a network can indicate its degree of interdisciplinarity. Betweenness centrality, clustering coefficient, and average similarity of networks are used to measure the interdisciplinarity of journals (Leydesdorf, 2007; Leydesdorff et al., 2018; Rafols et al., 2012). Recent studies have evaluated the validity and consistency of these bibliometrics and SNA indicators, highlighting the inconsistencies between these measures (Wang & Schneider, 2020; Zwanenburg et al., 2022). Nevertheless, these indicators provide a good platform for more effective and coherent interdisciplinarity measurement, and network-based discipline classification or grouping remains in development. Furthermore, attention should be focused on emphasized definitions and implied assumptions (Zwanenburg et al., 2022).

Interdisciplinarity in Nobel-winning research

Nobel-winning research is characterized by a wider knowledge span in the process of knowledge production and combination. Nobel-winning publications exhibit remarkable boundary-spanning traits and exceptional abilities to connect disparate and topically diverse clusters of research papers (Sebastian & Chen, 2021). Furthermore, these papers have significantly changed the existing knowledge space structure. Nevertheless, Nobel-winning publications cite a large number of journals with relatively low impact factors. For example, the most ground-breaking scientific work in physics is not necessarily published in the journals with the highest impact factor (Bjørk, 2020; Liang et al., 2019). Methods are the most popular article type that are integrated in the process of knowledge combination. Recent Nobel-winning research focused more on earlier knowledge due to an increasing citation time lag (Liang et al., 2019).

Regarding team cooperation, Nobel laureates are particularly positioned in the activities of scientific knowledge combination (Tong & Ahlgren, 2017). The laureates are generally located in the bridge position of the co-authored network when compared with a group of matched scientists and act as ‘structural holes’, which is a state that is more likely to increase social capital for the network (Wagner et al., 2015). The laureates are positioned closer to the edge of multiple nonbiomedical disciplines than other biomedical researchers. On average, the co-authoring steps of the laureates and interdisciplinary researchers (at least one) are approximately 2.8 (Chris, 2015). Nobel laureates are more loyal to the cooperation that they initiated prior to winning the prize. There is less collaboration with new co-authors post-award than pre-award; the greater the intensity of pre-award cooperation and the longer the period of pre-award collaboration, the higher the probability of remaining in the co-author network after the award (Chan et al., 2015). However, evidence supporting a positive relationship between the longevity of collaborative relationships and creativity is lacking. Scientific collaboration involves conceptual complementarities that may erode over repeated interactions (Chan et al., 2016). Nobel laureates form a distinct group in the network with greater numbers of Nobel laureate ancestors, descendants, mentees/grand mentees, and local academia (Chariker et al., 2017). The international collaboration in the closely related Nobel Prize research themes, such as Ribozyme, Ozone, and Fullerene, demonstrates an increasing trend with a large share of publications with at least 2 countries (Tong & Ahlgren, 2017).

The dissemination of the Nobel-winning research reveals a pattern of scientific paradigm change and interdisciplinary development of knowledge production (Mazloumian et al., 2011; Szell et al., 2018). Hence, the single-field nature of Nobel Prize selection in an interdisciplinary context has been challenged (Mukhopadhyay, 2009). Landmark papers of Nobel Prize laureates caused an increase in forward citation of their previous publications, thereby drawing the attention of the scientific community and presenting the Matthew effect, that is, the ‘rich-get-richer’ effect in publication citation bias proposed by Merton (1968). This further led to a sudden paradigm shift (Mazloumian et al., 2011). Three types of citation accumulation curves of achievements were identified: concave, convex, and straight curves (Liu & Rousseau, 2014), representing different types of dynamics between old ideas and new opinions. A concave curve reveals a major conflict between the new ideas and old knowledge systems, causing strong interest and increased citations. A convex curve occurs when an originally underestimated new idea rapidly spreads after its value is increasingly recognized. The evolution of instrument types from bounded to linked to extension, by analysing instrument-related physics awards, gradually generated a form of scientific knowledge, e.g., instrument knowledge (Marcovich & Shinn, 2017).

Despite an increasing interest in analysing Nobel achievements, there is limited understanding of interdisciplinarity features in Nobel-winning research, especially their characteristics of knowledge integration (Gingras & Wallace, 2010; Turki et al., 2020). Furthermore, an understanding of the dynamics and characteristics of scientific breakthroughs in terms of interdisciplinary knowledge combination is inadequate. The present study bridges the gap by analysing the dynamics and characteristics of interdisciplinary knowledge integration of Nobel-winning research and their reference data in the past 120 years via a combination of bibliometrics and SNA approaches.

Table 1 Sample Information

	Chemistry	Physics	Physiology or Medicine	Total
Nobel laureates	174	205	206	585
Award time	1908–2020	1913–2020	1912–2020	1908–2020
Publications	263	257	315	835
Publication period	1894–2012	1887–2010	1902–2007	1887–2012
Publications with retrievable references	210	224	284	718
Retrieved references	3735	2711	4448	10,894
Ratio of retrieved references	60.16%	58.67%	65.4%	61.60%

Research design

Sample selection and data sources

The data were extracted from three sources: (1) the official website of the Nobel Prize (nobelprize.org), which provides information on Nobel laureates, including a description of their key contributions and publications[1]; (2) a dataset of the publication records of the Nobel laureates awarded during 1901 to 2016, constructed by Li et al. (2019), which retrieved information from multiple sources, including the laureates' resumes, university websites, Wikipedia, and Microsoft Academic Graph, and manual processing and algorithmic disambiguation; and (3) Web of Science (WoS), for reference data of the key publications.

First, we obtained data pertaining to all laureates in Chemistry, Physics, and Physiology or Medicine from 1901–2020, comprising 186, 216, and 222 laureates, respectively, from the official website. We combined Physiology or Medicine into one research field in the following analysis by following the classification of the Nobel Prize. Subsequently, key publications were extracted from the official website for the Nobel laureates awarded during 2017 to 2020 and from the dataset of the publication records constructed by Li et al. (2019) (data source (2)) for the award period from 1901 to 2016. The 2 datasets were integrated using the laureates' names. Finally, we collected the reference information cited by these key publications from WoS, which generated a total of 835 key publications and 10,894 references. Laureates whose key publications were not able to be identified or retrieved were excluded from the analysis. Table 1 presents the detailed sample information.

The key publications published after the 1950s account for a relatively high proportion of awards publications, with 69.58%, 58.37%, and 69.84% in the fields of Chemistry, Physics, and Physiology or Medicine, respectively. This might be because expenditures on basic research greatly increased in developed countries post-World War II due to improvements in the scientific research environment, and many research papers accumulated during the War were later published, leading to a boost in scientific achievements. This general trend is consistent with Larivière et al. (2010)'s finding, which demonstrated that scientific

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[1] "Key Publications" and "Nobel-winning research" are interchangeable terms in this paper. Different expressions are used for clarification when necessary.

publications exponentially increased in the golden age of scientific development from 1945–1975 in the West and subsequently slowed down after the 1980s.

Methods and variables

To comprehensively investigate the integration of interdisciplinary knowledge, we constructed an analytical framework consisting of the 2 dimensions of diversity and coherence to analyse the interdisciplinary trends and characteristics of Nobel-winning research by using a combination of bibliometrics and the SNA approach. The two approaches essentially correspond to a distinction between node-level and network-level analyses. The former is used to analyse diversity indicators, while the latter is used to analyse the coherence dimension. We address interdisciplinary knowledge as a process of knowledge combination and integration; it is then necessary to understand to what extent specific topics, concepts, tools, data, etc., used in a research process are related. Hence, the use of both approaches can better capture the two aspects of interdisciplinary knowledge integration: the large-scale breadth of the knowledge base of scientific research and the novelty of their knowledge integration. Table 2 presents the conceptual framework of diversity and coherence indices.

(1) Diversity refers to the number, balance, and degree of difference between the combined knowledge (Ávila-Robinson et al., 2021; Chen et al., 2021a, 2021b; Leydesdorff & Rafols, 2011); diversity is measured based on the three dimensions of variety, balance, and disparity. For bibliometric indicators, we included 5 measures that have frequently been used in the literature. Variety is measured by the number of references and disciplines. The greater the average references and average disciplines are, the higher the variety. Based on the information on the laureate's name, prize year, title, publication year, and journal name, we collected the bibliographic data of references of Nobel-winning research in the core collection of the WoS database, i.e., the number of references (R_i) and retrieved references for each key publication. We used SC (subject category) in WoS as a discipline classification. The average references (R) is the average number of references (R_i) for all key publications, as shown in Eq. (1). The average discipline (S) is the average number of SCs involved in references for all key publications, as shown in Eq. (2). Table 5 in Appendix shows the number of publications per discipline category for the three time periods.

The balance of interdisciplinarity is measured by the complementary value of the Gini coefficient (1 − Gini) and information entropy. The Gini coefficient ranges from 0, indicating perfect equality, to 1, perfect inequality. A larger value corresponds to a lower balance, indicating that knowledge integration is more concentrated in a few disciplines. A lower Gini coefficient corresponds to a higher balance, indicating that knowledge integration is more dispersed in more disciplines. The information entropy increases with the number of discipline categories and the evenness of probability distributions.

