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Exploring the interdisciplinary evolution of a discipline: the case of Biochemistry and Molecular Biology

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Abstract This study explores interdisciplinarity evolution of Biochemistry and Molecular Biology (BMB) over a one-hundred-year period on several fronts, namely: change in interdisciplinarity, identification of core disciplines, disciplinary emergence, and potential discipline detection, in order to assess the evolution of interdisciplinarity over time. Science overlay maps and a StreamGraph were used to visualize interdisciplinary evolution. Our study confirms that interdisciplinarity evolves mainly from neighbouring fields to distant cognitive areas and provides evidence of an increasing tendency of BMB researchers to cite literature from other disciplines. Additionally, from our results, we can see that the top potential interdisciplinary relations belong to distant disciplines of BMB; their share of references is small, but is increasing markedly. On the whole, these results confirm the dynamic nature of interdisciplinary relations, and suggest that current scientific problems are increasingly addressed using knowledge from a wide variety of disciplines.

Keywords Interdisciplinarity · Bibliometrics · References · Information visualisation

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Introduction

Interdisciplinary research is often considered as the best approach for solving complex problems in modern science. Jahn et al. (2012, 9) posit that it "fundamentally addresses the relation between science and society." Similarly, Garner et al. (2013, 134) remind us that "a significant portion of major advances take place at the interstices among disciplines." As such, interdisciplinarity has been encouraged by science policy (Rafols and Meyer 2007) both by creating interdisciplinary centers and by funding interdisciplinary research projects (Bordons et al. 1999). Porter and Rafols (2009) mention that interdisciplinary research seems almost universally acclaimed as "the way to go." Likewise, Smajgl and Ward (2013, 52) state that "developing transdisciplinary endeavours has been a primary focus, catalysing methodological innovations." In this context, measuring and understanding interdisciplinary research is a topic that has received more attention in bibliometrics studies in the last decade.

However, very few studies have assessed the evolution of interdisciplinarity over time. In an attempt to answer this question, Porter and Rafols (2009) investigated the evolution of interdisciplinarity over a thirty-year period across six research domains. The results show notable changes in research practices over that time period, specifically in the number of cited disciplines and references per article, and co-authors per article. However, the Rao-Stirling Index only shows a modest increase. The authors suggest that this is due to the fact that the citations of an article remain mainly within neighbouring disciplinary areas. Similarly, Larivière and Gingras (2014) show that, after declining between 1945 and 1975, interdisciplinarity has been on the rise. Another recent study by Levitt et al. (2011) analyzed the evolution of interdisciplinarity in the Social Science Citation Index (SSCI) categories for three specific years (1980, 1990 and 2000). The authors showed that the median level of interdisciplinarity of these fields had decreased between 1980 and 1990, but then climbed back in 2000 to its 1980 level. Another team (van Leeuwen and Tijssen 2000), analyzed interdisciplinarity changes between 1985 and 1995 and found that very few disciplines displayed significant changes in levels of interdisciplinarity during that time. Chang and Huang (2012) used three bibliometrics methods (direct citation, bibliographic coupling, and co-authorship analysis) to investigate interdisciplinary changes in Library and Information Science over the past 30 years.

These different studies explored the characteristics and evolution of interdisciplinarity, focusing only on the number of disciplines cited or change in levels of interdisciplinarity over a few years. This article presents a more detailed analysis of the evolution of interdisciplinarity in Biochemistry and Molecular Biology (BMB) by considering several aspects. Using percentage of references and overlay mapping to identify the relative positions of disciplines, this study tries to confirm Porter and Rafols (2009) idea that interdisciplinarity develops through interaction with neighbouring disciplines first and then diffuses toward cognitively more distant disciplines.

The objective of this paper is to study the evolution, over the last century, of interdisciplinarity in science. Previous research has provided evidence that these practices were increasing (Larivière and Gingras 2014; Porter and Rafols 2009). However, none of these studies actually provide empirical data on the actual disciplines that contribute to this increase, as well as their evolution over the last century. Using data on approximately 1.5 million papers published in the field of BMB and the references they cite, this paper aims at confirming, at the level of a discipline, the trends on the increase of interdisciplinarity found at the macro-level, as well as assessing the evolution of the different disciplines that contribute to its development. The discipline of BMB was chosen given its interdisciplinary nature. Indeed, as shown by Kohler (1982), the discipline was created in the early 20th century as a combination of physiology/biology and chemistry. It then became tightly integrated into the realm of medical sciences, and is now one of the largest fields of science. Given this evolutionary pattern, BMB provides a unique window into the analysis of the evolution of interdisciplinarity in science.

Data and methods

Data collection

Our study uses the Thomson Reuters Web of Science (WoS) databases, which include over one century of both papers and references. For this study, we selected all publications (regardless of document type) in the field of BMB. The number of documents extracted with this query is 1,539,526 along with 47,673,791 corresponding references. These references include journal articles, conference papers, books, theses etc., but only references made to other source items (i.e., other journal articles) were considered, as they are the only references to which a NSF classification could be assigned, leaving us in the end with 40,855,852 references (85.7 % of all BMB references). These references can all be found in WoS. Given the fact that older papers, especially those published before 1910, cite a larger proportion of papers that are not indexed in WoS, we explore interdisciplinarity starting from 1910.

The disciplinary classification of journals used in our paper is that of the US National Science Foundation (NSF). The NSF classification includes 143 subclasses distributed amongst fourteen main general disciplinary classes (Hamilton 2003). Each journal is classified into only one subclass, which in turn is linked to only one main class. Our analysis usually refers to the finer classificatory level (subclasses) of scientific disciplines.

