Scientometrics (2021) 126:6201–6224
https://doi.org/10.1007/s11192-020-03821-x

Tracing the development of mapping knowledge domains

Ying Huang[1,2] · **Wolfgang Glänzel**[1,3] · **Lin Zhang**[1,2]

Received: 2 October 2020 / Accepted: 4 December 2020 / Published online: 13 February 2021

Abstract
Prof. Zeyuan Liu was the first to introduce the concept of knowledge-domain mapping to the scientific community in China. Knowledge-domain maps are useful tools for tracking the frontiers of science and technology, facilitating knowledge management, and assisting scientific and technological decision-making. Science overlay mapping as a type of knowledge-domain mapping can visualize the location of research within the sciences from both snapshots at any fixed time and from a dynamic perspective. Most current science overlay maps merely show the basic landscape of a research field during specific periods, but fail to track temporal changes and interactions between different research fields. Applying an individual document-based cross-citation approach to a dataset retrieved in the Web of Science Core Collection for the period 1999–2018, we have built a global science map based on cognitive similarities across the 16 ECOOM major research fields. Using citation-link strength (CLS), we then traced information flows to better understand how the internal structures of these research fields have evolved. The paper concludes with a brief description of the emergence and development of the mapping of knowledge domains in China, in general, and highlights the contribution of Zeyuan Liu to the topic of mapping knowledge domains, in particular.

Keywords Science overlay mapping · Mapping knowledge domains · Interdisciplinary research · Zeyuan Liu

Introduction

The structure and growth of scientific literature is complex and highly dynamic. The representation of this complexity and dynamics in a comprehensible way has become an important and multifaceted topic in scientometric research. The mapping of how knowledge interrelates different domains and shapes disciplines, forming an interdisciplinary and cross-cutting activity in the very intersection of information science, mathematics and

✉ Lin Zhang
zhanglin_1117@126.com

[1] Centre for R&D Monitoring (ECOOM) and Department of MSI, KU Leuven, Leuven, Belgium

[2] School of Information Management, Wuhan University, Wuhan, China

[3] Department of Science Policy and Scientometrics, Library of the Hungarian Academy of Sciences, Budapest, Hungary

computer science, has evolved to one of the most informative topics in scientometrics, reaching various communities far beyond our own field (cf. Fortunato et al. 2018). Science mapping, a data visualization tool to offer an overview of the scientific landscape, can be employed to reveal discipline structure, to track topic evolution, explore research front, etc. (Chen 2017). Methodologically based on data-mining, information processing and analysis, the application of computer linguistics, and visualization techniques, it provides useful tools for science policy and R&D management to monitor the evolution of science & technology, its impact on society and economy and thus to tackle society's most burning challenges.

A science mapping exercise may, among others, cover the structure and evolution of a scientific discipline, a larger research field, the network of a group of researchers, the detection of scientific communities or emerging research topics. By using different means of associating them, including co-word, co-citation, bibliographic coupling, co-authorship, or even direct citation—researchers can generate the different types of structures, networks of relations, and kinds of patterns they want to observe (Chen 2003). The interdisciplinary nature, the real complexity of this endeavor becomes evident if one considers the unique combination and integration of the above-mentioned bibliometric methods with advanced contemporary computer-science and -linguistic techniques into a truly multi-dimensional approach necessary to create a meaningful mapping of science and technology.

In this paper, we begin by using the program HistCite to identify significant works on science mapping using the citation links between them diachronically. Based on the limitations of current science overlay mappings, we then propose an enhanced science overlap mapping by employing citation-link strength (CLS) to trace information flow characteristics in order to better understand the internal structure and evolutionary interaction of research fields during the years 1999–2018. Finally, we briefly describe the emergence and development of mapping knowledge domains in China. Particularly, we highlight the scientific performance and academic contribution of Zeyuan Liu as a notable contributor to the field of mapping knowledge domains.[1]

The evolution of science mapping

The field of mapping scientific literature has existed for many decades (Boyack 2004). Due to broader information accessibility and new techniques of analysis, retrieval, and visualization, the development of the field of information visualization has enjoyed notable advances and attracted wide attention.

An overview of science mapping research

Different from the approach by Chen (2017) that aimed to provide a systematic review of the literature concerning major aspects of science mapping, we focused primarily on 'core' publications, i.e., documents that are strongly related to science mapping. We first retrieved literature from the three journal editions of the Web of Science Core Collection

[1] Liu, who passed away in February 2020, was the professor and dean of Humanities & Social Sciences College at the Dalian University of Technology and received the First Outstanding Contribution Award and was made a Lifetime Honorary Member of the Chinese Association for Science of Science and S&T Policy.

Table 1 The search query for retrieving publications on science mapping indexed in WoS (1955–2019)

No.	Search strategy	Records
#1	TS = (science NEAR/0 map* OR bibliometric NEAR/0 map* OR scientometric NEAR/0 map* OR "knowledge domain*" NEAR/0 map* OR science NEAR/0 visualiz* OR "knowledge domain*" NEAR/0 visualiz*)	529
#2	TS = (Bibexcel OR CitNetExplorer OR CiteSpace OR Gephi OR HistCite OR SciMAT OR Sci2 OR Netdraw OR VOSViewer)	678
#3	TS = (science NEAR/1 map* OR knowledge NEAR/1 map* OR bibliometric NEAR/1 map* OR scientometric NEAR/1 map* OR "knowledge domain*" NEAR/1 map* OR science NEAR/1 visualiz* OR knowledge NEAR/1 visualiz* OR "knowledge domain*" NEAR/1 visualiz*) AND (WC = (INFORMATION SCIENCE LIBRARY SCIENCE) OR TS = (bibliometric* OR scientometric*))	690
#4	#1 OR #2 OR #3 Refined by: Document Types: (Article OR Review)	1353

(WoS), that is from the Science Citation Index Expanded (SCIE), the Social Sciences Citation Index (SSCI) and the Arts & Humanities Citation Index (A&HCI) using the retrieval strategy outlined in Table 1. This resulted in a collection of 1353 records. Removing duplicates and early access records that were not yet assigned to specific issues resulted in an initial dataset of 1321 articles and reviews.

In a first step, we analyzed the retrieved dataset using HistCite, a software package developed for bibliometric analysis and information visualization, to supplement missing sets of papers, based on the assumption that if a set of papers is frequently cited by other publications in a certain domain field, then those documents are very likely to be related with the same topic and can thus be considered potentially relevant (Glänzel et al. 2006; Zitt and Bassecoulard 2006; Glänzel et al. 2009; Huang et al. 2015). We supplemented the seed document set by those cited references' the Local Citation Score (LCS) value—an indicator that shows the count of citations of a paper within the collection—of which was greater than 30. This resulted in a final sample of 1351 publications that was used as the basis of our science mapping.

After uploading the papers into HistCite and removing unlinked citations through Pajek, the 30 most frequently cited documents in the dataset and their internal links were identified and visualized using VOSViewer, as shown in Fig. 1. The bibliographic data of the corresponding articles is listed in "Appendix" Table 3.

Each node in Fig. 1 represents one of the thirty most influential papers indexed in the WoS, with the size of the node indicating its LCS value. We note that there are also frequently cited works that are published as monographs rather than within periodicals, such as Callon et al. (1986) and van Eck and Waltman (2014). At the same time, there may be concepts that are relevant to science mapping but explored and discussed in bibliometrics as well as in mapping studies, such as *h-index* (Hirsch 2005) and *g-index* (Egghe 2006). The idea of using Hirsch-type indices in structural science studies, notably in network analysis and community detection, was introduced and applied, among others, by Schubert et al. (2009) and Glänzel (2012), and the notions of the h-index and related indicators have thus become directly linked to science mapping.

A science mapping study typically consists of several components, including the relationships among a selection of scientific literature, the use of visual analytic tools and clustering algorithms and scientometric indicators. The study of science mapping goes back

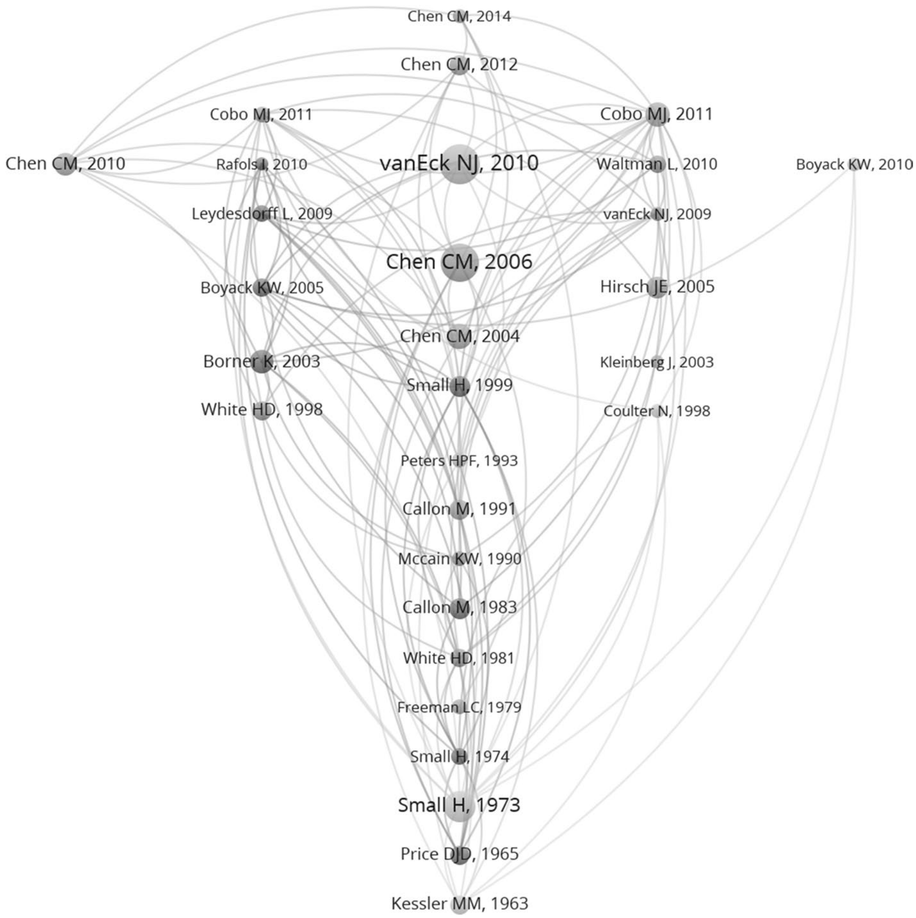


Fig. 1 The historiography of the 30 documents with the highest LCS in science mapping research