Disparity is measured by the average distance of disciplines, as shown in Eq. (5). A larger disparity represents a greater knowledge distance between disciplines. The benchmark value of the cosine similarity matrix for all disciplines is extracted from Leydesdorff et al. (2019) based on an estimation of citation data of 11,487 journals contained in the Journal Citation Reports 2016 (available at https://www.leydesdorff.net/software/mode2div/). We then adapt it to the reference data of Nobel-winning research by extracting relevant matrix elements.

(2) Coherence refers to interconnection between combined knowledge. This concept can be measured by the extent to which publication networks form an intense structure;

Table 2 Summary of the conceptual framework

Dimension	Characteristics	Indicators	Indices
Diversity	Variety	Average references (R)	$R = \sum R_i/N$,(1) where R_i is the number of references of key publication i, and N is the total number of key publications
		Average disciplines (S)	$S = \sum S_i/N$,(2) where S_i is the number of disciplines involved in references of key publication i, and N is the total number of key publications
	Balance	Complementary value of the Gini coefficient (G)_	$G = 1 - \frac{\sum(2i-n-1)x_i}{n\sum x_i}$,(3), where i is the rank of values (frequency of occurrence of a discipline) in ascending order, x_i is an observed value, n is the number of disciplines observed
	Balance + variety	Information entropy (H)	$H = -\sum_i p_i \times \log(p_i)$,(4) where p_i is frequency of occurrence of a discipline/sum of frequency of occurrence of all disciplines
	Disparity	Average distance of disciplines (Dis)	$\mathrm{Dis} = \frac{1}{n(n-1)}\sum_{i\neq j}\left(1 - S_{ij}\right)$, (5) where $S_{ij} = \frac{\sum_k^n x_{ik}x_{jk}}{\sqrt{\left(\sum_k^n x_{ik}^2\right)\left(\sum_k^n x_{jk}^2\right)}}$ is the cosine similarity of discipline i and j, x_{ik} is the number of cocitations between discipline i and k, and n is the number of disciplines
Coherence	The relational specific topics, concepts, tools, and data	Network density (D)	$D = 2l/n(n-1)$,(6) where l is the actual number of connections in the network; n is the number of nodes in the network

a more clustered network corresponds to a higher level of knowledge connection. We adopted network density, derived from the SNA approach, to measure coherence instead of using the mean linkage strength and mean path length of the network, as Rafols and Meyer (2010) proposed. This is more suitable because it measures the closeness of the connection between the points in a network, taking into account the inclusiveness and sum of the degrees of each point of the graph; hence, the overall integration degree between different knowledge components in a disciplinary network can be measured (Chen et al., 2021b).

The discipline co-occurrence network is constructed based on a co-occurrence matrix using the SCs of references. The rows and columns of the co-occurrence matrix are SCs, and the elements of the matrix represent the co-occurrence frequency of every two disciplines. Subsequently, the network graph is drawn using UCINET-NetDraw based on the constructed matrix. In the network, each block (node) represents one SC, and the connection means that the two disciplines appear in the SC logo of one reference simultaneously. The thickness of the connection indicates the co-occurrence frequency of the two disciplines, and the size of the block indicates the betweenness centrality of the discipline.

In addition to measuring the overall interconnection of integrated disciplines in Nobel-winning research using the indicator of network density, we adopt other SNA indicators and methods, such as betweenness centrality, the co-occurrence of disciplines, and discipline network diagrams, to analyse the key bridging disciplines of knowledge combination and the connectional structure of disciplines to obtain an in-depth understanding of the characteristics of knowledge combination in Nobel-winning research. We use the betweenness centrality of nodes to analyse the role of disciplines in the communication between different knowledge fields. The Freeman betweenness centrality is calculated using Eq. (7):

$$\mathrm{BC}(v) = \sum_{s \neq v \neq t} \frac{d_{\mathrm{st}}(v)}{d_{\mathrm{st}}}, \tag{7}$$

where $d_{\mathrm{st}}(v)$ is the number of shortest paths through v from point s to point t, and d_{st} is the total number of paths from s to t. The larger the value, the stronger the mediation effect.

To obtain comparable results across different networks, we further calculate weighted betweenness centrality, i.e., the relative Freeman betweenness centrality (RBC) as Eq. (8).

$$\mathrm{RBC}(v) = \frac{2\mathrm{BC}(v)}{n^2 - 3n + 2}, \tag{8}$$

where n is the number of nodes. Its value range is [0,1].

Following Leydesdorf (2007), we consider the journal or discipline as interdisciplinary if a journal or discipline is at the intermediate position between other journals or disciplines. Publications in such journals functioned as communication channels for other journals or disciplines (Silva et al., 2013).

Empirical results

Descriptive analysis

Based on the conceptual framework in Table 2, we estimated the varieties of key publications by Nobel laureates with an interval of a decade from 1887–2012. Disciplines were classified by the subject categories (SC) in the WoS database. The amount of knowledge

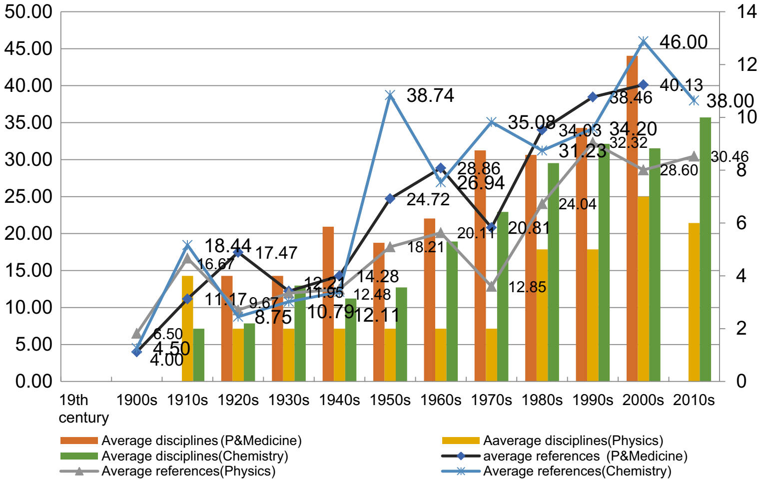

Fig. 1 Average references and disciplines of Nobel-winning research from 1901–2020 (award period)

and disciplines integrated in Nobel-winning research in natural science has been increasing for the past 120 years. As illustrated in Fig. 1, both the average number of references and the number of disciplines involved in the three fields present an upwards trend. The average number of references is approximately 1.58, 1.99, and 2.01 times for Chemistry, Physics, and Physiology or Medicine, respectively, in the mid-twentieth century than in the 2000s. Furthermore, the average disciplines are approximately 2.66, 3.00, and 1.97 times for Chemistry, Physics, and Physiology or Medicine, respectively, in the same time period.

Based on the trend change in the average references and distribution of the disciplines of these publications, we divided the development of natural sciences in terms of interdisciplinarity into three periods: the 1900s–1940s, 1950s–1970s, and 1980s and beyond (hereinafter 1900–‘40s, 1950s–‘70s, and 1980s–, respectively). We further analysed the interdisciplinary properties of the Nobel-winning research based on the three time periods.

Interdisciplinary dynamics and characteristics

Variety analysis

The estimations of diversity and coherence indices for the three fields across the three time periods are presented in Table 3. The varieties of the Nobel-winning research have dramatically increased over the three periods. During the three periods in the 1900s–‘40s, 1950s–‘70s, and 1980s and beyond, the average references are approximately 11, 25, and 35 for all Nobel-winning research, and average disciplines are approximately 3, 5, and 8. The highest increase occurs in the field of chemistry, 3.42 and 3.40 times that of the 1900s–‘40s in the following two periods. This might be because chemistry integrated a

Table 3 Interdisciplinary indicators along the three periods

	Indicator	Disciplines	1900s–‘40s	1950s–‘70s	1980s–
Diversity	Average references(R)	Chemistry	10.92	33.58	37.36
		Physics	11.45	17.06	28.85
		Physiology or Medicine	11.83	24.80	37.54
		Total	11.40	25.15	34.58
	Average disciplines(S)	Chemistry	2.74	5.09	9.03
		Physics	2.50	2.00	5.75
		Physiology or Medicine	4.62	6.71	10.16
		Total	3.29	4.60	8.31
	1-Gini coefficient	Chemistry	0.376	0.138	0.216
		Physics	0.279	0.137	0.174
		Physiology or Medicine	0.345	0.216	0.223
		Total	0.248	0.164	0.191
	Information entropy(H)	Chemistry	2.07	1.83	2.51
		Physics	1.16	0.82	1.38
		Physiology or Medicine	2.74	2.93	2.70
		Total	2.54	2.68	2.82
	Average distance of disciplines (Dis)	Chemistry	0.55	0.77	0.78
		Physics	0.59	0.70	0.73
		Physiology or Medicine	0.59	0.78	0.79
		Total	0.63	0.78	0.79
Coherence	Network density(D)	Chemistry	0.13	0.46	0.58
		Physics	0.17	0.14	0.23
		Physiology or Medicine	0.11	0.37	0.60
		Total	0.22	0.55	0.67
Sample size		Chemistry	42	104	64
		Physics	84	85	55
		Physiology or Medicine	80	141	63

larger amount of knowledge in the field of life sciences and biomedicine in later stages,[2] and this field accounts for 49.67% of discipline categories in the WoS classification system. There are five major categories, 151 middle categories, and 252 subcategories in the discipline classification system of WoS released in 2013. Seventy-five out of 151 middle categories belong to the major categories of life sciences and biomedicine.