Identifying related disciplines

To measure the extent of interdisciplinarity of BMB we only considered the disciplines that received a “large enough” number of citations from BMB. A requirement such as “large enough” is quite subjective and difficult to quantify exactly, and we based ourselves on previous studies to fix a threshold. Some papers use arbitrary citation numbers to identify emerging disciplines. Buter et al. (2011) identified converging research areas using field-to-field references and set the lower bound on the total number of references at 200, employing a three-year citation window. However, depending on the discipline, the threshold can vary from 100 (fuzzy set theory) (Berg and Wagner-Döbler 1996) to 250 (bioelectronics) (Hinze 1994). Based on these observations, we chose the higher boundary and determined that if one discipline is cited by BMB 250 times or more, it is enough to be considered as having an interdisciplinary relation with BMB.

As one would expect, BMB cites other disciplines unevenly. The disciplines that are cited more often by BMB have a closer relation with BMB and we call them “core disciplines.” It is obvious that core disciplines play an important role in the development of the citing discipline. Most studies identify the core disciplines without taking into account the respective size of disciplines. For instance, researchers from BMB are much more likely to cite papers from the field of Cancer rather than Microscopy, simply because of the fact that the former is larger than the latter. In this study we propose to identify core disciplines by comparing their share of references made by publications of the citing discipline (r_i) with their share of all papers published (p_i). First, we computed, for each discipline, its proportion of papers published in WoS over one century (all papers). Second, we did the same calculation, but in terms of references made by BMB papers. Disciplines were considered as "core" when their proportion of BMB references was higher than the proportion of BMB papers in all WoS.

Besides core disciplines, it is also worth focusing on cited disciplines that are increasingly developing interdisciplinary connections with BMB in recent years. The connections may indicate some new or future developing orientations in interdisciplinarity. These disciplines are defined as "potential disciplines" in this paper. In order to identify potential disciplines, several elements need to be considered.

Apart from the numbers of references given by publications in BMB, annual growth rate and total increment quantity of share of references given annually by publications in BMB is decisive. We measured annual growth rate and total increment quantity of all citing discipline for the last 10 years and selected the potential disciplines accordingly. Additionally, we determined that the annual growth rate should be positive over the last 5 years, that is, every subsequent year should have more references than the previous year.

Indicators of interdisciplinarity

From a bibliometric point of view, measuring interdisciplinary research is generally operationalized on the basis of interdisciplinary citation relationships. For instance, Porter and Chubin (1985) measure the degree of interdisciplinarity of an article by using the percentage of citations received or references made coming from a different discipline, an indicator which they name *Citations Outside Category* (COC). Subsequent research proposed similar indicators, such as that used at a more micro level by Tomov and Mutafov (1996) for andrology and reproduction, by Morillo et al. (2001) for chemistry, and by Rinia et al. (2002a) for all fields of science. Adams et al. (2007) also used the proportion of cited references made to different disciplines, as well as the number of distinct disciplines cited and the Shannon Diversity Index. Recently, a new indicator of interdisciplinarity, the Rao-Stirling diversity index, has been used by Carley and Porter (2012) to explore knowledge from the perspective of citing documents. Other researchers, like Levitt and Thelwall (2008), operationalized the concept using articles published in journals that are classified in more than one field by Thomson Reuters' WoS or by Elsevier's Scopus.

Other methods were also used to measure interdisciplinarity. For instance, Rinia et al. (2002b, 244) defined interdisciplinarity as the percentage of articles from a group of researchers that is published outside their "main" discipline. Qiu (1992) used the organizational affiliations of authors of published research to investigate interdisciplinary collaborations. Using Italy as a case study—as researchers from this country have to classify themselves into only one discipline—Abramo et al. (2012) identified interdisciplinarity through collaboration among co-authors from different disciplines. Additionally, some researches utilized authors' discipline of highest diploma to explore interdisciplinarity. Le Pair (1980) constructed a slightly different indicator, based on the migration of scientists from one discipline to another throughout the course of their career. Sugimoto et al. (2011) utilized academic genealogy from PhD dissertations in Library and Information Science over a period of 80 years (1930–2009) to describe the changing level of interdisciplinarity of the discipline.

In this paper, we compute COCs—based on annual references made by BMB papers—to analyze the change in the level of interdisciplinarity of BMB over one century period. The Rao-Stirling diversity index has been recommended (Rafols and Meyer 2010) as it captures not only the number of disciplines cited by a paper or their degree of concentration (as Herfindahl or Shannon indices do), but also how different these disciplines are.

In order to compute the Rao-Stirling diversity index, we constructed a discipline × discipline co-citation matrix (using 143 subclasses from the NSF classification system) based on all papers of WoS over the last 5 years (2008–2012). The formula of the Rao-Stirling diversity index is as follows:

$$I = 1 - \sum_{i,j} s_{ij} p_i p_j.$$

p_i is the proportion of references citing the discipline i in a given paper. The summation is taken over the cells of the discipline × discipline matrix; s_{ij} is the cosine measure of similarity between disciplines i and j (the cosine measure may be understood as a variation of correlation). The greater the degree of the interdisciplinary of a discipline, the higher value assigned to it by the index.

Simply displaying the disciplinary evolution by change of share of discipline in references is limiting because it is influenced by the size of the citing discipline and the cited discipline. Lee et al. (2009) measured the language preference of journals. They propose an indicator called "relative openness." In the measure of relative openness of a journal in language i for articles of a specific other language j, three parameters are included: (1) the share of references given to the citing language j by articles in a journal in language i ($r_{i,j}$), (2) the size (worldshare) of the citing language (α_i) and (3) the size of the cited language (α_j).

$$\mathrm{RO}_{i,j} = \mathrm{r}_{i,j} \times \alpha_i \times (1 - \alpha_j)$$

According to Rinia et al. (2002a, 355), this measure can be used in interdisciplinary research. Observed from the perspective of a cited discipline, this function can be perceived as an indicator of the cited discipline's impact on the citing discipline. In this study, we used this indicator to measure the impact of cited disciplines and to explore the evolution of interdisciplinarity by looking at changes in those disciplines' impact.

