Studies in the Dynamics of Science:

Exploring emergence, classification, and interdisciplinarity

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Abstract

The dynamic nature of science is embodied in the growth of knowledge in magnitude and the transformation of knowledge in structure. More specifically, the growth in magnitude is indicated by a sharp increase in the number of scientific publications in recent decades. The transformation of knowledge occurs as the boundaries of scientific disciplines become increasingly less distinct, resulting in a complicated situation wherein disciplines and interdisciplinary research topics coexist and co-evolve. Knowledge production in such a context creates challenges for the measurement of science.

This thesis aims to develop more flexible bibliometric methodologies in order to address some of the challenges to measuring science effectively. To be specific, this thesis 1) proposes a new approach for identifying emerging research topics; 2) measures the interdisciplinarity of research topics; 3) explores the accuracy of the journal classification systems of the Web of Science and Scopus; 4) examines the role of cognitive distance in grant decisions; and 5) investigates the effect of cognitive distance between collaborators on their research output.

The data used in this thesis are mainly from the in-house Web of Science and Scopus databases of the Centre for Science and Technology Studies (CWTS) at Leiden University. Quantitative analyses, in particular bibliometric analyses, are the main research methodologies employed in this thesis.

Furthermore, this thesis primarily offers methodological contributions, proposing a series of approaches designed to tackle the challenges created by the dynamics of science. While the major contribution of this dissertation lies in the improvement of certain bibliometric approaches, it also enhances the understanding of the current system of science. In particular, the approaches and research findings presented here have implications for various stakeholders, including publishing organizations, bibliographic database producers, research policy makers, and research funding agencies. Indeed, these approaches could be built into a software tool and thereby be made available to researchers beyond the field of bibliometric studies.

Keywords: science dynamics; bibliometrics; emerging research topics; interdisciplinary research; journal classification systems; cognitive distance; research policy

Sammanfattning

Vetenskapens dynamik tar sig uttryck såväl i kunskapens växt som i omvandlingen av kunskapens struktur. Mer precist kan hävdas att kunskapsväxten framgår av att antalet vetenskapliga publikationer kraftigt ökat under de senaste decennierna. Den samtidiga kunskapsomvandlingen tyder på att gränsdragningen mellan vetenskapliga discipliner blir alltmer svårdefinierad, vilket i sin tur bidrar till en komplex situation där discipliner och tvärvetenskapliga forskningsområden samexisterar och samevolverar. Kunskapsproduktion i ett sådant sammanhang medför utmaningar för hur vetenskap skall förstås, vägas och mätas.

Denna avhandling syftar till att utveckla mer flexibla bibliometriska metoder för att ta itu med dessa utmaningar. Strävan är att utveckla effektiva och relevanta mätverktyg för forskning. Mer specifikt, föreslår denna avhandling 1) innovativa metoder för att identifiera nya forskningsområden; 2) nya metoder för att identifiera tvärvetenskapliga forskningsområden; 3) metoder för att undersöka noggrannheten av klassificeringssystem från *Web of Science* och *Scopus*; 4) metoder för att granska betydelsen av kognitivt avstånd i beslut om forskningsbidrag; och 5) metoder för att undersöka effekten av kognitivt avstånd mellan samarbetspartner baserat på forskningens prestation och effekt.

Det empiriska underlag som används i denna avhandling är främst hämtat från *Web of Science* och *Scopus* databaser, vilka gjorts tillgängliga via Centrum för Teknik- och Vetenskapsstudier (CWTS) vid Leiden University. Kvantitativa analysmetoder, i synnerhet bibliometriska analyser, är de forskningsmetoder som främst kommit till användning i denna avhandling.

Avsikten med avhandlingen är i första hand att ge metodologiska bidrag med en serie av tillvägagångssätt för att bidra till arbetet med de utmaningar som vetenskapens innebär. Det kanske viktigaste bidraget är att förbättra flera av de bibliometriska metoder, men avhandlingen bör även bidra till en ökad förståelse av det samtida vetenskapssystemet. De föreslagna metoderna tillsammans med forskningsresultaten från denna avhandling har implikationer för olika intressenter inom forskningssystemet: förlag och tidskrifter, bibliografiska databasproducenter, forskningens beslutsfattare samt forskningsfinansiärer. Utöver detta bör framhållas att de föreslagna metoderna kan byggas till ett mjukvaruverktyg, och därmed göras tillgängliga för forskare även utanför det bibliometriska forskningsområdet.