The amount of knowledge integrated by the Nobel achievements is equivalent to or more than the overall level of the corresponding field during the same period estimated by Larivière et al. (2010)[3]; however, the number of integrated disciplines does not follow a

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[2] In 1900s–‘40s, 8 of the 16 disciplines involved in the references were in the LS&BM field, and 1980s–, 15 of the 31 new disciplines were in the LS&BM field. This is in line with the increasing trend of the number of disciplines in the LS&BM field in WoS, reflected by the number of SCs for each publication.

[3] The data used in Larivière et al. (2010) covers publications from 1900 to 2004. Three sources are included: data from 1900 to 1944 are drawn from the Century of Science in Thomson Scientific, which indexes 266 distinct journal titles covering most natural sciences and medical fields; data from 1945 to 1979 are from the natural sciences, engineering, and medical journals in the WoS; data from 1980 to 2004 are from the Science Citation Index in the WoS. Their data do not include articles in the fields of arts and

similar trend. The differences between Nobel-winning research in physiology or medicine and medical (MED) publications in Larivière et al. (2010) are 0, 7, and 8, respectively. The differences between Nobel-winning research in Chemistry, Physics, and natural science and engineering (NSE) publications reported by Larivière et al. (2010) are 0, 11, and 10. Therefore, the amount of knowledge integrated in Nobel-winning research has apparently been higher than the average level of general scientific research in the same period since the 1950s.

However, Nobel-winning research is not particularly prominent in terms of the number of integrated disciplines. Table 4 compares the variety of indices between key Nobel publications and general publications, as estimated by Porter and Rafols (2009). This reveals that Nobel achievements in physiology or medicine have a lower number of integrated disciplines than general publications from 1975–2005 (− 0.6 to − 2.49), suggesting that Nobel-winning achievements feature a higher level of knowledge concentration and are grounded in deep expertise in specialized disciplines. This is consistent with the findings for Nature publications from 1869–2019 reported by Gates et al. (2019) and for Nobel-winning publications from 1900–2016 reported by Li et al. (2022). The former contends that Nature publication only references 9 disciplines, while a currently published typical article references 11 disciplines. The latter finds that the diversity of references cited in Nobel-winning publications is generally lower than that in conventional articles from the same field or on the same topic.

Balance analysis

The variety and balance of knowledge integration in the field of natural science improves as information entropy (H) increases across the three time periods; however, the three fields follow different trends (Table 3), consistent with the 1-Gini. Both Chemistry and Physics follow an up-down-up development trend in terms of the concentrated degree of integrated disciplines, while Physiology or Medicine presents an up-down development trend. This implies that the distribution of the integrated disciplines in Chemistry and Physics shifts from centralization to decentralization. Conversely, the distribution of the disciplines in Physiology or Medicine initially disperses and subsequently becomes more concentrated.

This may be related to the development stage of the discipline and within-the-field knowledge breakthroughs. For most of the twentieth century, Physics and Chemistry were mainly at the stage of their own in-depth development; hence, knowledge production continuously developed within specific fields. Subsequently, as the discipline matured, the concepts, theories, tools, and methods of these 2 disciplines disseminated to other disciplines, contributing to discipline development (Schrödinger, 1944). Since the 1950s–'60s, due to important discoveries and pioneering works in particle physics, including the detection of cosmic neutrinos, astronomy, and astrophysics, a new research area, 'astroparticle physics', emerged and rapidly developed (Sun & Latora, 2020). The discipline with the highest frequency in Physics had shifted from physics to astronomy and astrophysics in

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Footnote 3 (continued)

humanities or the social sciences. Larivière et al. (2010) then divided these data into two scientific fields: medical fields (MED) and natural sciences and engineering (NSE), and calculated the average references of articles for each. Based on their results, we calculated the average references of each field for the three time periods (1900–'40s, 1950s–'70s, and 1980s–). As Century Science and SCI are both part of WoS, their classification of disciplines is comparable to ours.

Table 4 Comparison of Nobel key publications with general publications in terms of average disciplines

Fields	Results in Porter and Rafols (2009)				Nobel achievements in Physiology or Medicine	Results in Porter and Rafols (2009)	Nobel achievements in Physics	Nobel achievements in Chemistry
	Biotechnology and Applied Microbiology	Research and Experimental Medicine	Neuroscience	Average of the first three columns		Physics—Atoms, Molecules and Chemistry		
1975	7.29	8.81	8.94	8.35	7.75	6.04	2.00	4.00
1985	8.27	9.54	9.42	9.08	7.00	6.57	4.50	8.00
1995	9.42	11.19	10.86	10.49	8.00	7.55	5.00	8.50
2005	12.74	12.90	13.40	13.01	13.50	8.70	7.00	8.83

General publications refer to the publications used in Porter and Rafols (2009), which include papers published from 1975 to 2005 and their reference data in the WoS, for the six fields in Biotechnology & Applied Microbiology, Engineering, Electrical & Electronic, Mathematics, Medicine—Research & Experimental, Neurosciences, Physics—Atomic, Molecular & Chemical. These disciplines are identified by subject categories (SCs) in the WoS. We compare the average number of cited subject categories in the three fields (Biotechnology & Applied Microbiology, Medicine—Research & Experimental, Neurosciences) in Porter and Rafols (2009) with the average disciplines of the Nobel-winning research in Physiology or Medicine in the specific year. The comparison is made between Physics—Atomic, Molecular & Chemical in Porter and Rafols (2009) and the Nobel-winning researches in Physics in the specific year. The data of chemistry-related disciplines are not included in their paper, and we provide the data related to the Nobel-winning research of Chemistry here only as a reference the 1980s. Moreover, optics knowledge is widely cited, reflecting an interdisciplinary trend within the field of Physics.

The Physiology or Medical field demonstrates a trend of focusing on biochemistry and molecular biology (hereinafter BMB). Since the twentieth century, biochemistry has gradually influenced the advance of the medical revolution driven by Pasteur's work, evolving from the preparation of bacterial vaccines or immune sera based on a biological perspective to exploring the chemical mechanism of these therapies. Furthermore, these studies merge with research on chemically based metabolic diseases, for example, certain nutritional deficiencies. Biochemistry links these 2 streams of work (Bernal, 2010). Meanwhile, since the emergence of molecular biology, molecular-level studies on life phenomena have gradually become the mainstream research direction in the medical field and generated several new research topics in the treatment of human diseases and drug development (Zhou, 2005).

Disparity analysis

The disparity index reveals an increasing trend across the three time periods for both a single field and overall disciplines. However, the trend slowed from the 1950s to the 1980s–2010s, especially in the fields of Chemistry and Physiology or Medicine, implying that integrating long-distance knowledge was challenging.

Except for chemistry, physics and BMB were the main disciplines integrated in the field of Chemistry during the 1900s–'40s. This can be seen from the discipline frequency statistics of the references shown in Appendix Table 5. Subsequently, biophysics, electrochemistry, cell biology, virology, engineering, microscopy, spectroscopy, etc., which were emerging cross-disciplines, and biological science, engineering, and instrumentation disciplines, were gradually incorporated into the knowledge integration process. After the 1980s, environmental science and ecology as well as water resources emerged in the knowledge network. Although BMB became more prominent in the knowledge network in this period, it was generally considered an expansion of chemical research rather than a revolution in the theory or method of chemistry itself.

Multidisciplinary sciences and metallurgy and metallurgical engineering were the main disciplines integrated into the field of Physics during 1900–'40s. Subsequently, engineering, nuclear science& technology were gradually incorporated into the knowledge integration process. After the 1980s, optics and computer science emerged in the knowledge network. The disciplines of knowledge integration in physical research are relatively few and concentrated, so the knowledge distance in this field is relatively short.

In the field of Physiology or Medicine, physiology, BMB, and research and experimental medicine were the main integrated disciplines during the 1900s–'40s. Subsequently, in addition to more medical disciplines, engineering, crystallography, instruments and instrumentation were gradually incorporated into the process of knowledge integration. After 1980, there were no particularly important long-distance disciplines, and the frequency of the original disciplines increased. This implies that the process of knowledge production in Physiology or Medicine entered a more mature and specialized development stage.

Coherence analysis

Coherence, measured by overall network density, increased across the three time periods, while the three fields demonstrated various magnitudes, indicating a more intense connection among overall integrated knowledge (Table 3). The network density in the knowledge network of Chemistry and Physiology or Medicine is constantly increasing. It is observable that the disciplines included in the knowledge network of these two fields are gradually becoming interconnected, presenting a higher level of coherence. The knowledge network of Physics presents the lowest density and the slowest growth rate. This mainly because other disciplines integrated into the knowledge network of Physics are dominantly connected with physics, and connections between them are absent.