Using visualization techniques

We used visualization techniques to display the evolution of core disciplines. Techniques such as alluvial graph (Rosvall and Bergstrom 2010), ThemeRiver (Havre et al. 2000) and StreamGraph (Byron and Wattenberg 2008), were considered. These techniques can directly display the core disciplines evolution over a long period of time. For our analysis, StreamGraph was used as it is perfectly adaptable to our data. In the StreamGraph the stream flows from left to right through time, and its changing width depicts changes in the core disciplines impact of temporally associated documents. Coloured "currents" flowing within the stream narrow or widen to indicate decreases or increases in the impact of a discipline in the associated reference set.

Visualizing the chronological sequence of emerging disciplines is another way to illustrate the evolution of the interdisciplinarity of BMB. In this study, we traced the number of citations of all disciplines in references given by BMB every year and selected the disciplines receiving 250 citations or more. Based on this, we compared the change of cited disciplines annually and obtained the sequence of emerging disciplines for BMB.

Science overlay maps were also used to visualize this process. Maps of science allow visualization of elements (usually scientific disciplines) and the relationships that exist between them (Klavans and Boyack 2009). Science overlay maps are efficient to display disciplinary distribution and evolution (Rafols et al. 2010; Leydesdorff et al. 2013). The technique uses the units and positions derived from a global map of science, but overlays on them the data corresponding to the organizations or themes under study. Rafols et al. (2010) generated a matrix of citing SCs (WoS Subject Category) to cited SCs using Journal Citation Report and constructed a basemap of 221 SCs. Since we adopted the NSF Classification System for our study, we could not utilize their basemap and therefore had to produce our own. We constructed a discipline-to-discipline co-citation matrix using 10 years of data (2003–2012) from WoS. Salton's cosine was used for normalization in the co-citation value. We used VOS Viewer[1] to generate a global map of science based on the 143 disciplines (subclasses) of the NSF classification. The resulting map is illustrated in Fig. 1. Each node in the map corresponds to one the 143 sub-disciplines. Their relative positions are determined by their similarity, based on the VOS MDS algorithm (van Eck and Waltman 2010; van Eck et al. 2010). The colours in Fig. 1 correspond to the 14 NSF main disciplinary classes.

In the upper part of Fig. 1 we find Biomedical Research, Clinical Medicine and Biology, whereas in the bottom left we find Social Sciences, Psychology, Professional Fields, Humanities and Art. The bottom right consists of Chemistry, Physics, Engineering and Technology, Earth and Space Sciences and Mathematics. Health is found between the upper and bottom left. The global science map generated from the NSF classification is similar to the global science map reported in Rafols et al. (2010) and the consensus map of science produced by Klavans and Boyack (2009).

Results

Our analysis shows that the number of disciplines cited in BMB grows from 1 to 93 (spanning 12 NSF main classes) over the one hundred year period under study. This is typical of an evolution toward interdisciplinarity. Figure 2 shows the number of all disciplines cited by BMB in all articles. In total, BMB cited 95 disciplines (two-thirds of the 143 NSF disciplines). Arts and Humanities are the only two scientific group of disciplines not cited by BMB. From the data presented in Table 1, it is clear that Clinical Medicine, Biomedical Research and Biology play an important role in the development of BMB. Additionally, Physics and Chemistry are also quite important. The increasing number of cited disciplines indicates that BMB is becoming more interdisciplinary over time.

Two typical patterns emerge in the evolution of interdisciplinarity of BMB: (1) Cited disciplines retain their interdisciplinary relation with BMB, with some fluctuation, once they emerge (this is the case of 54 disciplines); (2) Cited disciplines emerge on a specific year, remain for a certain number of years and then disappear in the references of BMB (this is the case of 39 disciplines). This second pattern is more typical of disciplines with smaller number of papers.

Core and potential disciplines

Shares of publications from different disciplines are not evenly distributed in WoS. Figure 3 shows shares of publication of 143 disciplines from 1910 to 2012. If each discipline had the same size, the share of publications of each would be about 0.7 %. There are only

[1] http://www.vosviewer.com/.