to Kessler (1963), who proposed the use of *bibliographic coupling* (BC) as a method for the detection of thematic similarity of scientific documents, but he has not designed this concept for the purpose of science mapping. The application of BC to structural analysis had to wait more than three decades until Glänzel and Czerwon (1996) revitalized this principle for the application in new contexts using the mathematical-theoretical foundation elaborated by Sen and Gan (1983), long after the concept of co-citation analysis was elaborated and proposed, independently of each other, by Small (1973) and Marshakova (1973). One of the pioneering domain visualization studies based on citation data was done in the early 1960s by Garfield, who drew a historical map of DNA research manually (Garfield et al. 1964). Thereafter, research methods expanded to involve direct citation (de Solla Price 1965), document co-citation analysis (Small 1973; Marshakova 1973; Griffith et al. 1974; Small and Griffith 1974), author co-citation analysis (White and Griffith 1981; McCain 1990; White and McCain 1998; Ahlgren et al. 2003), co-word analysis (Callon et al. 1983, 1991; Peters and van Raan 1993a, b), and combined co-citation and word analysis (Braam et al. 1991). The idea of improving document-link-based studies was systematically developed further, e.g., by Boyack and Klavans (2010), Liu et al. (2012a, b) and Glänzel and Thijs (2017). At the same time, various conceptions and network indicators (especially centrality) were also proposed and refined to measure the nodes and attributes of networks (Freeman 1978), which provides an advanced way of exploring the role of disciplines in science mapping (Ni et al. 2011).

In 2003, chapter reviews on visualization techniques conducted by Börner et al. (2003) represented a new approach to science mapping research. In that review, the term “mapping knowledge domains” was proposed to describe “a newly evolving interdisciplinary area aimed at the process of charting, mining, analyzing, sorting, enabling navigation of, and displaying knowledge”. By making the structure of knowledge more visible, this new approach aimed at easing information access and supporting researchers in their search for knowledge (Shiffrin and Börner 2004).

In 2004, PNAS published a special issue, “Mapping knowledge domains”, led by Richard M. Shiffrin and Katy Börner and based on the May of 2003 Arthur M. Sackler’s Colloquium of the National Academy of Sciences on Mapping Knowledge Domains, which was held in Irvine, California, on 9–11 May 2003.[2] At this stage in the evolution of science mapping research, the focus on science mapping shifting from the single or combined methods to the process flow for mapping knowledge domains. For example, Chen (2004) proposed the progressive visualization methods, including time slicing, thresholding, modeling, pruning, merging, and mapping. Boyack et al. (2005) mapped networks based on the eight different similarity measures, and then compared two different accuracy measures: the first one is the scalability of the similarity algorithm, and the second is the readability of layouts based on clustering.

Since then, more and more bibliometric mapping tools or programs have been developed and employed, including CiteSpace (Chen 2004, 2006), HistCite (Garfield et al. 2006), VOSViewer (van Eck and Waltman 2009, 2010) and SciMAT (Cobo et al. 2011, 2012). These tools and related science mapping techniques have been applied to identify emerging trends and trace evolutionary pathways (Chen et al. 2012, 2014; Huang et al. 2017). Furthermore, mapping and clustering techniques are often used in conjunction with bibliometric and scientometric analyses to provide insights into the structure of a network (regarding, for example, documents, keywords, authors, or journals). Girvan–Newman modularity detection algorithms (Newman and Girvan 2004), VxOrd graph layout algorithm (Klavans and Boyack 2006), Fast unfolding modularity detection algorithms (Blondel et al. 2008), and the VOSViewer mapping technique (van Eck et al. 2010; Waltman et al. 2010) were all developed during this period.

From mapping knowledge domains to science overlap mapping

The emergence and development of science overlap mapping

Knowledge-domain mapping creates an image that shows the development process and the structural relationship of scientific knowledge. Börner et al. (2003) discussed several ways to improve the generation of domain visualizations and their potential interpretations. Based on their view, how to develop more robust and scalable algorithms and how

[2] http://www.nasonline.org/programs/nas-colloquia/completed_colloquia/mapping-knowledge-domains.html.

to employ the domain visualizations to help answer real-world questions are conclude as two primary future exploration directions. Science overlay maps—a visualization method of locating bodies of research within the sciences both at moments of time and dynamically—have attracted wide attention by meeting these two expectations. These readable maps are stable enough to allow "overlaying" publications or references against the background of a stable representation of global science to produce comparisons (Klavans and Boyack 2010). At the same time, they are useful for science policymaking, research and library management to landscape benchmarking, explore collaborations and track temporal changes (Rafols et al. 2010).

Citation patterns allow us to analyze the flow of knowledge and trace the interactions among authors and their roles in science (Moya-Anegón et al. 2004). Rosvall and Bergstrom (2008) pioneered work in science overlap mapping by tracing the flow of 6,434,916 citations among 6128 journals in the sciences and social sciences during 2004. Leydesdorff and Rafols (2009) subsequently used exploratory factor analysis to aggregate the WoS Subject Categories aggregated from the journal–journal citation matrix contained in the Journal Citation Reports (JCR). Their analysis, based on 14 factors, 172 WoS Subject Categories, and 6164 journals, generated interpreted nested maps of the disciplinary structure of science. Such analyses, although imprecise in terms of the attribution of journals to the subject categories, provided a comprehensive and reliable mapping on a large scale and facilitated the emergence of the global science mappings.

Targeting the emerging consensus on the global structure of these mappings, Rafols et al. (2010) formally proposed the term "science overlay maps" and presented a novel approach to visually locate bodies of research within the sciences. This "overlap" technique comprises two essential steps: (1) making a map based on the relations of an element type and (2) "overlaying" each element with information such as the number of articles, growth, etc. The generated map provides an intuitive way to locate or compare positions, shifts, and dissonances in the disciplinary activities at different institutional or thematic levels.

Figure 2 profiles the WoS Category (WC) distribution of research publications on science mapping. Each of the nodes in the map shows one WC representing a sub-discipline. The lines indicate the degree of similarity between two WCs, with darker and thicker lines indicating stronger similarity. The labels and colors display 19 macro-disciplines (groupings of WCs) that were obtained using factor analysis. In this map, the node sizes were proportionally determined based on the logarithm of the number of publication records (in the respective subject category) to keep the visualization readable. As shown, science mapping related studies mostly belong to 'Business & Management' and 'Computer Science', followed by 'Math Methods' and 'Environment Science & Technology'. At the WC level, the most notable category is Information Science & Library Science (507 records, Business & Management), followed by Computer Science, Interdisciplinary Applications (252 records, Computer Science), and Computer Science, Information Systems (158, Computer Science). It is worth mentioning that most of the top 30 influential papers in the field of science mapping on WoS (List in Table 3) are published in the journals allocated the above three WCs.