The number of integrated disciplines increased from 16 to 44 in the knowledge network of Chemistry across the three periods, among which the number of disciplines connected with at least one discipline increased from 7 to 35, an increase of 4 times, and the network density increased from 0.13 to 0.58. The number of integrated disciplines increased from 16 to 44 in the knowledge network of Physiology or Medicine across the three periods, among which the number of disciplines connected with at least one discipline increased from 13 to 45, an increase of 2 times, and the network density increased from 0.11 to 0.60, presenting the highest increase in terms of knowledge coherence. The number of integrated disciplines increased from 9 to 18 in the knowledge network of Physics across the three periods, among which the number of disciplines connected with at least one discipline increased from 6 to 18, an increase of 2 times, and the network density increased from 0.17 to 0.23. Hence, network density can properly capture the level of knowledge coherence in an integrated knowledge network.

Additionally, bridging disciplines that facilitate knowledge exchange have shifted in the knowledge network (Figs. 2, 3, and 4). Chemistry and Physiology or Medicine have experienced a more prominent shift, while Physics has remained relatively stable. Bridging disciplines in Chemistry have shifted from physics, BMB, and chemistry to BMB dominance. Bridging disciplines in Physics have shifted from the absolute centre of physics to the dual centre of physics and engineering; however, the relationship between physics and other subjects has remained the main connection. This explains the lower density of Physics networks in 1950s–'70s. Bridging disciplines in Physiology or Medicine have gradually shifted from microbiology, immunology, and physiology to BMB, cell biology, neuroscience and neurology, genes and genetics.

Source: Illustrated based on the co-occurrence matrix of the disciplines involved in the references. The size of the square indicates the betweenness centrality of the disciplines, and the thickness of the line indicates the frequency of co-occurrence between disciplines (similar rules apply to both Figs. 3 and 4).

The main bridging disciplines for the three fields can be divided into two categories: basic disciplines and engineering technology disciplines. First, combining the BC and RBC results shown in Table 6 of the Appendix, it is arguable that chemistry, physics, and BMB are basic disciplines with relatively large intermediate centrality in the three fields across three periods, especially after the 1950s. These disciplines have the most basic research objects, strong universality of concepts and theories, and high maturity of methods or tools. Their development and knowledge diffusion will have a great impact on other disciplines. For example, in Chemistry, the award-winning achievements before 1960 were awarded to the three fields of physical chemistry, organic chemistry, and inorganic, analytical, and radiochemistry on an equal basis. Among them, radiochemistry and physical chemistry, led by chemical thermodynamics, won many awards, reflecting their primary importance in chemistry and the new academic development introduced by the progress of physics (Noboru, 2018). Physics is one of the main disciplines of knowledge integration in Chemistry. After more than half a century, biochemistry emerged to play a more important role in Chemistry. Since then, the number of awards in biochemistry and molecular biology

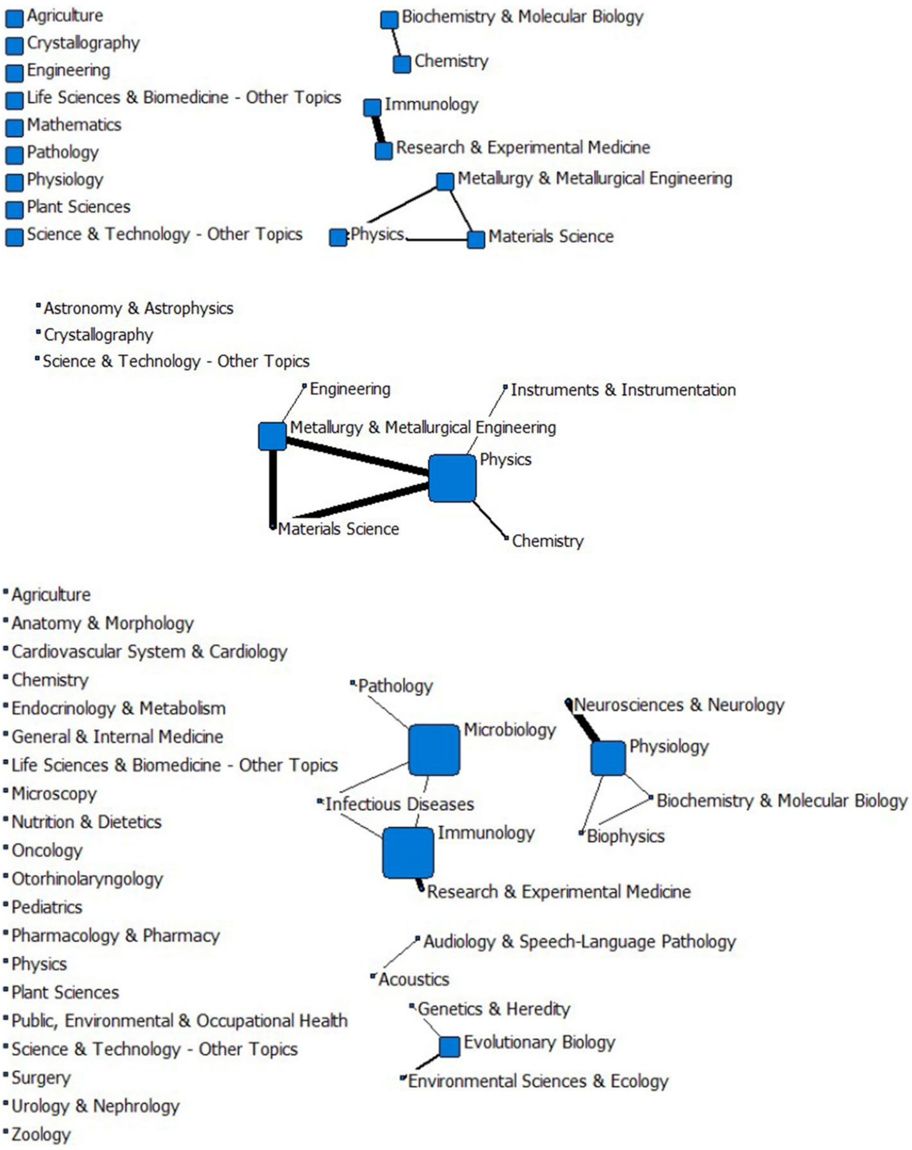

Fig. 2 Disciplinary networks of Nobel-winning research in Chemistry, Physics, and Physiology or Medicine (from top to bottom) in the 1900s–'40s

has increased dramatically, and achievements in biochemistry and molecular biology have won both the Chemistry and Physiology or Medicine Prizes.

Second, engineering technology disciplines, such as engineering, instruments and instrumentation, computer science, etc., show increasingly high betweenness centrality in the knowledge network, especially in the fields of Chemistry and Physics (Fig. 4 and Appendix Table 6). Their functions have evolved from simply applying and measuring to driving the formation of new knowledge as well as extensively linking more material