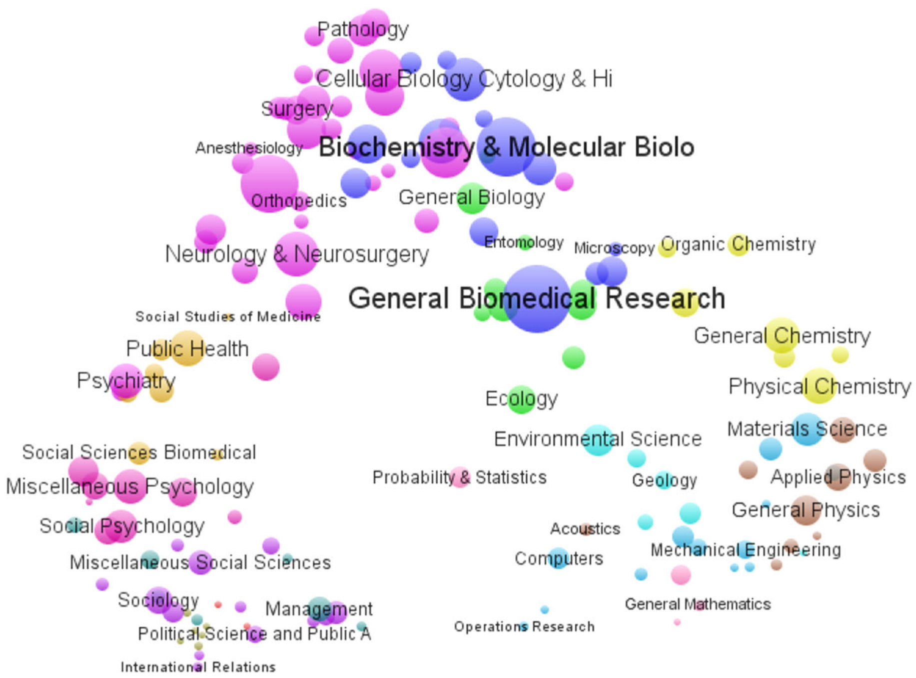

Fig. 1 Global map of science based NSF classification system

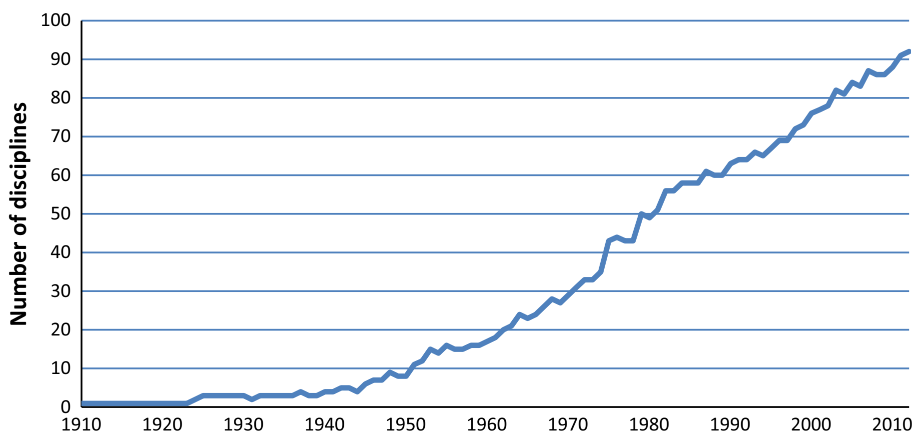

Fig. 2 Increasing number of disciplines cited by BMB, 1910–2012

50 disciplines for which paper ratio is more than 0.7 %. General and Internal Medicine is the largest discipline and its paper ratio accounts for 5.3 %. The paper ratios of General Chemistry, Biochemistry and Molecular Biology and General Biomedical Research also are above 3 %. For most disciplines, shares of publication are <0.7 %.

By comparing the shares of references made by publications of BMB (r_i) with their share of all papers published (p_i), fifteen disciplines were identified as core disciplines,

Table 1 Discipline distribution of references made by BMB

NSF main class	Number of disciplines cited
Clinical Medicine	34
Biomedical Research	15
Biology	10
Physics	8
Chemistry	7
Earth and Space	5
Engineering and Technology	5
Health	3
Psychology	3
Mathematics	2
Professional Fields	2
Social Sciences	1

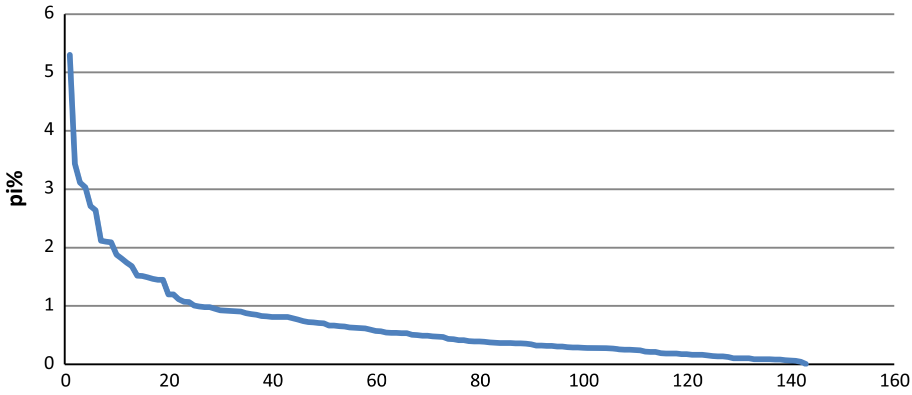

Fig. 3 Shares of publications of 143 disciplines, 1910–2012

based on our definition (Table 2). These core disciplines account for 81.7 % of the references given by BMB publications. This indicates that BMB researchers rely heavily on these core disciplines. From Table 2 we can see that BMB researchers most frequently cite publications in their own disciplines (45.3 % of references). General Biomedical Research is another important discipline upon which BMB researchers rely heavily on. Together the two disciplines account for 58.61 % of the references present in BMB publications. From the perspective of NSF disciplines, BMB researchers unsurprisingly focus mainly on Biomedical Research and Clinical Medicine, then on Biology and Chemistry to a lesser degree.

Table 3 lists the top five potential disciplines that have the greatest increase in terms of citations received over the last 10 years. Although these disciplines account for a small proportion of all references made by BMB, their importance is increasing markedly, and given their cognitive distance from BMB, it is interesting to note them. Figure 4 shows the growth curve of references made by publications of BMB (r_i) for the top five disciplines in the latest 10 years under study.