Carley et al. (2017) revisited previous work on science overlay maps by updating the underlying citation matrix and generating new clusters of scientific disciplines to enhance the visualizations, and then to provide a more accessible way to meet various scientometric applications. Figure 3 visualizes the distribution of cited journals by subject categories among science mapping research publications using the approach proposed by Carley et al. (2017). The definition of the factors presented in this figure is the same as in Fig. 2. It indicates that science mapping research has integrated broad knowledge from 'Computer

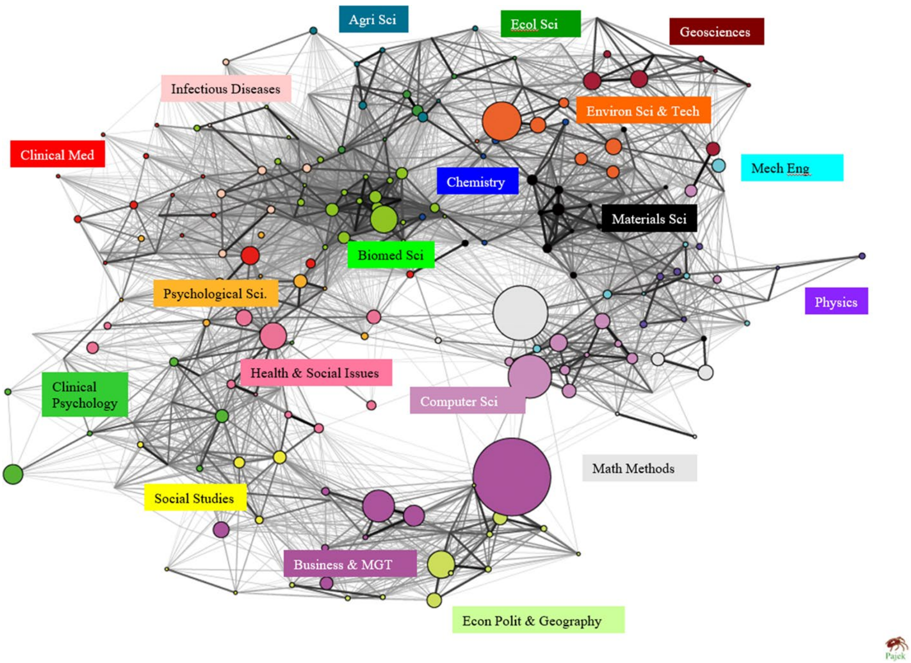


Fig. 2 Publications profiles of science mapping research overlaid on the map of science

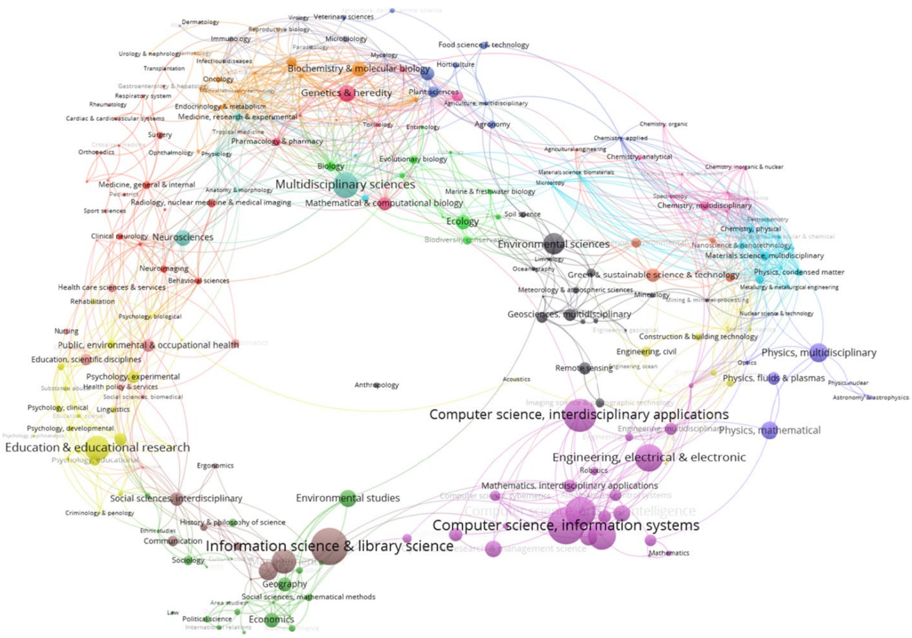


Fig. 3 Subject distribution of cited journals of the science mapping research overlaid on the map of science

Science, Information Systems' (6181 records), 'Information Science & Library Science' (6153 records), 'Computer Science, Interdisciplinary Applications' (4874 records) and 'Computer Science, Artificial Intelligence' (4080 records).

Overlap mapping techniques have been applied to different bibliographic databases (Leydesdorff et al. 2015, 2016), different data types (Kay et al. 2014; Leydesdorff et al. 2014), and has been treated as a tool of "strategic intelligence" to aid in guiding policy-making regarding emerging technologies (Rotolo et al. 2017). In Chen and Leydesdorff (2014), the authors introduced a novel design of dual-map thematic overlays on global maps of science, which can be employed to contrast publication portfolios of multiple comparable units of interest.

Directional and evolutionary science overlay mapping

Most of the current science overlay mappings provide the benchmark landscape of research field distribution during specific periods but cannot track temporal changes and interactions between different research fields. In order to address this issue, we have constructed the global science map based on cross-similarity among the 16 ECOOM major science fields from the revised Leuven-Budapest Classification Scheme (Glänzel and Schubert 2003; revised version: Glänzel et al. 2016)[3] based on individual-document based cross-citation links in the WoS in the period 1999–2018. We then employed the citation-link strength (CLS) to trace information flow characteristics to better understand the internal structure and evolutionary interaction of research fields.

We extracted references for papers indexed in the WoS publication database from 1999 to 2018, capturing nearly 450 million citation links. We pinned subsequent analysis to the approximately 20 million articles that had at least one reference and one citation, and the resulting corpus integrated the disciplinary information for about 34 million articles.

To identify disciplines, we relied on relatively broad categorization (i.e., at the major-field and subfield level) rather than on the 250+ WoS categories. In addition, we still took advantage of the link between the articles and the journal they published, which means each article links to one or more disciplines based on the journal in which it is published. For instance, articles in the Journal of Bacteriology are assigned to microbiology. These links are necessarily imperfect, but at our level of aggregation, they provide an acceptable basis.

We used the bibliometric measures derived from the properties of a complete journal cross-citation matrix rather than bibliographic coupling. The cross-citation matrix shares the similar advantage of bibliographic coupling in that there is no delay in calculating the link between publications or journals as all data needed are present in the database upon publication or indexing (Thijs et al. 2015). Where a cross-citation matrix offers an advantage over bibliographic coupling is in providing the possibility of analyzing the direction of information flows among the units under study (Zhang et al. 2009).

After obtaining all cross-citations between all publications indexed between 1999 and 2018 in WoS, we aggregated the cross-citation matrix of individual publications into journal level, and then into the subject field level through a publication-journal-field classification scheme. The cross-citation interrelation among the 16 ECOOM major fields is

[3] All items extracted from the WoS database have been assigned to 16 broad fields and 74 individual subfields according to the modified Leuven-Budapest classification system (see Table 4).

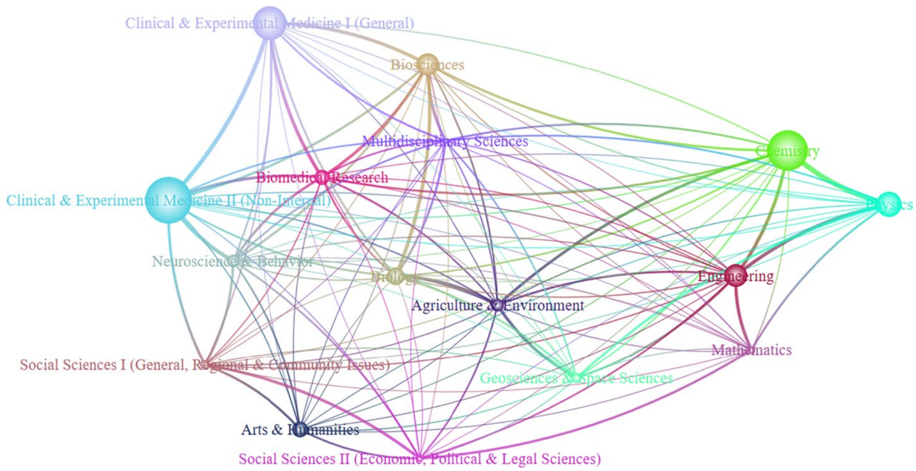


Fig. 4 The cross-citation relationship among the 16 ECOOM major fields excluding subject self-citations (1999–2018)

shown in Fig. 4, where the node sizes are proportional to the number of papers published in each field and the relative width of lines indicates a relatively stronger cross-citation relationship.

We can draw three main findings from Fig. 4 and the cross-citation matrix. First, for most of the major fields, the knowledge flow across their own fields is the most remarkable characteristic, except for the major fields Multidisciplinary Research and Biomedical Research. In other words, an article with references mainly from chemistry typically attracts the largest of citations from other chemistry papers. Second, interdisciplinary interrelations among different fields are quite common: about half of papers that have citation links are linked to other categories. Third, the major fields that share similar knowledge background [e.g., Clinical and Experimental Medicine I (General & Internal Medicine) and Clinical and Experimental Medicine II (Non-Internal Medicine Specialties)] and closely linked fields (e.g., Chemistry and Physics) indicate more cross-citation activities, which meets our expectations.

To better trace the directionality of cross-disciplinary interactions among the above broad fields, we normalized the citation matrix of all subject fields based on the following formula (Zhang et al. 2016).

$$S_{ij} = \frac{c_{ij}}{\sqrt{\left(\mathrm{TC}_i + \mathrm{TR}_i\right)\left(\mathrm{TC}_j + \mathrm{TR}_\mathrm{j}\right)}},$$

where i and j refer to subject fields ($i \neq j$), c_{ij} is equal to the total number of the citations cited from subject fields i to j; TC_k denotes the total number of citations received by subject field k ($k = i, j$) (from other subject fields) and TR_k denotes the total number of citations given by subject field k ($k = i, j$) (to other subject fields).