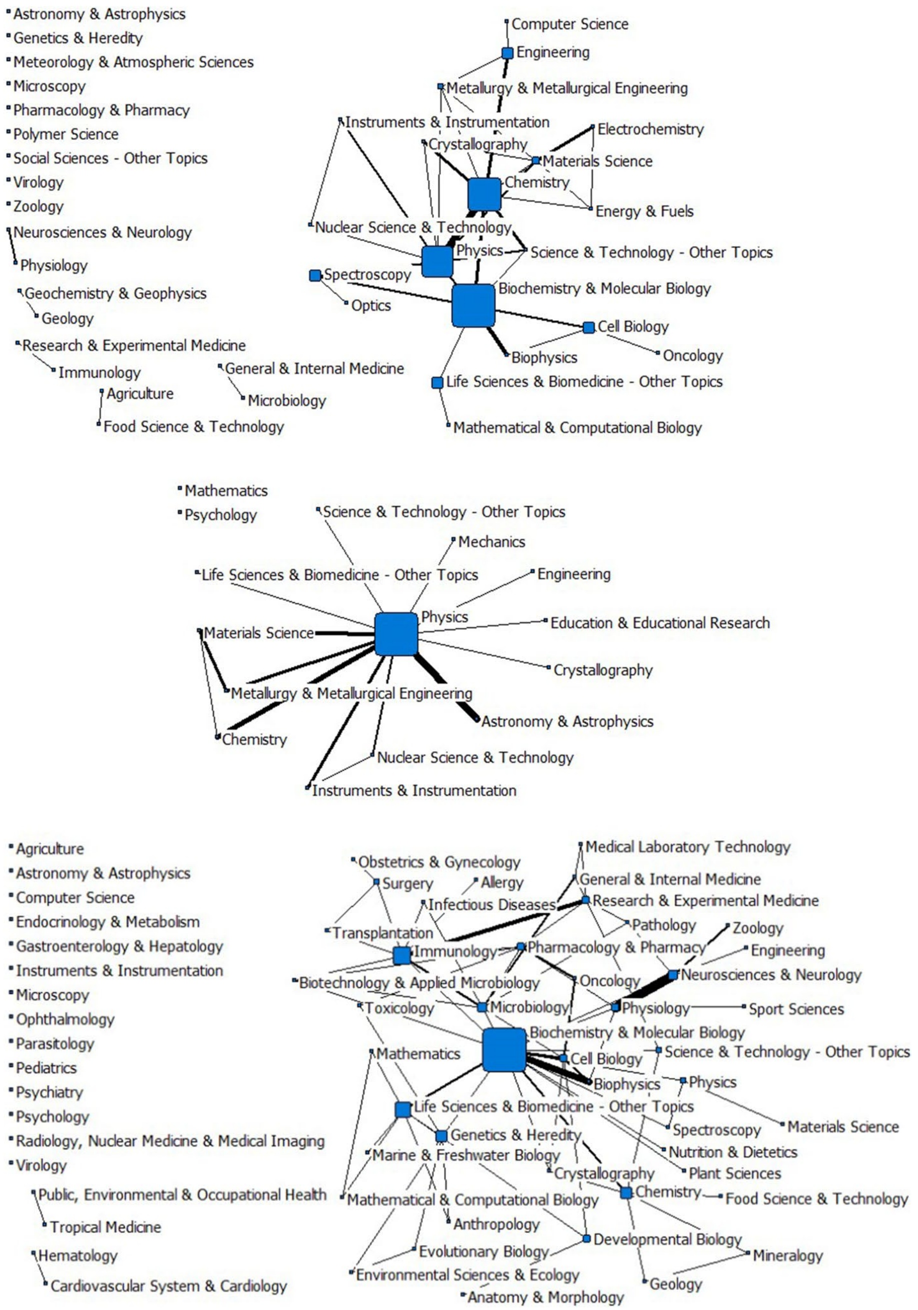

Fig. 3 Disciplinary networks of Nobel-winning research in Chemistry, Physics, Physiology or Medicine (from top to bottom) in the 1950s–'70s

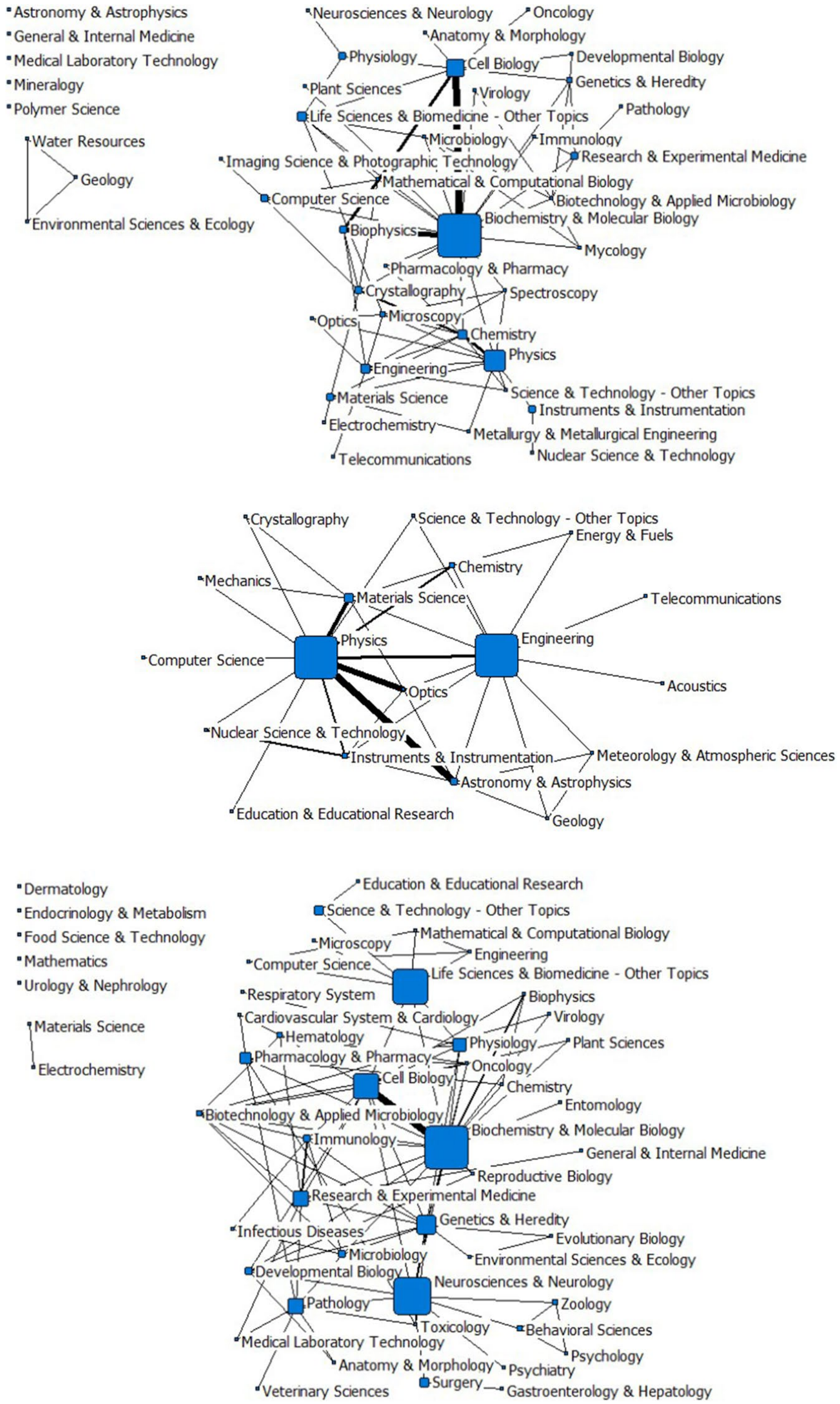

Fig. 4 Disciplinary networks of Nobel-winning research in Chemistry, Physics, Physiology or Medicine (from top to bottom) in the 1980s–

disciplines (as an intermediary). This is more prominent in Physics, as instruments evolved in a pattern of "bounded-linked-extension" in prize-winning achievements from 1901 to 2012 (Marcovich & Shinn, 2017), reflecting the promise and power of instrumentation in experimental and theoretical explorations.

Robustness checks

To check the robustness of the results on diversity analysis, we conduct econometric analyses on the dynamics of diversity indicators at the publication levels by including the controls at the publication level. Following Zhou et al. (2022), we build a linear model as shown in Eq. (9) to control the relevant factors that may influence the interdisciplinary levels. In this way, we intend to control the systematic change in scientific publications to a certain degree.

$$Div_i = \mathrm{Time}_i + Team_i + \mathrm{Ref\,n}_i + \mathrm{Ref\,a}_i + \varepsilon_i, \tag{9}$$

where Div_i represents the estimated diversity indicators for each publication i, namely, number of disciplines, Shannon information entropy, 1-gini coefficients, and disparity index; Time_i is a categorial variable, with 0, 1, and 2 representing publications in the period of 1900–1949, 1950–1979, or 1980–2012, respectively. The coefficients of Time_i represent the after controlling the publication. The control variables include the number of authors (Team_i), number of references ($\mathrm{Ref\,n}_i$), and age of references ($\mathrm{Ref\,a}_i$). Those controls are selected by considering the data availability and relevant literatures. The results are shown in Table 5. The detailed estimation results are shown in Tables 8, 9, 10 in Appendix.

The results generally confirm the robustness of the main estimation. As shown in Table 5, most of the controlled coefficients have significant signs consistently with the raw results, with slightly smaller magnitudes. The results on variety and disparity indicators are more consistent with results of pooled samples, except for insignificant results on the increases in number of references and disciplines in Physics during the 1950s–'70s, as well as the controlled average distance of knowledge in Physiology or Medicine in the 1980s–.

While some results on balance indicators are not consistent with those of pooled samples, the two indicators of information entropy and $1-$ Gini coefficient do not change uniformly. Inconsistent with previous result, the $1-$ Gini coefficient in Physics further decreases during 1980s–; the raw and controlled changes in information entropy indicator in Physiology or Medicine during the 1980s– further increases. The controlled change in $1-$ Gini coefficient during 1950s–'70s is not significant in Chemistry. The raw results on balance and disparity results are not identical to those of the pooled sample, as they are not a linear combination.