Table 2 Core disciplines cited by BMB

Discipline	NSF main class	r_i (%)	p_i (%)
Biochemistry and Molecular Biology	Biomedical Research	45.32	3.12
General Biomedical Research	Biomedical Research	13.30	3.03
Cellular Biology Cytology and Histology	Biomedical Research	4.01	0.79
Genetics and Heredity	Biomedical Research	3.67	0.98
Immunology	Clinical Medicine	2.53	1.45
Pharmacology	Clinical Medicine	2.38	2.12
Microbiology	Biomedical Research	2.07	0.83
Cancer	Clinical Medicine	2.01	1.51
Endocrinology	Clinical Medicine	1.61	0.91
Physiology	Biomedical Research	1.57	0.72
Analytical Chemistry	Chemistry	0.96	0.92
Virology	Biomedical Research	0.92	0.29
Biophysics	Biomedical Research	0.71	0.26
Embryology	Biomedical Research	0.45	0.11
Miscellaneous Biology	Biology	0.19	0.17

Change in interdisciplinarity

Figure 5 shows the evolution of interdisciplinarity of BMB over the past century. It is evident that BMB is becoming more interdisciplinary over time. Porter and Rafols (2009) investigated interdisciplinarity changes of six disciplines from 1975 to 2005 [Biotechnology and Applied Microbiology; Engineering (Electrical and Electronic); Mathematics; Medicine (Research and Experimental); Neurosciences; Physics (Atomic, Molecular and Chemical)]. Their results showed major increases in the number of cited disciplines and references per article (about 50 % growth for both), and co-authors per article (about 75 % growth). However, the Rao-Stirling Index only showed a modest increase (around 5 % growth). In our research, the Rao-Stirling Index for BMB doubles over the century with a 32 % increase during the same period that Porter and Rafols studied (1975–2005) showing that the rise in interdisciplinarity is stronger in BMB than in the six disciplines which Porter and Rafols investigated.

Evolution of core disciplines

We now examine the emerging year of each core discipline cited by BMB (Table 4). From the data, we can see that, all core disciplines emerge before the 1950s, except for Biophysics, Embryology, Virology and Miscellaneous Biology (especially, Miscellaneous Biology does not emerge until 1995). This is likely due to the fact that these cited disciplines are themselves younger disciplines. Figure 6 shows the core disciplines overlay map based on the science map from the NSF classification system. The overlay map illustrates clearly that the core disciplines of BMB mainly surround BMB and are the neighbour disciplines of BMB. By comparing Table 4 and Fig. 6 we can easily conclude that the closest disciplines are the ones that get cited by BMB the earliest.

The core disciplines themselves have various development patterns over the last Century. Unsurprisingly, BMB remains at the core of its disciplinary development, but its share

Table 3 Top five increasing disciplines in the past 10 years

Discipline	NSF main class	p_i (%)	r_i (%)	Total increasing quantity
Applied Mathematics	Mathematics	0.76	0.07	10.314
Materials Science	Engineering and Technology	2.28	0.15	9.058
Geriatrics and Gerontology	Health	0.27	0.04	7.009
Economics	Social Sciences	0.79	0.01	5.235
Fluids and Plasmas	Physics	0.27	0.01	4.593

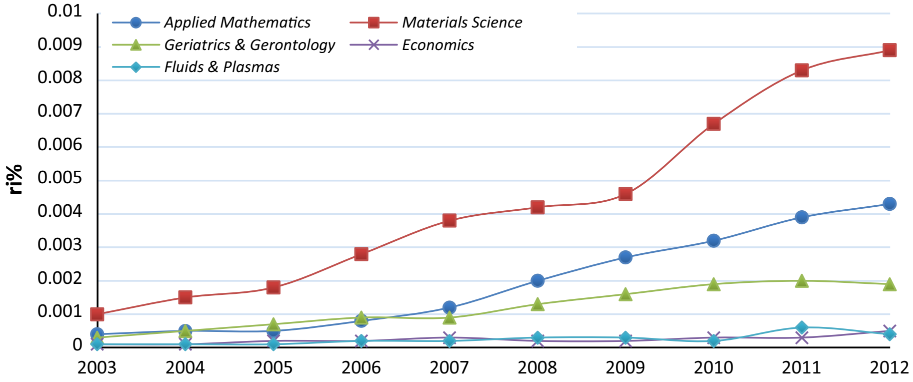

Fig. 4 Five potential disciplines r_i % growth, 2003–2012

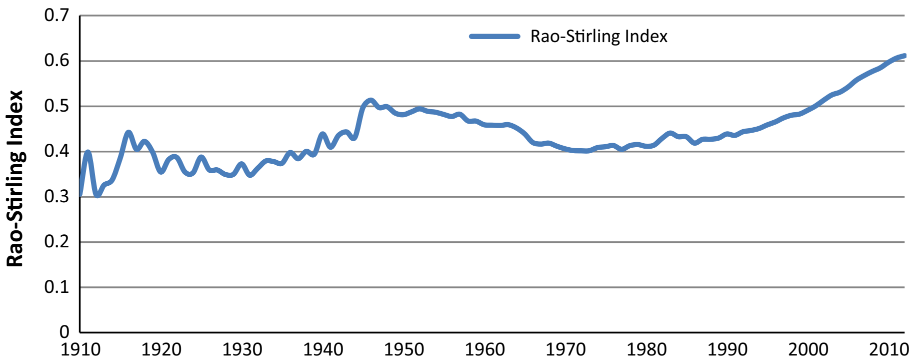

Fig. 5 Interdisciplinarity evolution of BMB (Rao-Stirling), 1910–2012

of references decreases steadily (from 74.0 % in 1910 to 32.1 % in 2012). The level of interdisciplinarity of BMB is increasing as more disciplines contribute to its development. Given the intrinsic interdisciplinary nature of BMB, it could be assumed that BMB researchers borrow methods and techniques, or use theories, data and findings from various disciplines to solve problems and that, they therefore cite publications from other disciplines. We further used StreamGraph (Byron and Wattenberg 2008) and relative openness to display the impact evolution of core disciplines (Fig. 7). The width of each stream