The citation flow among the 16 ECOOM broad fields between the WoS publications is shown in Fig. 5, where the arrow indicates the direction from knowledge emitter (cited) to knowledge receiver (citing). From Fig. 5, we can deduce the following three findings. First, 'Clinical and Experimental Medicine I (General & Internal)', 'Clinical and Experimental

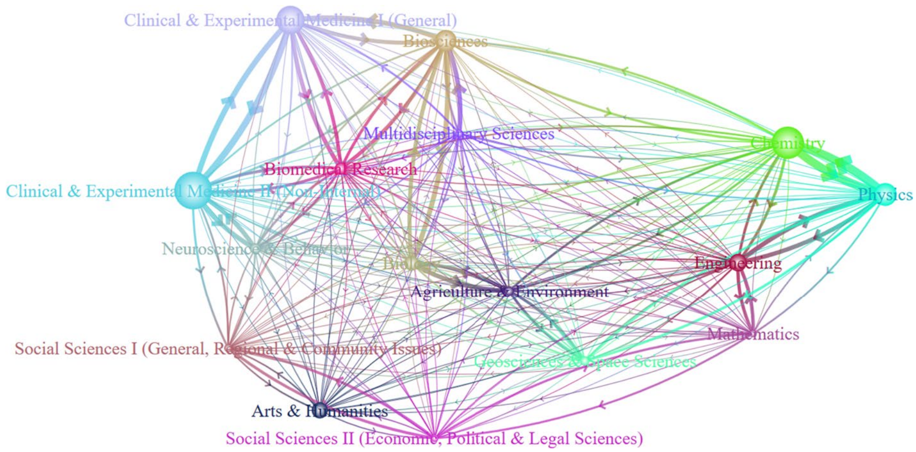


Fig. 5 The interactive citation flow among the 16 ECOOM major fields in the period 1999–2018

Medicine II (Non-internal Medicine)', and 'Chemistry' are the three subject fields with the most publications in WoS between 1999 and 2018. Second, the interactive citation relation between 'Chemistry' and 'Physics' is the most prevailing, which reveals the close knowledge integration between these two traditional fields. The relations between 'Clinical and Experimental Medicine I (General & Internal)' and 'Clinical and Experimental Medicine II (Non-internal Medicine)', 'Clinical and Experimental Medicine I (General & Internal)' and 'Bioscience', 'Biology' and 'Bioscience', 'Agriculture & Environment' are also prominent. Third, there are some notable imbalances in the flow of knowledge; for example, 'Multidisciplinary Science' contributes more citations to 'Biosciences' than it receives.

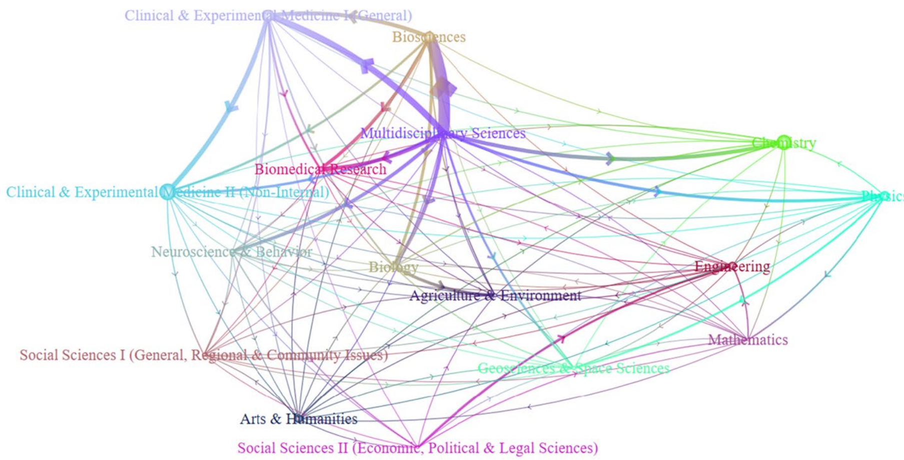
In order to better understand the internal structure and evolutionary interaction of research fields, we employ the citation-link strength (CLS) to trace the information flow characteristics. The formula is defined as follows (Zhang et al. 2009).

$$\mathrm{CLS}_{ij} = \frac{c_{ij}}{\sqrt{\mathrm{TC}_i * \mathrm{TR}_j}},$$

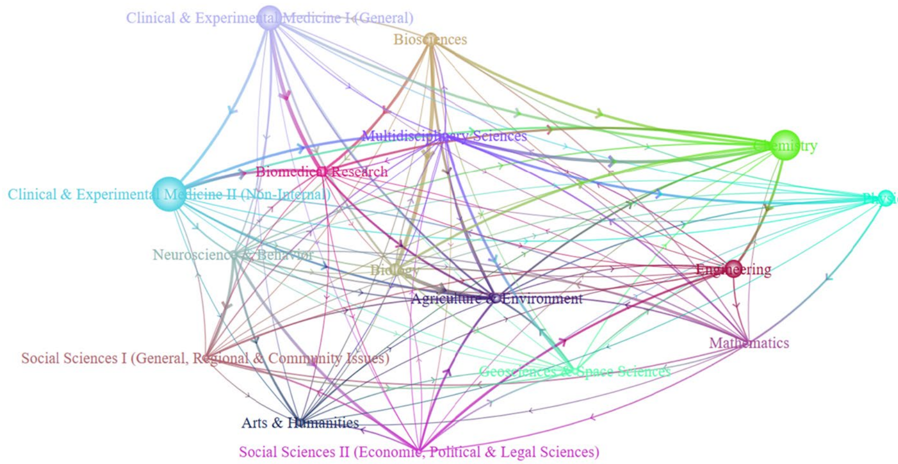
where i and j refer to subject fields ($i \neq j$), TC_i is the total number of citations of subject fields i, TR_j the total number of references of subject fields j and c_{ij} is the number of citations of subject fields i receives from subject fields j. This indicator measures the strength of the citation links between two subject fields in the asymmetric matrix, which are directional as a citation from subject field i to subject field j differs from a citation from j to i.

The analysis of the direction of knowledge flow among different subject fields provides a macro-level view, and the knowledge flow among different 16 ECOOM major fields between 1999 and 2003 and 2014 and 2018, respectively, are visualized in Fig. 6a, b. The thickness of lines is proportional to the value of CLS_{ij}–CLS_{ji} between each two pairs of fields i and j, and the size of the nodes is set proportional to the number of documents in the respective field.

Some interesting findings can be concluded from the visualization in Fig. 6. First, 'Multidisciplinary Sciences' was always the "contributor" that had the most pronounced asymmetric links with other fields, which is mainly due to the large and influential multidisciplinary



(a) between 1999 and 2003



(b) between 2014 and 2018

Fig. 6 The direction of knowledge flow among the 16 ECOOM major fields **a** between 1999 and 2003; **b** between 2014 and 2018

journals (e.g., *Nature*, *Science, PNS US*, *PLoS ONE*, etc). Second, the distribution of knowledge flow becomes more balanced from the first period to the second, and the interactive trends of knowledge flow become more apparent. For example, 'Biosciences' no longer heavily relies on knowledge absorption from 'Multidisciplinary Sciences', while the citation flows among the subject fields in social sciences and natural sciences have become stronger.

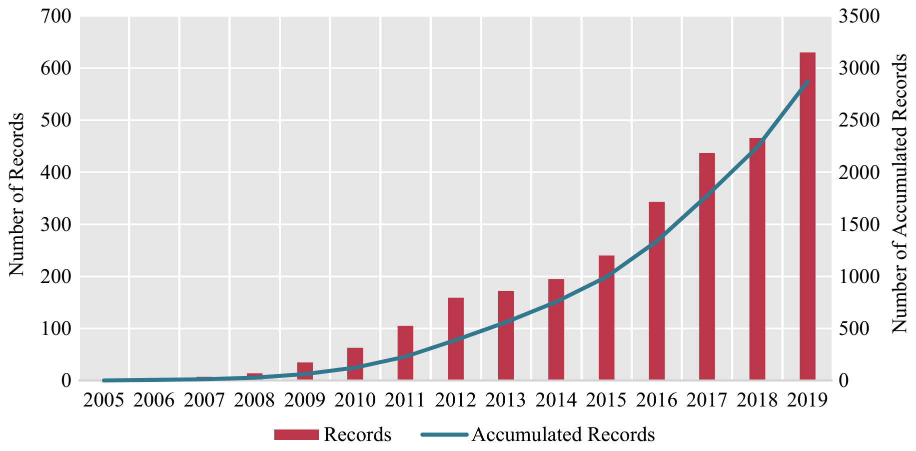


Fig. 7 The publication trends of science mapping research in CNKI

Mapping knowledge domains in China and Zeyuan Liu

Unlike the international research output on science mapping studies, the Chinese scientometrics community was not engaged in explorative studies in science mapping until 2005, when Zeyuan Liu and his team at WISE[4] Lab of Dalian University of Technology first introduced mapping knowledge domains and information visualization to the scientific community in China. In 2008, Chaomei Chen, the pioneer of science mapping research and developer of CiteSpace, was employed as the Chang Jiang Scholar at the Dalian University of Technology. Subsequently, Zeyuan Liu and Chaomei Chen established the Joint-Institute for the Study of Knowledge Visualization and Science Discovery, Dalian University of Technology (China)-Drexel University (USA), to promote the development of science mapping research.