Nyckelord: vetenskapens dynamik; bibliometri; växande forskningsområden; tvärvetenskaplig forskning; klassificeringssystem; kognitivt avstånd; forskningspolitik

摘要

科学发展的动态性一方面表现为知识在规模或数量上的增长， 另一方面体现在学科结构上的变化。具体来说，在规模上知识增长表现为科技论文在近几十年的增长速度极快；而知识在结构上的变化表现为传统的学科边界越来越模糊，这形成了一种传统学科与交叉学科共存并且共同进化的情景。这种背景下的知识生产方式对科学研究的测度提出了挑战。从而，科学研究管理的有效性也将受到严重的影响。

本文基于荷兰莱顿大学科学与技术研究中心提供的结构化的文献数据库，采用定量研究方法，特别是文献计量学分析方法，试图应对在科学研究的定量测度中的遇到挑战和问题。具体来讲，本文首先研究了如何识别新兴的迅速发展的研究课题；其次检查和比较了 Web of Science 和 Scopus 期刊分类系统的准确性；研究了测量研究课题的交叉性方法；探索了认知距离对于科研基金评审结果的影响；最后检验了认知距离对于合作者科研产出的影响。

本文所提出的分析方法可用解决当前因科学发展的动态性而给测度科学研究带来的某些问题，这将有利于提高我们对现今知识系统的认识。此外，本文所提出的方法以及所得到的结论也有益于不同的利益相关者。对于科研管理机构，关于识别迅速发展的新兴的研究课题以及测量研究课题交叉性的研究将有助于他们更好地监测和管理科学研究的发展；关于认知距离在科研基金评审中的作用也有助于同行评议政策的改进，使得基金评审更加公平；对于认知距离与研究产出的研究一方面帮助我们认识合作者之间的认知距离对于知识生产的影响，另一方面也将对诸如大学人事管理，高技术移民和合作政策等方面产生指导性的意义。最后，本文所提出的分析方法也可以嵌入软件，从而有助于文献计量学领域之外的学者。

关键词： 科学的动态性；科技政策； 新兴学科；交叉学科；分类系统；认知距离；同行评议；引文行为

Acknowledgement

The journey toward a Ph.D. is fraught with pleasures and challenges. The highlights may be investigating the problems that are most interesting, exploring answers and solutions to certain puzzles, and expecting research findings to be accepted by peers. A source of discouragement might be disappointment in empirical results obtained from a well-designed approach, infeasible research projects recognized after struggling with the work for a long period, and rejected papers, even though the paper has carefully revised according to a reviewer's suggestions. However, this is perhaps the only way to becoming a Ph.D., and my experience is no exception. Here, I would like to acknowledge many people who have accompanied me to experience these joys and also the pains of the past four and half years.

First of all, I am grateful to my supervisor, Ulf Sandström. I still remember my first day arrived in Sweden, when Ulf picked me up at the airport. For a Chinese student, it is an unbelievable thing. This is my first impression of Ulf. Despite his primary workload is not at KTH, Ulf often came all the way to KTH to address all kinds of problems of mine. In terms of research, he provided me the great freedom of choosing a research theme and always positively commented on my work, increasing my confidence in research. Thank you Ulf for believing in me. Of course, we sometimes have had our disagreements on which approach to take, but Ulf finally and always respected my choices. Thank you for enrolling me as a Ph.D. student, offering me the opportunity to learn at KTH, and supporting my research from various aspects. I will always admire your kindness. In addition, I am also grateful to my co-supervisor, Staffan Laestadius, as well the previous and current head of our division, Niklas Arvidsson, and Cali Nuur.

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Next, I would like to express my gratitude to my co-author and friend, Wei Si. Our study has been accomplished largely because of her dedication and persistence. It is my great honor to work with such an excellent researcher. I have learned so much doing this work alongside her. In addition, I would like to thank my fellow Ph.D. students at the Department of Industrial Economics and Management, Pranpreya, Ding, Richard, Vicky, Michael, and Anna. Many thanks to Pranpreya (my ex-officemate)—I miss the time that we shared in the office and work together. You are so well organized, and you know almost everything; it is so nice to have your influence over the last four years. Many thanks as well to Richard (my current officemate); chatting with you has been a respite from the tough work. Many thanks to Ding for helping me overcome many challenges.