Table 4 Core disciplines emerging year

Discipline	Emerging year
Biochemistry and Molecular Biology	1910
Physiology	1925
General Biomedical Research	1939
Immunology	1946
Microbiology	1946
Cancer	1948
Endocrinology	1948
Genetics and Heredity	1951
Pharmacology	1951
Cellular Biology Cytology and Histology	1952
Analytical Chemistry	1952
Virology	1962
Biophysics	1967
Embryology	1978
Miscellaneous Biology	1995

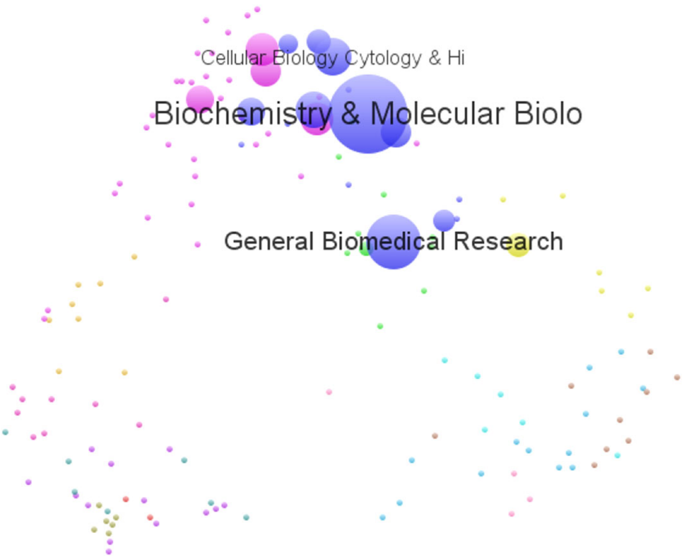

Fig. 6 The overlay map of core disciplines of BMB

shows the impact of each core discipline on BMB.[2] From Fig. 7, we can see that, besides BMB, General Biomedical Research is the most cited discipline. However, the importance of the specific disciplines varies considerably over the period under study. In the early

[2] Due to the fact that BMB accounts for a large proportion of the references it makes the StreamGraph displays all core discipline except for BMB as it would occupy a large space and squeeze other core disciplines' space in the map.

stage, Physiology accounts for most interdisciplinary relations, followed by Pharmacology and Immunology. The relative importance of these disciplines decreases over time, as we observe a diversification of disciplines on which BMB research is based, such as Cellular Biology Cytology and Histology, Genetics and Heredity and Cancer, as well as an important increase of references made to General Biomedical Research, the discipline in which journals such as *Science*, *Nature*, and *PNAS* are classed.

The evolution of the core disciplines in this study is consistent with the history of biochemistry described by Kohler (Kohler 1982).[3] Kohler explains that Physiology was important for Biochemistry in its early stage, but that Medical Sciences became more important for Biochemistry in the 1940s. Figure 6 also illustrates this trend.

Disciplinary emergence is interesting to present the chronological sequence of cited disciplines by BMB researchers. We chose to display the evolution of interdisciplinarity from the level of NSF discipline and then focus on some benchmarks in the development of BMB as a discipline. Let us consider the core disciplines in the emerging sequence of interdisciplinary relations (Fig. 8). The year of appearance corresponds to the time the discipline reached a certain number of citations received (as mentioned earlier, 250 citation was deemed significant).

In the NSF classification, BMB is a subclass of Biomedical Research, so at the beginning (1910) BMB only cites publications from the discipline itself, and then starts citing publications from other disciplines such as Chemistry (1924), Clinical Medicine (1937) and Biology (1949). These three NSF main scientific classes are close to BMB on the global science map based on the NSF classification system (refer to Fig. 1). With the development of BMB, some publications from more distant disciplines such as Physics emerge in the referenced disciplines in 1961. Psychology, Earth and Space Sciences, Engineering and Technology and Mathematics also appear one after the other in the referenced disciplines between 1982 and 1993. It is worth noting that two “professional fields” (Library and Information Science, Management) and Social Sciences, which may be considered as distant disciplines, emerge in the referenced disciplines respectively in 2003 and 2012 probably reflecting the recent debates on the uses of bibliometrics to evaluate research in BMB.

According to the emerging chronological sequence of disciplines referenced by BMB and the cognitive distance between these disciplines, we can identify four phases in the development of BMB’s interdisciplinarity. The first phase spans 50 years, from 1910 to 1960. In this phase, 18 disciplines emerge (including 7 from Biomedical Research, 6 from Clinical Medicine, 4 from Chemistry and 1 from Biology which is understandable since BMB is a fundamental discipline of Clinical Medicine and Biomedical Research). It is in this phase that all the core disciplines emerge (except for Virology, Biophysics, Embryology and Miscellaneous Biology). This phase corresponds to the early developments of BMB and is similar to the history of Biochemistry described by Kohler (1982) who states that Biochemistry early developments stem from Medicine Science, Physiology and Chemistry. In our research, the first phase is similar to this description. The second phase covers 20 years from 1961 to 1981 during which 34 new disciplines emerge: 14 disciplines from Clinical Medicine, 6 disciplines from Biomedical Research, 8 disciplines from Biology, 3 disciplines from Chemistry and 3 disciplines from Physics. The number of disciplines from Biomedical Research and Clinical Medicine increases but the remarkable

[3] Molecular Biology could be regarded as being part of Biochemistry. After the publication of the double-helix structure of DNA in 1953, research concerning DNA in Biochemistry is usually called Molecular Biology.