We conducted a search for science mapping related scientific papers using the search query "TS = science mapping (知识图谱/知识地图)" in CNKI (Chinese National Knowledge Infrastructure), which is the largest continuously updated database of Chinese journals in the world. We restricted the obtained document set to papers published in the journals of the Chinese Social Sciences Citation Index (CSSCI) and the "A Guide to the Core Journals of China" (GCJC), two influential lists in the journal evaluation system in China (Huang et al. 2020). All retrieved publications were manually checked, and not relevant publications were removed. The final corpus comprises 2872 publications between 2005 and 2019, with the annual trend of science mapping research in CNKI shown in Fig. 7 indicates a clear growth trend.

A close look at these records reveals that Liu was the most productive author on this topic, publishing 34 papers during this period. He was also the author of 5 of the 15 most frequently cited papers in the field of mapping knowledge domain on CNKI listed in Table 2. The paper entitled "The methodology function of CiteSpace mapping knowledge domains" was selected into "The 4th China Association for Science and Technology (CAST) Outstanding Science and Technology Paper Program", which aimed to select the most outstanding papers published in Chinese journals during 2015–2019.

4 The 'WISE' is the abbreviation for Webometrics, Informetrics, Scientometrics, and Econometrics.

Table 2 The 15 most highly cited paper in the field of Mapping Knowledge Domain on CNKI

No.	Title	Authors	Journal name	Year	Citations	Download
1	The methodology function of CiteSpace mapping knowledge domains	Chen Yue; Chen Chaomei; **Liu Zeyuan**; Hu Zhigang; Wang Xianwen	Studies in Science of Science	2015	1381	33741
2	The rise of mapping knowledge domains	Chen Yue; **Liu Zeyuan**	Studies in Science of Science	2005	772	7737
3	Knowledge graph construction techniques	Liu Qiao; Li Yang; Duan Hong; Liu Yao; Qin Zhiguang	Journal of Computer Research and Development	2016	482	24109
4	History and theory of mapping knowledge domains	Chen Yue; **Liu Zeyuan**; Chen Jin; Hou Jianhua	Studies in Science of Science	2008	370	7278
5	Mapping knowledge domain: a new field of information management and knowledge management	Qin Changjiang; Hou Hanqing	Journal of Academic Libraries	2009	319	8447
6	The knowledge map of the evolution and research frontiers of the bibliometrics	Zhao Rongying; Xu Limin	Journal of Library Science in China	2010	310	9859
7	Review on the application of CiteSpace at home and abroad	Hou Jianhua; Hu Zhigang	Journal of Modern Information	2013	296	8055
8	Review on knowledge graph techniques	Xu Zenglin; Sheng Yongpan; He Lirong; Wang Yafang	Journal of University of Electronic Science and Technology of China	2016	253	10251
9	Mapping of science studies: the trend of research fronts	Hou Haiyan; **Liu Zeyuan**; Chen Yue; Jiang Chunlin; Yin Lichun	Science Research Management	2006	249	3937
10	Review of development and application of Delphi method in China: one of series papers of Nanjing university knowledge mapping research group	Yuan Qinjian; Zong Qianjin; Shen Hongzhou	Journal of Modern Information	2011	223	4411
11	Research review on application of knowledge mapping in China	Hu Zewen; Sun Jianjun; Wu Yishan	Library and Information Service	2013	222	13237
12	Innovation ecosystem: origin, knowledge evolution and theoretical framework	Mei Liang; Chen Jin; Liu Yang	Studies in Science of Science	2014	216	10,961
13	Knowledge representation learning: A review	Liu Zhiyuan; Sun Maosong; Lin Yankai; Xie Ruobing	Journal of Computer Research and Development	2016	202	6199

Table 2 (continued)

No.	Title	Authors	Journal name	Year	Citations	Download
14	The knowledge mapping of domestic ecological security research: a bibliometric analysis based on CiteSpace	Qin Xiaonan; Lu Xiaoli; Wu Chunyou	Acta Ecologica Sinica	2014	202	11324
15	Quantitative analysis on the research front of international scientometrics based on mapping of knowledge	Hou Haiyan; **Liu Zeyuan**; Luan Chunjuan	Science Research Management	2009	192	3240

All the above publications are written in Chinese. The data of "download" and "citations" are updated on July 28, 2020

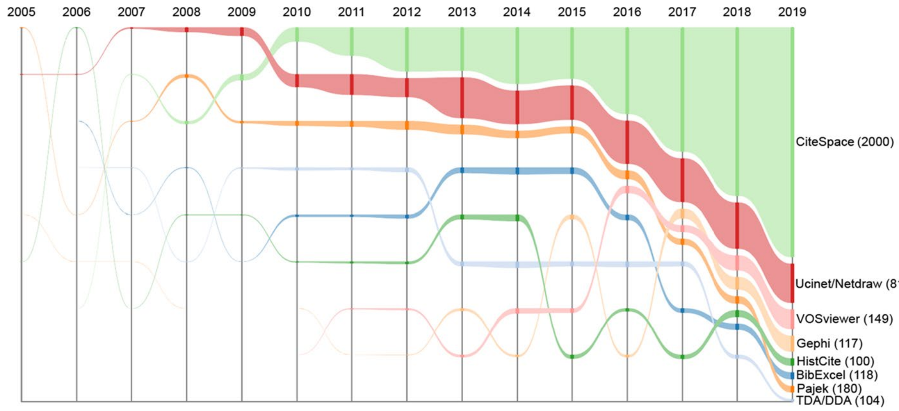


Fig. 8 Number of publications on the bibliometric mapping software tools by year

In addition to science mapping research, the related bibliometric mapping tools have become popular in China since 2005. We selected 11 bibliometric software tools [Bibexcel, CitNetExplorer, CiteSpace, Derwent Data Analyzer (DDA)/Thomson Data Analyzer (TDA), Gephi, HistCite, SciMAT, Sci2 Tool, Pajek, Ucinet/Netdraw, and VOSViewer] as candidates for further analysis. We then searched CNKI journal papers indexed in the CSSCI and GCJC databases, which mentioned these tools in the title, keywords, or abstract fields. The top 8 software tools referred to in more than 100 publications are presented in Fig. 8 (36, 8 and 3 publications discussed or employed Sci2 Tool, SciMAT, and CitNetExplorer, respectively). In contrast to the findings by Pan et al. (2018), who concluded that VOSViewer is more frequently used than CiteSpace and HistCite by searching WoS for English-language journal papers, CiteSpace appears to be the most popular bibliometric mapping software in the Chinese scientific community, followed by Ucinet/Netdraw and VOSViewer. The popular application of CiteSpace is largely due to the promotion conducted by the joint-Institute lead by Zeyuan Liu and Chaomei Chen, who hosted several workshops on mapping knowledge domains since 2009.

In addition to promoting the application of science mapping tool, Liu and his team published a series of books to introduce the theory and applications in various fields. One of the most influential books is "Mapping Knowledge Domains: Methods and Application" (Liu et al. 2008), which systematically describes the principles and methods of scientific knowledge mapping and their application to disciplinary frontiers and scientific and technological cooperation fields. The book provides an in-depth exploration and analysis of the development of scientific disciplines, the detection of knowledge frontiers, and the laws of scientific cooperation, representing pioneering scientometric work in China. Besides, Liu edited a series entitled "Knowledge Metrics and Knowledge mapping" in 2008 (volume 1) and 2012 (volume 2). This series includes 10 books, whose topics range from mapping knowledge domains in specific fields (e.g., citation analysis, technology innovation frontiers, management science, science of science, scientometrics), bibliometrics analysis of scientific collaboration and output, evaluation and management of tacit knowledge, patentometrics and patent strategy/patent system, and spatial metrics of regional S&T, etc.

Another notable contribution of Liu is introducing knowledge mapping to explore the structure of technological science and their interactions with natural science and engineering technology. In the masterpiece "Mapping of fronts of technological sciences and china strategy" (Liu et al. 2012a, b), Liu and his team combined mapping knowledge domain and expert consultation to depict a series of knowledge mappings in nine major technological science fields. These maps are beneficial to trace the development of emerging frontiers and then offer decision support for national S&T policies and R&D strategies.

Final words

The question of how to scientifically, systematically and accurately analyze the structure and dynamics of scientific knowledge has become a focal point in bibliometric studies. Researchers have proposed a variety of methods, techniques and software applications to facilitate the analysis. Solutions extend from clustering methods in complex networks to adopting network topology features for monitoring the evolution of scientific structure, and there has been much improvement in both bibliometric methods and computer-science based algorithms to depict the structure and evolution of science in a more profound and accurate manner.

Most of the current science overlay mappings provide the benchmark landscape of subject distribution during specific periods but still cannot track the temporal changes and interactions across research fields. We first constructed the global science map based on cross-similarity among the 16 ECOOM major fields, and then employed citation-link strength (CLS) to trace the information flow characteristics to better understand the internal structure and evolutionary interrelations of research fields. Enhanced science overlap mappings like these can be used to trace the diffusion of a research topic across disciplines, model the evolution over time of cross-disciplinary citations, and explore the multidisciplinary knowledge flow and dynamic patterns.