Last, I would like to thank my lovely parents, Jing Qi and Zhichun Wang, for their endless love and for giving me tremendous freedom and supporting all my choices. No matter where I am, your love always keeps me striving forward. I also would like to thank my cousins, who all treat me like sister. My cousin, Yufeng Guo, deserves my great thanks, for always assisting me in solving all kinds of troubles, trusting and supporting me no matter what I attempt, and always motivating me to be a strong person.

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Qi Wang

Easter in Stockholm, 2016

List of appended papers

Paper I — Wang, Q. (2016). A bibliometric model for identifying emerging research topics. Submitted in *Journal of the Association for Information Science and Technology*

Paper II — Wang, Q. & Waltman, L. (2016). Large-scale comparison between the journal classification systems of Web of Science and Scopus. *Journal of Informetrics*, 10, 347-364.

Paper III — Wang, Q. (2016). Measure the interdisciplinarity of research topics. Working paper

Paper IV — Wang, Q. & Sandström, U. (2015). Defining the role of cognitive distance in the peer review process with an explorative study of a grant scheme in infection biology. *Research Evaluation*, 24, 271-281.

Paper V — Si, W. & Wang, Q. (2016). Heterogeneous expertise, knowledge spillover and productivity: Does cognitive distance in research collaboration matter. Working paper

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1. Introduction

Knowledge production is a dynamic process. Now that scientific documents are essential carriers of new knowledge, the dynamic nature of knowledge production is reflected in the system of science, not only in an increase in its size but also in the transformation of its structure (Van den Besselaar & Heimeriks, 2001). The increase in size is reflected in the growing number of academic publications, for researchers in most fields publish their results in academic journals. In terms of the structure of science, the system of science is separated into various research areas according to the similarity of the research. For instance, academic journals are classified into subject categories or research fields in bibliographic databases according to their aims, scope, and research content. The transformation in its structure challenges traditional classification systems of science.

Regarding the dynamics of science, previous studies have put forward various theories to interpret the pattern of knowledge production. The best known of these theories is that of Mode 2 knowledge production, which was proposed by Gibbon and colleagues in 1994. Mode 2 refers to knowledge production “in broader, transdisciplinary social and economic contexts” (Gibbons et al., 1994, p. 1). Mode 2 knowledge has been characterized by application-oriented, transdisciplinary research and by heterogeneity, in the context of which there is a requirement for novel quality control approaches. By contrast, Mode 1 refers to knowledge production that is academic-oriented, disciplinary, homogeneous, and autonomous. The most prominent distinction in the shift from Mode 1 to Mode 2 knowledge production is transdisciplinarity, which refers to “the integration of different skills in a framework of action” (Gibbons et al., 1994, p. 4). Of course, other theories have also been proposed from different perspectives in order to model knowledge production in contemporary societies. Etzkowitz and Leydesdorff (1998; 2000), for instance, have put forward a Triple Helix model, in the course of which they emphasize that “industry, university and government are increasingly interdependent” (Hessels & Van Lente, 2008, p. 747). In other words, the exploration of knowledge production should not be limited to the academic context; instead, extrinsic factors should also to be taken into consideration when elaborating the dynamics of knowledge production.

The dynamics of science, then, challenge existing approaches used for measuring and evaluating the current science system, even as the measurement of science is an important procedure for the effective management of scientific research. For instance, research-funding agencies play an essential role in the development of science and technology, for research has become capital-intensive, and scholars need regular grants to support their work. On the one hand, as demands for investment in science and technology increase, funding agencies are likely to influence research development through their policies. For instance, research topics on a priority-funding list may energize research interests. On the other hand, since funding is a scarce resource, it is necessary to ensure that grants are allocated to outstanding researchers and to research projects with a substantial potential impact. The measurement and evaluation of science are therefore useful for ensuring proper resource allocation. In this case, funding agencies may be interested in identifying emerging research topics in order to capture the dynamics of science.