Table 5 Robustness checks: OLS estimation results for diversity indicators

Indicators	Variety			Balance				Disparity	
	References number	Disciplines number		1 – Gini coefficient		Information entropy		Average distance of disciplines	
	Raw	Raw	Controlled	Raw	Controlled	Raw	Controlled	Raw	Controlled
Chemistry 1950s–‘70s	17.24***	1.92*	0.39	– 0.20***	– 0.04	– 0.19***	– 0.12***	0.18***	0.10***
	(6.71)	(0.66)	(0.65)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)
1980s–	18.25***	6.40***	4.18***	– 0.12*	– 0.08*	0.48***	0.36***	0.32***	0.21***
	(11.28)	(0.72)	(0.75)	(0.06)	(0.08)	(0.05)	(0.06)	(0.06)	(0.07)
Physics 1950s–‘70s	1.30	– 0.10	– 0.21	– 0.09***	– 0.07***	– 0.06**	– 0.07***	0.08*	0.07
	(7.81)	(0.21)	(0.21)	(0.04)	(0.04)	(0.03)	(0.03)	(0.05)	(0.05)
1980s–	20.87**	1.90***	1.55***	– 0.34***	– 0.28***	0.16***	0.13***	0.19***	0.15**
	(8.52)	(0.24)	(0.25)	(0.04)	(0.05)	(0.03)	(0.04)	(0.06)	(0.07)
Physiology or Medicine 1950s–‘70s	5.47**	3.09***	1.82***	– 0.27***	– 0.21***	0.21***	0.16***	0.11**	0.09***
	(3.02)	(0.52)	(0.47)	(0.03)	(0.03)	(0.04)	(0.04)	(0.05)	(0.03)
1980s–	17.16***	5.87***	2.59***	– 0.34***	– 0.17***	0.36***	0.22***	0.12***	0.53
	(3.56)	(0.61)	(0.66)	(0.02)	(0.05)	(0.04)	(0.05)	(0.06)	(0.04)

Baseline time is the period of 1900 to 1949. Standard errors are in the parentheses. Significance levels: *, **, and *** represent significance levels at 10, 5 and 1%, respectively

Conclusions

This study analysed the interdisciplinary dynamics and characteristics in natural science from the perspective of knowledge integration using Nobel-winning research and their references data. This corresponds to 585 laureates in Chemistry, Physics, and Physiology or Medicine awarded from 1901 to 2020, 835 key publications published from 1887 to 2012, and 10,894 citation publications. The main findings, their policy implications, and research limitations are as follows.

Research findings and discussions

Interdisciplinary knowledge integration is an essential feature of original scientific breakthroughs, although influential achievements typically result from a novel combination of a larger amount of distant knowledge but in fewer disciplines. Nobel achievements in natural sciences are increasingly presented as the outcome of high-level knowledge integration both in their own discipline and with other disciplines. The number of references and disciplines per article of the achievements in the three fields has increased over the past 120 years. However, the number of integrated disciplines is not significant when compared to general publications at a comparable stage and is mainly focused on a few disciplines. While the disparity indicator shows that distant disciplines are gradually integrated into the scope of knowledge production in the three fields, the overall distribution of disciplines presents an increasing trend of concentration as it becomes less balanced. These three aspects of findings demonstrate that scientific breakthroughs require a novel combination of profound knowledge within narrow knowledge domains. Hence, this study complements Chen et al. (2021b)'s finding by demonstrating that scientific breakthroughs broadly feature a high concentration degree and a low level of balance across three fields over a long time. Meanwhile, in line with Uzzi et al. (2013) and Li et al. (2022), influential scientific achievements result from a combination of profound knowledge and innovative thinking that may be disseminated from other fields.

(2) The development of various disciplines in natural science has followed different dynamics of interdisciplinary processes for more than 120 years, as the characteristics of the three fields in variety, balance and disparity show different trends. First, the concentration dynamics of integrated disciplines vary across the three fields. Both Chemistry and Physics experienced a dynamic shift from centralization to decentralization in terms of the balance degree of integrated disciplines, while the distribution of the integrated disciplines in Physiology or Medicine initially dispersed and subsequently became more concentrated. Initially, Chemistry and Physics mainly integrated two to three disciplines, and then, during the 1950s–'70s, concentrated on their own disciplines, circa the 1970s, and subsequently slightly diverged to other one to two disciplines, as reflected in the up-down-up-shaped curve of the $1 - $Gini coefficient and information entropy values. This is related to the gradual fragmentation of these 2 fields into many small specialties since the 1950s, additionally reflecting the lack of major paradigm shifts in physics and chemistry since the middle of the last century (Gingras & Wallace, 2010). Meanwhile, as the disciplines mature, their concepts, theories, tools, and methods are diffused to other disciplines. The most obvious example is the wide emergence of biochemistry and biophysics.

Conversely, Physiology or Medicine showed a dynamic shift from decentralization to centralization in terms of the balance degree of integrated disciplines. Physiology or medicine has made breakthroughs in theories and experiments, benefiting from the dissemination of physics and chemistry knowledge, thereby entering a period of rapid specialized development since the 1950s. The most frequent interdisciplinary relationship in this field prominently changed from physiology–neuroscience to BMB–cell biology, highlighting a paradigm shift in this field. Biochemistry and molecular biology have gradually become the focus of the field. However, such major changes are not observed in the two disciplines of chemistry or physics, as there are no obviously important long-distance discipline knowledge integration or changes in interdisciplinary relations.

Furthermore, Physics presents the lowest variety, the lowest balance, and the lowest disparity, while Physiology or Medical shows the highest diversity, the highest balance, and the highest disparity. The magnitudes of various indicators in Chemistry are slightly less than those in Physiology or Medical. These findings indicate that scientific fields with similar comprehensive interdisciplinary indicators may vary remarkably in distinct characteristics of diversity, especially in long-term development trends. Hence, this study expands Zhang et al. (2019) findings by demonstrating the need to analyse the three aspects of diversity separately to precisely understand the characteristics of interdisciplinarity. By distinguishing the three aspects of diversity in three fields over a long time, we are able to identify the different development trends across the three fields, thus providing new evidence on the dynamics between balance and scientific breakthroughs across a long time period. It deepens the understanding of the relationship between distinct and comprehensive interdisciplinary characteristics and the quality of scientific research. Hence, this study completes studies by Wang et al. (2015), Yegros-Yegros et al. (2015), and Zhang et al. (2021).

(3) Nobel-winning research presents a trend of a greater degree of knowledge interconnection, and the migration of combined research methods, tools, and basic disciplines contributes to the increasingly intense structure of knowledge combination. This can be seen from the increasing coherence of disciplinary networks as well as the prominent bridging roles of basic disciplines, engineering, and instrumentation disciplines in the network of knowledge integration.

Bridging disciplines, which facilitate knowledge exchange, have shifted in disciplinary networks across the three time periods. Chemistry and physiology or medicine have experienced a more prominent shift, while physics has remained relatively stable. Bridging disciplines in chemistry have shifted from physics, BMB, and chemistry to BMB dominance, while those in physics have shifted from the absolute centre of physics to the dual centre of physics and engineering, although the relationship between physics and other subjects is predominant. Bridging disciplines in physiology or medicine have gradually shifted from microbiology, immunology, and physiology to BMB, cell biology, neuroscience and neurology, and genes and genetics.

These changes indicate that disciplines with strong fundamental research content and high universality of research tools/methods influence knowledge communication among all three disciplines, suggesting that a sound accumulation of basic knowledge, such as physics, chemistry, and BMB, is the foundation of high-quality interdisciplinary research.

Unlike most extant research on interdisciplinarity, this study addresses the feature of knowledge combination in a network and the interconnection of knowledge as an important perspective to understand the interdisciplinary nature, in addition to diversity analysis (Rafols & Meyer, 2010; Rafols et al., 2012; Zwanenburg et al., 2022). By combining the bibliometrics and SNA approaches to better capture the large-scale breadth of the knowledge base of scientific breakthroughs and the novelty of their knowledge integration, we reveal that the interdisciplinary nature of scientific breakthroughs features a trend of increasing diversity and coherence concurrently, resulting from deep and novel integration of multi-/interdisciplinary knowledge, albeit to a different degree across the three fields. This completes the understanding of the interdisciplinary characteristics of scientific breakthroughs (Chen et al., 2021a; Li et al., 2022; Zhang et al., 2019).

4.2 Policy implications

These research findings have two relevant policy implications. Firstly, policy-makers should consider the characteristics and dynamics of interdisciplinary knowledge integration in different disciplines and development stages when promoting high-quality scientific research. The necessity and feasibility of coordinated development among disciplines could be evaluated before issuing such policies.

Secondly, policy aimed at promoting interdisciplinary research should address the role of basic disciplines, engineering disciplines, and tool disciplines in bridging the integration of knowledge among disciplines. Knowledge among various disciplines of science is connected in a more extensive and closer pattern, although a deep disciplinary research foundation is the premise of successful interdisciplinary research. A stronger foundation in these disciplines is more conducive to driving the development of interdisciplinary research and making scientific breakthroughs.

4.3 Limitations and future research

Our results should be viewed in light of the following three limitations, which also provide avenues for future research. First, the sample publication data are limited to the WoS. More data sources, such as Scopus, PubMed, Google Scholar, etc., could be incorporated into studies in the future. Second, we rely on SCs as the discipline classification, which is classified at the journal level rather than at the article level. Although this is the most common and dominant classification method in the literature, the disciplines of articles and journals are not fully identical. Third, the findings about the comparison of Nobel achievements with general publications are based on a comparison with the research findings by Porter and Rafols (2009) and Larivière et al. (2010). The research fields of their data do not completely overlap with those of the sample data in this study. Such differences should be considered when understanding the comparison arguments. More comparable datasets could be constructed and estimated in future studies and research efforts. Additionally, a non-parametric matching approach could be used to conduct such an analysis (Li et al., 2022).