The bibliometric analysis of publications in CNKI and literature review of published on science mapping research confirms that Liu has made significant contributions to promoting and applying the concept and tools of science mapping in Chinese academic circles. He is the pioneer who first introduced the mapping knowledge domains to the scientific community in China, and he is an outstanding researcher who employed the science mapping approach to technological science, rather than merely scientometrics and science of science. Unfortunately, most current publications on mapping knowledge domains in China merely employ science mapping techniques to various fields (not limited to Information Science, Science of Science and Management) rather than make a novel contribution to this field. In addition, these knowledge visualization tools are "abused" and "misused" seriously because some researchers lack sufficient understanding of the methodology function of mapping knowledge. We hope more and more Chinese scholars contribute novel techniques, practical algorithms, and inspiring explorations to science mapping research. Such efforts would be an adequate tribute to the memory of Zeyuan Liu.

Acknowledgements This work is supported by the National Natural Science Foundation of China (Grant Nos. 72004169; 71974150; 71573085; 71904096), the National Social Science Foundation of China (Grant No. 18VSJ087), and the National Laboratory Center for Library and Information Science in Wuhan University. We also thank Dr. Yuqin Liu, who provides the license of the powerful visualization tool—ITGInsight.

Appendix

See Tables 3 and 4.

Table 3 The top 30 influential papers in the field of science mapping in WoS

No.	Title	Authors (full name)	Publication name	Year	LCS	GCS
1	Bibliographic coupling between scientific papers	Kessler, Myer M.	American Documentation	1963	53	812
2	Networks of scientific papers	Price, Derek J. deSolla	Science	1965	53	1603
3	Co-citation in scientific literature: New measure of relationship between two documents	Small, Henry	Journal of The American Society for Information Science	1973	106	1607
4	Structure of scientific literatures 1: Identifying and graphing specialties	Small, Henry; Griffith, Belver C	Science Studies	1974	44	506
5	Centrality in social networks conceptual clarification	Freeman, Linton C.	Social Networks	1979	47	6921
6	Author co-citation: A literature measure of intellectual structure	White, Howard D.; Griffith, Belver C.	Journal of The American Society for Information Science	1981	41	594
7	From translations to problematic networks: An introduction to co-word analysis	Callon, Michel; Courtial, Jean-Pierre; Turner, William A.; Bauin, Serge	Social Science Information	1983	61	452
8	Mapping authors in intellectual space: A technical overview	McCain, Katherine W.	Journal of The American Society for Information Science	1990	35	459
9	Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemistry	Callon, Michel; Courtial, Jean-Pierre; Laville, Françoise	Scientometrics	1991	63	408
10	Co-word-based science maps of chemical-engineering 1: Representations by direct multidimensional-scaling	Peters, H. P. F.; van Raan, Anthony FJ	Research Policy	1993	41	119
11	Visualizing a discipline: An author co-citation analysis of information science, 1972-1995	White, Howard D.; McCain, Katherine W.	Journal of The American Society for Information Science	1998	44	694
12	Software engineering as seen through its research literature: A study in co-word analysis	Coulter, Neal S.; MonarchIra, Ira; Konda, Suresh	Journal of The American Society for Information Science	1998	37	194
13	Visualizing science by citation mapping	Small, Henry	Journal of The American Society for Information Science	1999	71	399

Table 3 (continued)

No.	Title	Authors (full name)	Publication name	Year	LCS	GCS
14	Visualizing knowledge domains	Börner, Katy; Chen, Chaomei; Boyack, Kevin W.	Annual Review of Information Science and Technology	2003	79	552
15	Bursty and Hierarchical Structure in Streams	Kleinberg, Jon	Data Mining and Knowledge Discovery volume	2003	41	375
16	Searching for intellectual turning points: Progressive knowledge domain visualization	Chen, Chaomei	Proceedings of The National Academy of Sciences of The United States of America	2004	37	416
17	Mapping the backbone of science	Boyack, Kevin W.; Klavans, Richard; Börner, Katy	Scientometrics	2005	65	453
18	An index to quantify an individual's scientific research output	Hirsch, Jorge E.	Proceedings of The National Academy of Sciences of The United States of America	2005	40	4501
19	Citespace II: Detecting and visualizing emerging trends and transient patterns in scientific literature	Chen, Chaomei	Journal of The American Society for Information Science and Technology	2006	90	980
20	A global map of science based on the ISI subject categories	Leydesdorff, Loet; Rafols, Ismael	Journal of The American Society for Information Science and Technology	2009	56	320
21	How to normalize cooccurrence data? An analysis of some well-known similarity measures	van Eck, Nees Jan; Waltman, Ludo	Journal of The American Society for Information Science and Technology	2009	35	208
22	Software survey: Vosviewer, a computer program for bibliometric mapping	van Eck, Nees Jan; Waltman, Ludo	Scientometrics	2010	101	1399
23	The structure and dynamics of co-citation clusters: A multiple-perspective co-citation analysis	Chen, Chaomei; Ibekwe-SanJuan, Fidelia; Hou, Jianhua	Journal of The American Society for Information Science and Technology	2010	45	306
24	Science overlay maps: A new tool for research policy and library management	Rafols, Ismael; Porter, Alan L.; Leydesdorff, Loet	Journal of The American Society for Information Science and Technology	2010	40	224
25	A unified approach to mapping and clustering of bibliometric networks	Waltman, Ludo; van Eck, Nees Jan; Noyons, Ed C. M.	Journal of Informetrics	2010	37	357
26	Co-citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately?	Boyack, Kevin W.; Klavans, Richard	Journal of The American Society for Information Science and Technology	2010	29	335

Table 3 (continued)

No.	Title	Authors (full name)	Publication name	Year	LCS	GCS
27	Science mapping software tools: Review, analysis, and cooperative study among tools	Cobo, Manuel J.; López-Herrera, Antonio G.; Herrera-Viedma, Enrique; Herrera, Francisco	Journal of The American Society for Information Science and Technology	2011	71	397
28	An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the fuzzy sets theory field	Cobo, Manuel J.; López-Herrera, Antonio G.; Herrera-Viedma, Enrique; Herrera, Francisco	Journal of Informetrics	2011	45	182
29	Emerging trends in regenerative medicine: a scientometric analysis in CiteSpace	Chen, Chaomei; Hu, Zhigang; Liu, Shengbo; Tseng, Hung	Expert Opinion on Biological Therapy	2012	77	186
30	Emerging trends and new developments in regenerative medicine: a scientometric update (2000–2014)	Chen, Chaomei; Dubin, Rachael; Kim, Meen C.	Expert Opinion on Biological Therapy	2014	46	93

Global Citation Score (GCS) shows the total number of citations to a paper in WoS Core Collection; Local Citation Score (LCS) shows the count of citations to a paper within the collection

Table 4 Leuven-Budapest Classification Scheme for the Sciences, Social Sciences and Humanities

0. Multidisciplinary Sciences		C. Chemistry	
X0	Multidisciplinary Sciences	C0	Multidisciplinary Chemistry
A. Agriculture & Environment		C1	Analytical, Inorganic & Nuclear Chemistry
A1	Agricultural Science & Technology	C2	Applied Chemistry & Chemical Engineering
A2	Plant & Soil Science & Technology	C3	Organic & Medicinal Chemistry
A3	Environmental Science & Technology	C4	Physical Chemistry
A4	Food & Animal Science & Technology	C5	Polymer Science
Z. Biology (Organismic & Supraorganismic Level)		C6	Materials Science
Z1	Animal Sciences	P. Physics	
Z2	Aquatic Sciences	P0	Multidisciplinary Physics
Z3	Microbiology	P1	Applied Physics
Z4	Plant Sciences	P2	Atomic, Molecular & Chemical Physics
Z5	Pure & Applied Ecology	P3	Classical Physics
Z6	Veterinary Sciences	P4	Mathematical & Theoretical Physics
B. Biosciences (General, Cellular & Subcellular Biology; Genetics)		P5	Particle & Nuclear Physics
B0	Multidisciplinary Biology	P6	Physics of Solids, Fluids, and Plasmas
B1	Biochemistry/Biophysics/Molecular Biology	G. Geosciences & Space Sciences	
B2	Cell Biology	G1	Astronomy & Astrophysics
B3	Genetics & Developmental Biology	G2	Geosciences & Technology
R. Biomedical Research		G3	Hydrology/Oceanography
R1	Anatomy & Pathology	G4	Meteorology/Atmospheric & Aerospace Science & Technology
R2	Biomaterials & Bioengineering	G5	Mineralogy & Petrology
R3	Experimental/Laboratory Medicine	E. Engineering	
R4	Pharmacology & Toxicology	E1	Computer Science/Information Technology
R5	Physiology	E2	Electrical & Electronic Engineering
I. Clinical and Experimental Medicine I (General & Internal Medicine)		E3	Energy & Fuels
I1	Cardiovascular & Respiratory Medicine	E4	General & Traditional Engineering
I2	Endocrinology & Metabolism	H. Mathematics	
I3	General & Internal Medicine	H1	Applied Mathematics
I4	Hematology & Oncology	H2	Pure Mathematics
I5	Immunology	Y. Social Sciences I (General, Regional & Community Issues)	
M. Clinical and Experimental Medicine II (Non-Internal Medicine Specialties)		Y1	Education, Media & Information Science
M1	Age & Gender-Related Medicine	Y2	Sociology & Anthropology
M2	Dentistry	Y3	Community & Social Issues
M3	Dermatology/Urogenital System	L. Social Sciences II (Economic, Political & Legal Sciences)	
M4	Ophthalmology/Otolaryngology	L1	Business, Economics, Planning
M5	Paramedicine	L2	Political Science & Administration
M6	Psychiatry & Neurology	L3	Law
M7	Radiology & Nuclear Medicine	K. Arts & Humanities	
M8	Rheumatology/Orthopedics	K0	Multidisciplinary

Table 4 (continued)

M9	Surgery	K1	Arts & Design
N. Neuroscience & Behavior		K2	Architecture
N1	Neurosciences & Psychopharmacology	K3	History & Archaeology
N2	Psychology & Behavioral Sciences	K4	Philosophy & Religion
		K5	Linguistics
		K6	Literature

References

Ahlgren, P., Jarneving, B., & Rousseau, R. (2003). Requirements for a cocitation similarity measure, with special reference to Pearson's correlation coefficient. *Journal of the American Society for Information Science and Technology, 54*(6), 550–560. https://doi.org/10.1002/asi.10242.