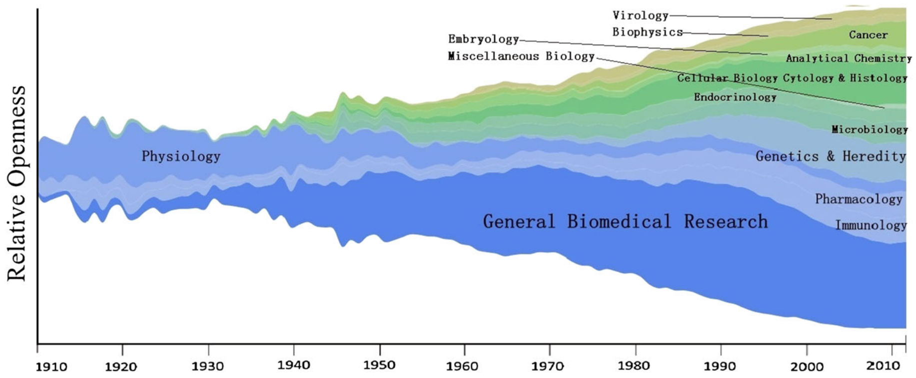

Fig. 7 Proportion of cited references by BMB papers, by discipline, 1900–2012

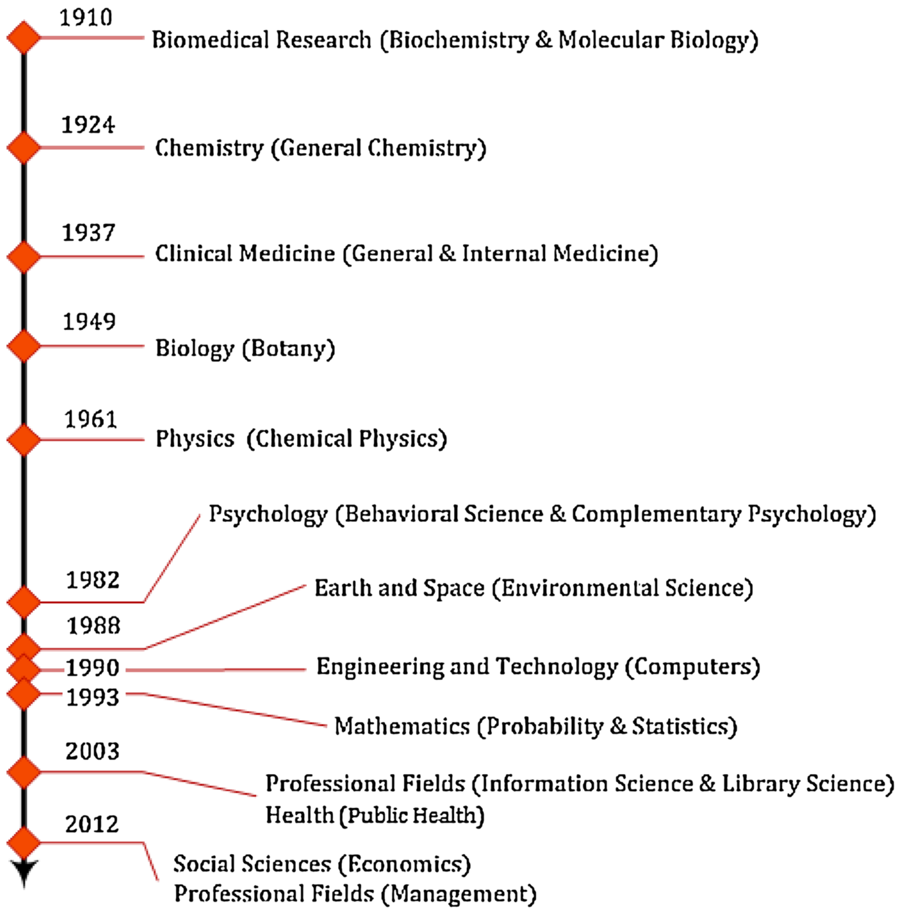

Fig. 8 Discipline emerging sequence for Biochemistry and Molecular Biology

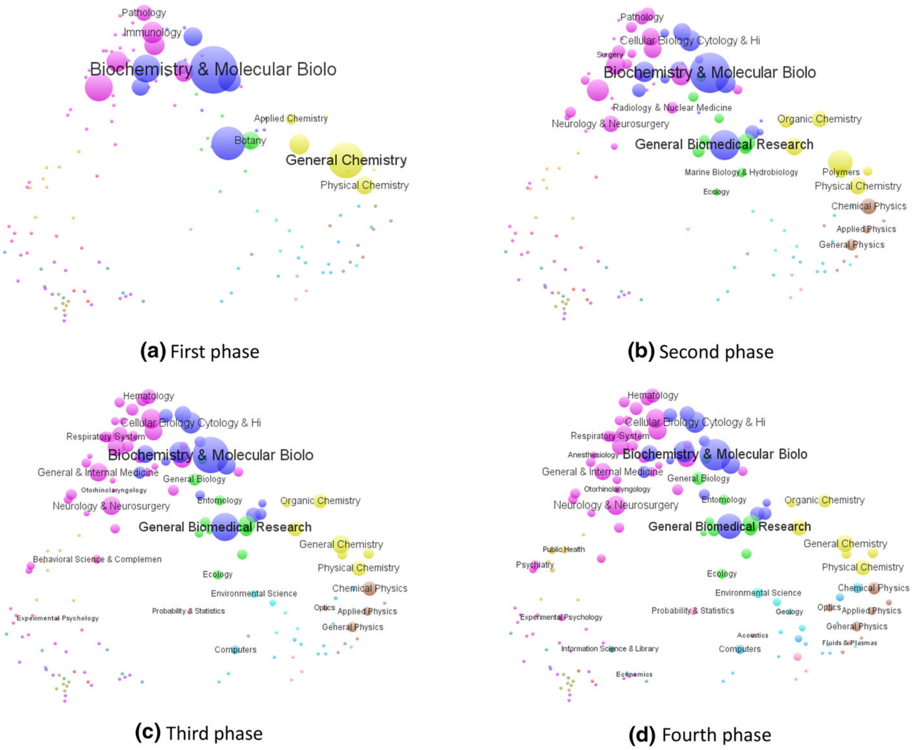

Fig. 9 Overlay map of four phases of BMB interdisciplinary evolution

point in this phase is that three disciplines emerge from Physics, showing that BMB starts to extend beyond its neighbouring disciplines. The third phase covers another twenty-year period, from 1982 to 2002. Twenty-seven new disciplines emerge in this phase, including 14 from Clinical Medicine and 2 from Biomedical Research. Physics and Biology also respectively contribute 2 new disciplines. More distant disciplines are becoming more prominent in this phase; these include Engineering and Technology (four disciplines), Psychology (two disciplines), Earth and Space (two disciplines) and Mathematics (one discipline). The fourth phase which starts in 2003 sees 16 new disciplines emerging. In this phase, no new disciplines from Biomedical Research and Clinical Medicine emerge. Physics, Earth and Space, Psychology, and Engineering and Technology, each contribute 4, 3, 1 and 1 disciplines respectively, while new disciplines from Health (3 disciplines), Professional Fields (2 disciplines) and Social Sciences (1 discipline) appear. It is worth mentioning that, in this phase, Library and Information Science (from Professional Fields) emerges in the references of BMB papers. This shows that in this phase BMB continues to cite more distant disciplines.

We constructed the overlay maps of the four phases (Fig. 9) which shows the cited disciplines developing gradually. The series of maps illustrates that the evolution of the interdisciplinarity of BMB gradually diffuses from neighboring disciplinary areas (in the first two phases) to distant disciplinary areas (in the third and fourth phases) over a 100-year period. First, Biomedical Research, Clinical Medicine, Biology and Chemistry are the most important fundamental disciplines of BMB. Those disciplines' locations in the science map are close and can be considered as neighbouring disciplines. Second, the four phases confirm that the development of interdisciplinarity starts mainly with neighbouring fields and then continues to distant cognitive areas.

Discussion and conclusion

This paper provided evidence of the dynamic nature of BMBs interdisciplinary relations, and of an increasing tendency of BMB researchers to cite literature from other disciplines. This tendency dates from the 1970s, following a few decades of increasing *disciplinarity*. After the Second World War, science grew exponentially, mainly because of the emergence of new disciplines. This period of exponential growth ended in the mid-1970s (Larivière et al. 2008). Since then, science has grown more linearly, which might explain why researchers are increasingly using knowledge from other disciplines to solve the research problems which, we can assume, they cannot solve with the traditional methods of their disciplines. Our results also show an increasing diversification of the disciplines used by BMB researchers, which is likely due to the diversification of science in general.