Appendix

See Tables 6, 7, 8, 9, and 10.

Table 6 Discipline frequency of references of Nobel-winning research in three fields across three periods

	1900–‘40s		1950s–‘70s		1980s–	
	Freq	SC	Freq	SC	Freq	SC
Chemistry						
1	51	Chemistry	1261	Chemistry	548	Biochemistry & Molecular Biology
2	27	Physics	586	Physics	287	Science & Technology—other topics
3	25	Biochemistry & Molecular Biology	287	Biochemistry & Molecular Biology	214	Chemistry
4	13	Research & Experimental Medicine	183	Science & Technology—other topics	165	Cell Biology
5	12	Immunology	64	Materials Science	128	Biophysics
6	10	Plant Sciences	35	Biophysics	125	Physics
7	10	Science & Technology—other topics	33	Life Sciences & Biomedicine—other topics	85	Microscopy
8	3	Pathology	30	Virology	59	Life Sciences & Biomedicine—other topics
9	2	Agriculture	26	Engineering	50	Genetics & Heredity
10	2	Physiology	25	Physiology	35	Crystallography
11	1	Life Sciences & Biomedicine—other topics	23	Electrochemistry	28	Materials Science
12	1	Engineering	22	Crystallography	25	Microbiology
13	1	Crystallography	17	Instruments & Instrumentation	24	Physiology
14	1	Metallurgy & Metallurgical Engineering	16	Spectroscopy	24	Optics
15	1	Mathematics	14	Cell Biology	17	Virology
16	1	Materials Science	13	Astronomy & Astrophysics	17	Biotechnology & Applied Microbiology
17			13	Metallurgy & Metallurgical Engineering	13	Polymer Science
18			7	Polymer Science	12	Engineering
19			7	Microbiology	11	Neurosciences & Neurology
20			7	Neurosciences & Neurology	10	Spectroscopy
21			6	Optics	8	Research & Experimental Medicine
22			6	Science & Technology—other topics	8	Electrochemistry
23			4	Microscopy	7	General & Internal Medicine
24			4	Pharmacology & Pharmacy	6	Developmental Biology

Table 6 (continued)

	1900–‘40s		1950s–‘70s		1980s–	
	Freq	SC	Freq	SC	Freq	SC
25			3	Research & Experimental Medicine	6	Instruments & Instrumentation
26			3	Oncology	6	Immunology
27			2	Social Sciences—other topics	4	Mathematical & Computational Biology
28			2	Agriculture	3	Computer Science
29			2	Geochemistry & Geophysics	3	Pharmacology & Pharmacy
30			2	Geology	3	Plant Sciences
31			2	Energy & Fuels	3	Metallurgy & Metallurgical Engineering
32			2	Food Science & Technology	1	Geology
33			2	Nuclear Science & Technology	1	Environmental Sciences & Ecology
34			2	Mathematical & Computational Biology	1	Anatomy & Morphology
35			2	Meteorology & Atmospheric Sciences	1	Water Resources
36			1	Zoology	1	Astronomy & Astrophysics
37			1	Computer Science	1	Telecommunications
38			1	Immunology	1	Oncology
39			1	Genetics & Heredity	1	Nuclear Science & Technology
40			1	General & Internal Medicine	1	Mycology
41					1	Medical Laboratory Technology
42					1	Imaging Science & Photographic Technology
43					1	Mineralogy
44					1	Pathology
Physics						
1	299	Physics	716	Physics	864	Astronomy & Astrophysics
2	76	Science & Technology—other topics	66	Astronomy & Astrophysics	536	Physics
3	31	Metallurgy & Metallurgical Engineering	48	Science & Technology—other topics	109	Optics

Table 6 (continued)

	1900–'40s		1950s–'70s		1980s–	
	Freq	SC	Freq	SC	Freq	SC
4	30	Materials Science	12	Engineering	78	Science & Technology—other topics
5	17	Chemistry	12	Chemistry	46	Materials Science
6	4	Crystallography	8	Materials Science	39	Engineering
7	3	Astronomy & Astrophysics	6	Instruments & Instrumentation	21	Chemistry
8	1	Engineering	5	Metallurgy & Metallurgical Engineering	17	Instruments & Instrumentation
9	1	Instruments & Instrumentation	5	Nuclear Science & Technology	7	Nuclear Science & Technology
10			1	Education & Educational Research	6	Crystallography
11			1	Psychology	2	Computer Science
12			1	Crystallography	1	Telecommunications
13			1	Mechanics	1	Meteorology & Atmospheric Sciences
14			1	Mathematics	1	Education & Educational Research
15			1	Life Sciences & Biomedicine—other topics	1	Acoustics
16					1	Energy & Fuels
17					1	Mechanics
18					1	Geology
Physiology or medicine						
1	87	Physiology	625	Biochemistry & Molecular Biology	558	Biochemistry & Molecular Biology
2	53	Biochemistry & Molecular Biology	345	Science & Technology—other topics	426	Science & Technology—other topics
3	43	Research & Experimental Medicine	304	Physiology	358	Cell Biology
4	32	Science & Technology—other topics	220	Neurosciences & Neurology	163	Immunology
5	27	General & Internal Medicine	154	Research & Experimental Medicine	122	Neurosciences & Neurology
6	27	Neurosciences & Neurology	152	Immunology	101	Genetics & Heredity
7	21	Life Sciences & Biomedicine—other topics	130	Biophysics	72	Life Sciences & Biomedicine—other topics
8	19	Immunology	125	Life Sciences & Biomedicine—other topics	60	Developmental Biology

Table 6 (continued)

	1900–‘40s		1950s–‘70s		1980s–	
	Freq	SC	Freq	SC	Freq	SC
9	15	Genetics & Heredity	110	General & Internal Medicine	59	Research & Experimental Medicine
10	15	Microbiology	96	Microbiology	55	Biophysics
11	9	Chemistry	87	Chemistry	51	Pharmacology & Pharmacy
12	9	Pathology	71	Oncology	43	Virology
13	7	Evolutionary Biology	69	Cell Biology	39	Physiology
14	6	Environmental Sciences & Ecology	63	Pharmacology & Pharmacy	36	Pathology
15	5	Agriculture	55	Virology	35	General & Internal Medicine
16	5	Plant Sciences	41	Pathology	34	Microbiology
17	4	Anatomy & Morphology	39	Zoology	33	Oncology
18	3	Zoology	38	Hematology	25	Gastroenterology & Hepatology
19	2	Pharmacology & Pharmacy	33	Anatomy & Morphology	23	Veterinary Sciences
20	2	Physics	33	Genetics & Heredity	20	Hematology
21	2	Urology & Nephrology	26	Endocrinology & Metabolism	20	Biotechnology & Applied Microbiology
22	2	Acoustics	17	Developmental Biology	15	Chemistry
23	2	Nutrition & Dietetics	14	Physics	14	Infectious Diseases
24	2	Audiology & Speech-Language Pathology	8	Medical Laboratory Technology	10	Cardiovascular System & Cardiology
25	2	Infectious Diseases	8	Infectious Diseases	7	Zoology
26	2	Otorhinolaryngology	7	Biotechnology & Applied Microbiology	6	Mathematical & Computational Biology
27	2	Endocrinology & Metabolism	6	Allergy	6	Food Science & Technology
28	1	Cardiovascular System & Cardiology	5	Environmental Sciences & Ecology	6	Plant Sciences
29	1	Surgery	5	Evolutionary Biology	4	Surgery
30	1	Biophysics	5	Surgery	4	Toxicology
31	1	Oncology	5	Psychology	3	Anatomy & Morphology
32	1	Pediatrics	4	Radiology, Nuclear Medicine & Medical Imaging	3	Entomology

Table 6 (continued)

	1900–‘40s		1950s–‘70s		1980s–	
	Freq	SC	Freq	SC	Freq	SC
33	1	Public, Environmental & Occupational Health	4	Engineering	2	Dermatology
34	1	Microscopy	4	Plant Sciences	2	Reproductive Biology
35			4	Crystallography	2	Urology & Nephrology
36			4	Transplantation	2	Behavioral Sciences
37			3	Cardiovascular System & Cardiology	2	Microscopy
38			3	Psychiatry	2	Environmental Sciences & Ecology
39			3	Mathematical & Computational Biology	2	Evolutionary Biology
40			3	Microscopy	1	Engineering
41			2	Gastroenterology & Hepatology	1	Medical Laboratory Technology
42			2	Marine & Freshwater Biology	1	Materials Science
43			2	Toxicology	1	Mathematics
44			2	Public, Environmental & Occupational Health	1	Psychiatry
45			2	Instruments & Instrumentation	1	Electrochemistry
46			2	Anthropology	1	Education & Educational Research
47			2	Ophthalmology	1	Psychology
48			2	Nutrition & Dietetics	1	Respiratory System
49			1	Sport Sciences	1	Computer Science
50			1	Science & Technology—other topics	1	Endocrinology & Metabolism
51			1	Tropical Medicine		
52			1	Spectroscopy		
53			1	Food Science & Technology		
54			1	Geology		
55			1	Computer Science		
56			1	Agriculture		