Blondel, V. D., Guillaume, J.-L., Lambiotte, R., & Lefebvre, E. (2008). Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment, 2008*(10), P10008. https://doi.org/10.1088/1742-5468/2008/10/p10008.

Börner, K., Chen, C., & Boyack, K. W. (2003). Visualizing knowledge domains. *Annual Review of Information Science and Technology, 37*(1), 179–255. https://doi.org/10.1002/aris.1440370106.

Boyack, K. W. (2004). Mapping knowledge domains: Characterizing PNAS. *Proceedings of the National Academy of Sciences, 101*(suppl 1), 5192–5199. https://doi.org/10.1073/pnas.0307509100.

Boyack, K., & Klavans, R. (2010). Co-citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately? *Journal of the American Society for Information Science and Technology, 61*(12), 2389–2404. https://doi.org/10.1002/asi.21419.

Boyack, K. W., Klavans, R., & Börner, K. (2005). Mapping the backbone of science. *Scientometrics, 64*(3), 351–374. https://doi.org/10.1007/s11192-005-0255-6.

Braam, R. R., Moed, H. F., & van Raan, A. F. J. (1991). Mapping of science by combined co-citation and word analysis. I. Structural aspects. *Journal of the American Society for Information Science, 42*(4), 233–251. https://doi.org/10.1002/(sici)1097-4571(199105)42:4%3c233:aid-asi1%3e3.0.co;2-i.

Callon, M., Courtial, J.-P., & Laville, F. (1991). Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemistry. *Scientometrics, 22*(1), 155–205. https://doi.org/10.1007/BF02019280.

Callon, M., Courtial, J.-P., Turner, W. A., & Bauin, S. (1983). From translations to problematic networks: An introduction to co-word analysis. *Social Science Information, 22*(2), 191–235. https://doi.org/10.1177/053901883022002003.

Callon, M., Rip, A., & Law, J. (1986). *Mapping the dynamics of science and technology: Sociology of science in the real world*. London: Springer.

Carley, S., Porter, A. L., Rafols, I., & Leydesdorff, L. (2017). Visualization of disciplinary profiles: Enhanced science overlay maps. *Journal of Data and Information Science, 2*(3), 68–111. https://doi.org/10.1515/jdis-2017-0015.

Chen, C. (2003). *Mapping scientific frontiers: The quest for knowledge visualization*. London: Springer.

Chen, C. (2004). Searching for intellectual turning points: Progressive knowledge domain visualization. *Proceedings of the National Academy of Sciences, 101*(suppl 1), 5303–5310. https://doi.org/10.1073/pnas.0307513100.

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology, 57*(3), 359–377. https://doi.org/10.1002/asi.20317.

Chen, C. (2017). Science mapping: A systematic review of the literature (review). *Journal of Data and Information Science, 2*(2), 1–40. https://doi.org/10.1515/jdis-2017-0006.

Chen, C., Dubin, R., & Kim, M. C. (2014). Emerging trends and new developments in regenerative medicine: A scientometric update (2000–2014). *Expert Opinion on Biological Therapy, 14*(9), 1295–1317. https://doi.org/10.1517/14712598.2014.920813.

Chen, C., Hu, Z., Liu, S., & Tseng, H. (2012). Emerging trends in regenerative medicine: A scientometric analysis in CiteSpace. *Expert Opinion on Biological Therapy, 12*(5), 593–608. https://doi.org/10.1517/14712598.2012.674507.

Chen, C., & Leydesdorff, L. (2014). Patterns of connections and movements in dual-map overlays: A new method of publication portfolio analysis. *Journal of the Association for Information Science and Technology, 65*(2), 334–351. https://doi.org/10.1002/asi.22968.

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *Journal of Informetrics, 5*(1), 146–166. https://doi.org/10.1016/j.joi.2010.10.002.

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2012). SciMAT: A new science mapping analysis software tool. *Journal of the American Society for Information Science and Technology, 63*(8), 1609–1630. https://doi.org/10.1002/asi.22688.

de Solla Price, D. J. (1965). Networks of Scientific Papers. *Science, 149*(3683), 510–515. https://doi.org/10.1126/science.149.3683.510.

Egghe, L. (2006). Theory and practise of the g-index. *Scientometrics, 69*(1), 131–152. https://doi.org/10.1007/s11192-006-0144-7.

Fortunato, S., Bergstrom, C. T., Börner, K., Evans, J. A., Helbing, D., Milojević, S., et al. (2018). Science of science. *Science*. https://doi.org/10.1126/science.aao0185.

Freeman, L. C. (1978). Centrality in social networks conceptual clarification. *Social Networks, 1*(3), 215–239. https://doi.org/10.1016/0378-8733(78)90021-7.

Garfield, E., Paris, S. W., & Stock, W. G. (2006). HistCite™: A software tool for informetric analysis of citation linkage. *Information Wissenschaft und Praxis, 57*(8), 391–400.

Garfield, E., Sher, I. H., & Torpie, R. J. (1964). *The use of citation data in writing the history of science*. Philadelphia: Institute for Scientific Information.

Glänzel, W. (2012). The role of core documents in bibliometric network analysis and their relation with h-type indices. *Scientometrics, 93*(1), 113–123. https://doi.org/10.1007/s11192-012-0639-3.

Glänzel, W., & Czerwon, H. J. (1996). A new methodological approach to bibliographic coupling and its application to the national, regional and institutional level. *Scientometrics, 37*(2), 195–221. https://doi.org/10.1007/BF02093621.

Glänzel, W., Janssens, F., Speybroeck, S., Schubert, A., Thijs, B., & Rafols, I. (2006). Towards a bibliometrics-aided data retrieval for scientometric purposes. In *Book of abstracts of the 9th international conference on science and technology indicators*. Leuven, Belgium, 7–9 September 2006, pp. 206–208.

Glänzel, W., Janssens, F., & Thijs, B. (2009). A comparative analysis of publication activity and citation impact based on the core literature in bioinformatics. *Scientometrics, 79*(1), 109–129. https://doi.org/10.1007/s11192-009-0407-1.

Glänzel, W., & Schubert, A. (2003). A new classification scheme of science fields and subfields designed for scientometric evaluation purposes. *Scientometrics, 56*(3), 357–367. https://doi.org/10.1023/A:1022378804087.

Glänzel, W., & Thijs, B. (2017). Using hybrid methods and 'core documents' for the representation of clusters and topics: The astronomy dataset. *Scientometrics, 111*(2), 1071–1087. https://doi.org/10.1007/s11192-017-2301-6.

Glänzel, W., Thijs, B., & Chi, P.-S. (2016). The challenges to expand bibliometric studies from periodical literature to monographic literature with a new data source: The book citation index. *Scientometrics, 109*(3), 2165–2179. https://doi.org/10.1007/s11192-016-2046-7.

Griffith, B. C., Small, H. G., Stonehill, J. A., & Dey, S. (1974). The structure of scientific literatures II: Toward a macro- and microstructure for science. *Science Studies, 4*(4), 339–365. https://doi.org/10.1177/030631277400400402.

Hirsch, J. E. (2005). An index to quantify an individual's scientific research output. *Proceedings of the National Academy of Sciences of the United States of America, 102*(46), 16569–16572. https://doi.org/10.1073/pnas.0507655102.

Huang, Y., Li, R., Zhang, L., & Sivertsen, G. (2021). A comprehensive analysis of the journal evaluation system in China. *Quantitative Science Studies*. https://doi.org/10.31235/osf.io/7cfxd.

Huang, Y., Schuehle, J., Porter, A. L., & Youtie, J. (2015). A systematic method to create search strategies for emerging technologies based on the Web of Science: Illustrated for 'Big Data'. *Scientometrics, 105*(3), 2005–2022. https://doi.org/10.1007/s11192-015-1638-y.

Huang, Y., Zhu, D., Qian, Y., Zhang, Y., Porter, A. L., Liu, Y., et al. (2017). A hybrid method to trace technology evolution pathways: A case study of 3D printing. *Scientometrics, 111*(1), 185–204. https://doi.org/10.1007/s11192-017-2271-8.