Numerous bibliometrics indicators have been developed and proposed to measure interdisciplinarity and disciplinary evolution. Using different indicators may produce different results. Also, the evolution of interdisciplinarity is clearly related to the characteristics of each discipline. For BMB, our study shows that both the number of related disciplines and the Rao-Stirling Index increases markedly. The findings reveal that the level of BMB's interdisciplinarity has been increasing over time with a few fluctuations, indicating that BMB researchers increasingly cite more sources from outside their own discipline. Our study confirms that interdisciplinarity evolves mainly from neighbouring fields to distant cognitive areas. Additionally, detecting potential related disciplines provides hints as to where future interdisciplinarity may emerge. From our results, we can see that the top potential interdisciplinary relations belong to distant disciplines of BMB; their share of references is small, but is increasing markedly.

The methodology used in this research has its limitations. First, despite important changes in the structure of scientific disciplines during the last century, our list of disciplines remains the same throughout the period studied. However, given that very few fields have ceased to exist and that many fields have emerged, using a contemporary classification should not cause important anachronisms. Second, we have classification information only for references made to articles published in journals and that are also in the WoS databases, but we can consider that the results obtained for the references made to source items are a representative sample of the whole population of all possible references (Larivière and Gingras 2014). Third, this method only considers references from journals, regardless of other types of references such as conference papers, books, theses and so on. Additionally, in this study the lower boundary for the number of references (250) is subjective. This boundary is difficult to determine exactly, so it could be adjusted according to research needs. Lowering the lower boundary would make it possible to detect related disciplines earlier, but the number of emerging disciplines would be greater and the results would become somewhat unreliable. Along these lines, using a relative boundary rather than an absolute one would perhaps prevent some disciplines to appear as contributors to BMB knowledge, as their proportion of references made by BMB papers remains low despite meeting the 250 papers threshold.

In conclusion, we examined the evolution of the interdisciplinarity of BMB over a period of over a century by cross discipline citations and science overlay map. The framework includes looking at changes in levels of interdisciplinarity, identification of core disciplines contributing to a chosen field (here BMB) knowledge base, and disciplinary emergence and potential disciplines for new interdisciplinarity relations. Though it is here limited to BMB, our approach can help policy makers or funding agencies comprehend more holistically the interdisciplinary nature a given discipline. This framework could also be used to study the evolution of other disciplines. For instance, it would be very interesting to compare the results obtained here with those for smaller technical specialties such as Microscopy, or with more clinical fields like Cancer or Cardiovascular system research.

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