Table 6 (continued)

	1900–'40s		1950s–'70s		1980s–	
	Freq	SC	Freq	SC	Freq	SC
57			1	Astronomy & Astrophysics		
58			1	Materials Science		
59			1	Parasitology		
60			1	Pediatrics		
61			1	Obstetrics & Gynecology		
62			1	Mathematics		
63			1	Mineralogy		

Table 7 Betweenness centrality of main disciplines in three fields across three periods

	1900–'40s			1950s–'70s			1980s–		
	SC	BC	RBC%	SC	BC	RBC%	SC	BC	RBC%
Chemistry									
	Mean	0	0	Mean	7.231	1.029	Mean	23.409	2.592
1				Biochemistry & Molecular Biology	80.667	11.475	Biochemistry & Molecular Biology	337.724	37.400
2				Chemistry	59.167	8.416	Physics	144.424	15.994
3				Physics	58.167	8.274	Cell Biology	110.943	12.286
4				Life Sciences & Biomedicine—other topics	18.000	2.560	Life Sciences & Biomedicine—other topics	50.369	5.578
5				Cell Biology	18.000	2.560	Chemistry	47.876	5.302
6				Engineering	18.000	2.560	Engineering	45.650	5.055
7				Spectroscopy	18.000	2.560	Materials Science	38.833	4.300
8							Research & Experimental Medicine	35.333	3.913
9							Physiology	34.000	3.765
10							Computer Science	34.000	3.765
11							Instruments & Instrumentation	34.000	3.765
12							Crystallography	29.195	3.233
13							Biophysics	25.490	2.823
Physics									
	Mean	1.222	4.365	Mean	4.200	4.615	Mean	7.944	5.842
1	Physics	7.000	25.000	Physics	62.500	68.681	Physics	59.833	43.995
2	Metallurgy & Metallurgical Engineering	4.000	14.286				Engineering	59.833	43.995
3							Materials Science	8.167	6.005
4							Astronomy & Astrophysics	7.333	5.392
5							Instruments & Instrumentation	3.833	2.819

Table 7 (continued)

	1900–'40s			1950s–'70s			1980s–		
	SC	BC	RBC%	SC	BC	RBC%	SC	BC	RBC%
Physiology or Medicine									
	Mean	0.265	0.050	Mean	29.016	1.586	Mean	31.360	2.667
1	Microbiology	3.000	0.568	Biochemistry & Molecular Biology	580.182	31.704	Biochemistry & Molecular Biology	281.831	23.965
2	Immunology	3.000	0.568	Immunology	191.805	10.481	Neurosciences & Neurology	245.238	20.854
3				Life Sciences & Biomedicine—other topics	166.440	9.095	Life Sciences & Biomedicine—other topics	227.000	19.303
4				Chemistry	123.033	6.723	Cell Biology	159.064	13.526
5				Genetics & Heredity	120.638	6.592	Genetics & Heredity	118.490	10.076
6				Neurosciences & Neurology	94.167	5.146	Pathology	87.686	7.456
7				Microbiology	91.229	4.985	Research & Experimental Medicine	82.321	7.000
8				Cell Biology	71.789	3.923	Physiology	72.833	6.193
9				Physiology	55.050	3.008	Pharmacology & Pharmacy	51.674	4.394
10				Pharmacology & Pharmacy	52.190	2.852	Surgery	41.000	3.486
11				Research & Experimental Medicine	51.798	2.830	Science & Technology—other topics	41.000	3.486
12				Developmental Biology	46.583	2.546			
13				Physics	42.000	2.295			
14				Surgery	42.000	2.295			

BC refers to Freeman betweenness calculated as Eq. (7). RBC refers to the relative Freeman betweenness calculated as Eq. (8)

Table 8 OLS regression results on diversity indicators in Chemistry

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	References number	Disciplines number		1 − Gini coefficient		Information entropy		Disparity	
T1	17.24**	1.92***	0.39	− 0.20***	− 0.04	− 0.19***	− 0.12**	0.18***	0.10*
	(2.57)	(2.90)	(0.60)	(− 3.37)	(− 0.99)	(− 4.09)	(− 2.44)	(3.22)	(1.70)
T2	18.25**	6.40***	4.18***	− 0.12***	− 0.08*	0.48***	0.37***	0.32***	0.21***
	(2.50)	(8.95)	(5.58)	(− 4.91)	(− 1.85)	(9.33)	(6.46)	(5.33)	(3.12)
Team			0.30**		− 0.01		0.02*		0.01
			(2.54)		(− 1.59)		(1.76)		(1.08)
Refa			0.02		− 0.00		0.00		0.01
			(0.35)		(− 1.47)		(0.58)		(1.20)
Refn			0.08***		− 0.00***		0.00***		0.00***
			(6.17)		(− 6.42)		(3.60)		(3.21)
Cons.	15.56***	2.03***	1.02*	0.83***	0.89***	0.19***	0.13***	0.40***	0.34***
	(2.69)	(3.55)	(1.68)	(26.58)	(26.81)	(4.63)	(2.89)	(8.42)	(6.21)
N	216	218	218	218	218	218	218	218	218
$R-2$	0.03	0.32	0.45	0.10	0.27	0.31	0.37	0.12	0.17

t-statistics in parentheses. Baseline period is 1900–1949; T1 represents 1950–1979; T2 represents 1980s–. Significance levels: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Table 9 OLS regression results on diversity indicators in Physics

	(1) References number	(2) Disciplines number	(3)	(4) 1 − Gini coefficient	(5)	(6) Information entropy	(7)	(8) Disparity	(9)
T1	1.30	− 0.10	− 0.21	− 0.09**	− 0.07*	− 0.06**	− 0.07**	0.08*	0.07
	(0.19)	(− 0.46)	(− 1.01)	(− 2.26)	(− 1.92)	(− 2.04)	(− 2.44)	(1.76)	(1.49)
T2	20.87***	1.90***	1.55***	− 0.34***	− 0.28***	0.16***	0.13***	0.19***	0.15***
	(2.74)	(8.00)	(6.19)	(− 7.62)	(− 6.05)	(4.76)	(3.75)	(3.68)	(2.66)
Team			0.00		0.00		0.00		0.00
			(0.36)		(0.11)		(1.03)		(0.84)
Refa			0.07***		− 0.01*		0.01***		0.01
			(3.01)		(− 1.95)		(3.10)		(1.60)
Refn			0.01***		− 0.00***		− 0.00		0.00
			(3.26)		(− 3.48)		(− 1.13)		(0.59)
Cons	16.62***	2.13***	1.81***	0.83***	0.88***	0.22***	0.18***	0.37***	0.34***
	(3.14)	(12.91)	(9.92)	(27.22)	(25.76)	(9.64)	(7.10)	(10.57)	(8.33)
N	203	203	203	203	203	203	203	203	203
$R{-}2$	0.05	0.32	0.39	0.24	0.30	0.21	0.25	0.06	0.08

t-statistics in parentheses. Baseline period is 1900–1949; T1 represents 1950–1979; T2 represents 1980s–. Significance levels: $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$. Publications with non-retrievable "Research Areas" in their references are excluded from the analysis

Table 10 OLS regression results on diversity indicators in Physiology or Medicine

	(1) References number	(2) Disciplines number	(3)	(4) 1 – Gini coefficient	(5)	(6) Information entropy	(7)	(8) Disparity	(9)
T1	5.47**	3.09***	1.82***	– 0.27***	– 0.21***	0.21***	0.16***	0.11***	0.09***
	(2.79)	(5.95)	(3.84)	(– 9.47)	(– 7.76)	(5.92)	(4.57)	(3.67)	(2.88)
T2	17.16***	5.87***	2.59***	– 0.34***	– 0.17***	0.36***	0.22***	0.12***	0.00
	(3.29)	(9.59)	(3.90)	(– 10.10)	(– 4.61)	(8.62)	(4.35)	(2.67)	(0.08)
Team			0.11		– 0.01*		0.01**		0.01*
			(1.56)		(– 1.66)		(2.19)		(1.92)
Refa			0.13**		– 0.01**		0.01*		0.01***
			(2.10)		(– 2.32)		(1.91)		(4.07)
Refn			0.12***		– 0.01***		0.00***		0.00***
			(9.06)		(– 8.10)		(4.29)		(3.12)
Cons	18.77***	3.81***	1.84***	0.79***	0.90***	0.43***	0.31***	0.38***	0.27***
	(6.88)	(8.62)	(3.35)	(32.46)	(29.13)	(14.14)	(7.60)	(17.62)	(9.17)
N	273	273	273	273	273	273	273	273	273
R−2	0.09	0.25	0.45	0.31	0.46	0.22	0.29	0.05	0.15

t-statistics in parentheses. Baseline period is 1900–1949; T1 represents 1950–1979; T2 represents 1980s–. Significance levels: ***$p<0.01$, **$p<0.05$, *$p<0.1$. Publications with non-retrievable "Research Areas" in their references are excluded from the analysis

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Declarations

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