Kay, L., Newman, N., Youtie, J., Porter, A. L., & Rafols, I. (2014). Patent overlay mapping: Visualizing technological distance. *Journal of the Association for Information Science and Technology, 65*(12), 2432–2443. https://doi.org/10.1002/asi.23146.

Kessler, M. M. (1963). Bibliographic coupling between scientific papers. *American Documentation, 14*(1), 10–25. https://doi.org/10.1002/asi.5090140103.

Klavans, R., & Boyack, K. W. (2006). Quantitative evaluation of large maps of science. *Scientometrics, 68*(3), 475–499. https://doi.org/10.1007/s11192-006-0125-x.
Klavans, R., & Boyack, K. W. (2010). Toward an objective, reliable and accurate method for measuring research leadership. *Scientometrics, 82*(3), 539–553. https://doi.org/10.1007/s11192-010-0188-6.
Leydesdorff, L., de Moya-Anegón, F., & de Nooy, W. (2016). Aggregated journal–journal citation relations in scopus and web of science matched and compared in terms of networks, maps, and interactive overlays. *Journal of the Association for Information Science and Technology, 67*(9), 2194–2211. https://doi.org/10.1002/asi.23372.
Leydesdorff, L., de Moya-Anegón, F., & Guerrero-Bote, V. P. (2015). Journal maps, interactive overlays, and the measurement of interdisciplinarity on the basis of Scopus data (1996–2012). *Journal of the Association for Information Science and Technology, 66*(5), 1001–1016. https://doi.org/10.1002/asi.23243.
Leydesdorff, L., Kushnir, D., & Rafols, I. (2014). Interactive overlay maps for US patent (USPTO) data based on International Patent Classification (IPC). *Scientometrics, 98*(3), 1583–1599. https://doi.org/10.1007/s11192-012-0923-2.
Leydesdorff, L., & Rafols, I. (2009). A global map of science based on the ISI subject categories. *Journal of the American Society for Information Science and Technology, 60*(2), 348–362. https://doi.org/10.1002/asi.20967.
Liu, Z., Chen, Y., & Hou, H. (2008). *Mapping knowledge domains: Methods and application*. Beijing: People's Publishing House. **(In Chinese)**.
Liu, Z., Chen, Y., & Hou, H. (2012a). *Mapping of fronts of technological sciences and China strategy*. Beijing: People's Publishing House. **(In Chinese)**.
Liu, X., Glänzel, W., & De Moor, B. (2012b). Optimal and hierarchical clustering of large-scale hybrid networks for scientific mapping. *Scientometrics, 91*(2), 473–493. https://doi.org/10.1007/s11192-011-0600-x.
Marshakova, I. V. (1973). System of connections between documents based on references (as the Science Citation Index). *Nauchno-Tekhnicheskaya Informatsiya, Seriya, 2*(6), 3–8. **(In Russian)**.
McCain, K. W. (1990). Mapping authors in intellectual space: A technical overview. *Journal of the American Society for Information Science, 41*(6), 433–443. https://doi.org/10.1002/(sici)1097-4571(199009)41:6%3c433:Aid-asi11%3e3.0.Co;2-q.
Moya-Anegón, F., Vargas-Quesada, B., Herrero-Solana, V., Chinchilla-Rodríguez, Z., Corera-Álvarez, E., & Munoz-Fernández, F. J. (2004). A new technique for building maps of large scientific domains based on the co-citation of classes and categories. *Scientometrics, 61*(1), 129–145. https://doi.org/10.1023/B:SCIE.0000037368.31217.34.
Newman, M. E. J., & Girvan, M. (2004). Finding and evaluating community structure in networks. *Physical Review E, 69*(2), 026113. https://doi.org/10.1103/PhysRevE.69.026113.
Ni, C., Sugimoto, C., & Jiang, J. (2011) 'Degree, closeness, and betweenness: Application of group centrality measurements to explore macro-disciplinary evolution diachronically' *Proceedings of ISSI*, pp. 1–13.
Pan, X., Yan, E., Cui, M., & Hua, W. (2018). Examining the usage, citation, and diffusion patterns of bibliometric mapping software: A comparative study of three tools. *Journal of Informetrics, 12*(2), 481–493. https://doi.org/10.1016/j.joi.2018.03.005.
Peters, H. P., & van Raan, A. F. (1993a). Co-word-based science maps of chemical engineering. Part I: Representations by direct multidimensional scaling. *Research Policy, 22*(1), 23–45. https://doi.org/10.1016/0048-7333(93)90031-c.
Peters, H. P., & van Raan, A. F. (1993b). Co-word-based science maps of chemical engineering. Part II: Representations by combined clustering and multidimensional scaling. *Research Policy, 22*(1), 47–71. https://doi.org/10.1016/0048-7333(93)90032-d.
Rafols, I., Porter, A. L., & Leydesdorff, L. (2010). Science overlay maps: A new tool for research policy and library management. *Journal of the American Society for Information Science and Technology, 61*(9), 1871–1887. https://doi.org/10.1002/asi.21368.
Rosvall, M., & Bergstrom, C. T. (2008). Maps of random walks on complex networks reveal community structure. *Proceedings of the National Academy of Sciences, 105*(4), 1118–1123. https://doi.org/10.1073/pnas.0706851105.
Rotolo, D., Rafols, I., Hopkins, M. M., & Leydesdorff, L. (2017). Strategic intelligence on emerging technologies: Scientometric overlay mapping. *Journal of the Association for Information Science and Technology, 68*(1), 214–233. https://doi.org/10.1002/asi.23631.
Schubert, A., Korn, A., & Telcs, A. (2009). Hirsch-type indices for characterizing networks. *Scientometrics, 78*(2), 375–382. https://doi.org/10.1007/s11192-008-2218-1.

Sen, S. K., & Gan, S. K. (1983). A mathematical extension of the idea of bibliographic coupling and its applications. *Annals of Library Science and Documentation, 30,* 78–82.
Shiffrin, R. M., & Börner, K. (2004). Mapping knowledge domains. *Proceedings of the National Academy of Sciences, 101*(suppl 1), 5183–5185. https://doi.org/10.1073/pnas.0307852100.
Small, H. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents. *Journal of the American Society for Information Science, 24*(4), 265–269. https://doi.org/10.1002/asi.4630240406.
Small, H., & Griffith, B. C. (1974). The Structure of Scientific Literatures I: Identifying and Graphing Specialties. *Science Studies, 4*(1), 17–40. https://doi.org/10.1177/030631277400400102.
Thijs, B., Zhang, L., & Glänzel, W. (2015). Bibliographic coupling and hierarchical clustering for the validation and improvement of subject-classification schemes. *Scientometrics, 105*(3), 1453–1467. https://doi.org/10.1007/s11192-015-1641-3.
van Eck, N. J., & Waltman, L. (2009). How to normalize cooccurrence data? An analysis of some well-known similarity measures. *Journal of the American Society for Information Science and Technology, 60*(8), 1635–1651. https://doi.org/10.1002/asi.21075.
van Eck, N. J., & Waltman, L. (2010). Software survey: VOSViewer, a computer program for bibliometric mapping. *Scientometrics, 84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3.
van Eck, N. J., & Waltman, L. (2014). Visualizing bibliometric networks. In Y. Ding, R. Rousseau, & D. Wolfram (Eds.), *Measuring scholarly impact: Methods and practice* (pp. 285–320). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-10377-8_13.
van Eck, N. J., Waltman, L., Dekker, R., & van den Berg, J. (2010). A comparison of two techniques for bibliometric mapping: Multidimensional scaling and VOS. *Journal of the American Society for Information Science and Technology, 61*(12), 2405–2416. https://doi.org/10.1002/asi.21421.
Waltman, L., van Eck, N. J., & Noyons, E. C. M. (2010). A unified approach to mapping and clustering of bibliometric networks. *Journal of Informetrics, 4*(4), 629–635. https://doi.org/10.1016/j.joi.2010.07.002.
White, H. D., & Griffith, B. C. (1981). Author co-citation: A literature measure of intellectual structure. *Journal of the American Society for Information Science, 32*(3), 163–171. https://doi.org/10.1002/asi.4630320302.
White, H. D., & McCain, K. W. (1998). Visualizing a discipline: An author co-citation analysis of information science, 1972–1995. *Journal of the American Society for Information Science, 49*(4), 327–355. https://doi.org/10.1002/(sici)1097-4571(19980401)49:4%3c327:Aid-asi4%3e3.0.Co;2-4.
Zhang, L., Glänzel, W., & Liang, L. (2009). Tracing the role of individual journals in a cross-citation network based on different indicators. *Scientometrics, 81*(3), 821–838. https://doi.org/10.1007/s11192-008-2245-y.
Zhang, L., Rousseau, R., & Glänzel, W. (2016). Diversity of references as an indicator of the interdisciplinarity of journals: Taking similarity between subject fields into account. *Journal of the Association for Information Science and Technology, 67*(5), 1257–1265. https://doi.org/10.1002/asi.23487.
Zitt, M., & Bassecoulard, E. (2006). Delineating complex scientific fields by hybrid lexical-citation method: An application to nanoscience. *Information Processing and Management, 42*(6), 1513–1531. https://doi.org/10.1016/j.ipm.2006.03.016.