This dissertation is motivated by the ongoing challenges involved in measuring science. More specifically, the focus is on the measurement of research performance, in an attempt to satisfy the various demands of research management, and on the quantitative study of science. Furthermore, this thesis aims to develop effective and flexible approaches for addressing the difficulties that arise in the dynamic context of science.

The dissertation consists of two parts, a cover essay and five appended studies.[1] The cover essay introduces the research background, presents the overall research aim and scope, and briefly summarizes the results and contribution. In the following sections of this cover essay, I will first discuss the dynamics of science in detail and clarify the relevant concepts. Section 3 describes research questions raised by knowledge dynamics. A brief introduction of the data and methodologies is provided in Section 4. Section 5 summarizes each appended paper. Finally, the contribution and limitations are discussed in Section 6.

[1] Some texts in the cover essay directly cite the appended papers. For the purposes of facilitating the flow of this essay, quotation marks are excluded in these cases.

2. Background: The dynamics of science

This section introduces the background of this thesis. The growth of knowledge in magnitude and the transformation of knowledge in structure are discussed in subsections 2.1 and 2.2, respectively. In subsection 2.3, the concepts that are fundamental to this thesis are elaborated.

2.1. The increasing magnitude of knowledge

Scientific publications are essential carriers of knowledge, serving as channels for the communion and diffusion of novel thoughts and experimental results. The growth of knowledge can therefore be measured in terms of the annual number of publications. The Web of Science (WoS) is one of the most important and frequently used bibliographic databases for researchers worldwide. To illustrate the increase in magnitude, publications of the document types of *article* and *review* between 1980 and 2014 were retrieved. Fig. 1 shows the yearly number of publications over the last 35 years.

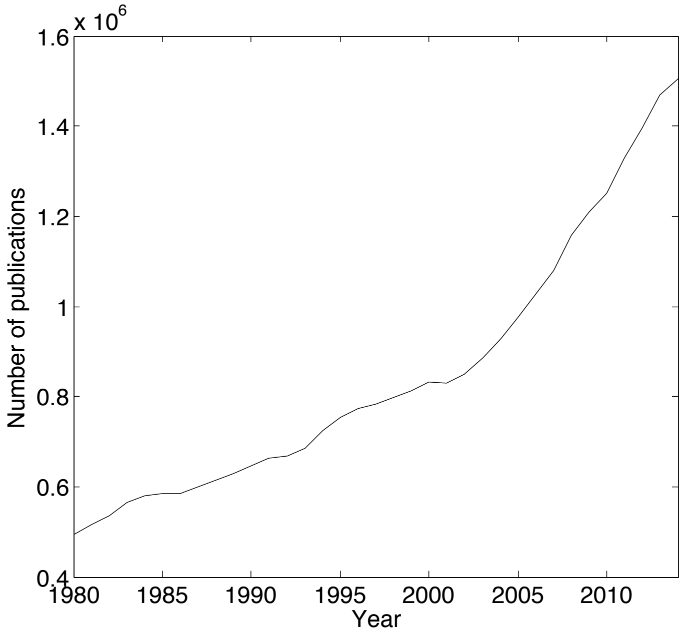

Fig. 1. Number of publications in the WoS from 1980 to 2014

As can be seen from Fig. 1, the number of publications has increased rapidly. Moreover, the growth in yearly publications in the second half of this time window (roughly from 1995 to 2014) is even more rapid than in the first half.

It should be noted that the WoS just indexes a limited number of academic journals; in this respect, it can be considered a subset of the whole scientific publications. For this reason, the actual number of scientific publications is much larger than those that the WoS covers. Despite this limitation, the information provided by the WoS offers insight into the growth in scientific work.

The increase of science and knowledge can also be observed in terms of the number of researchers. Fig. 2 illustrates the number of researchers per million people in the years 1996 and 2009 using data obtained from the Trends Shaping Education 2013 from the Organisation for Economic Cooperation Development (OECD). As shown, except for the Russian Federation, all of the countries surveyed show an upward trend. Finland has the greatest employment of researchers per capita, and Portugal shows the greatest magnitude of growth. These statistics verify indirectly the growth in the magnitude of science.

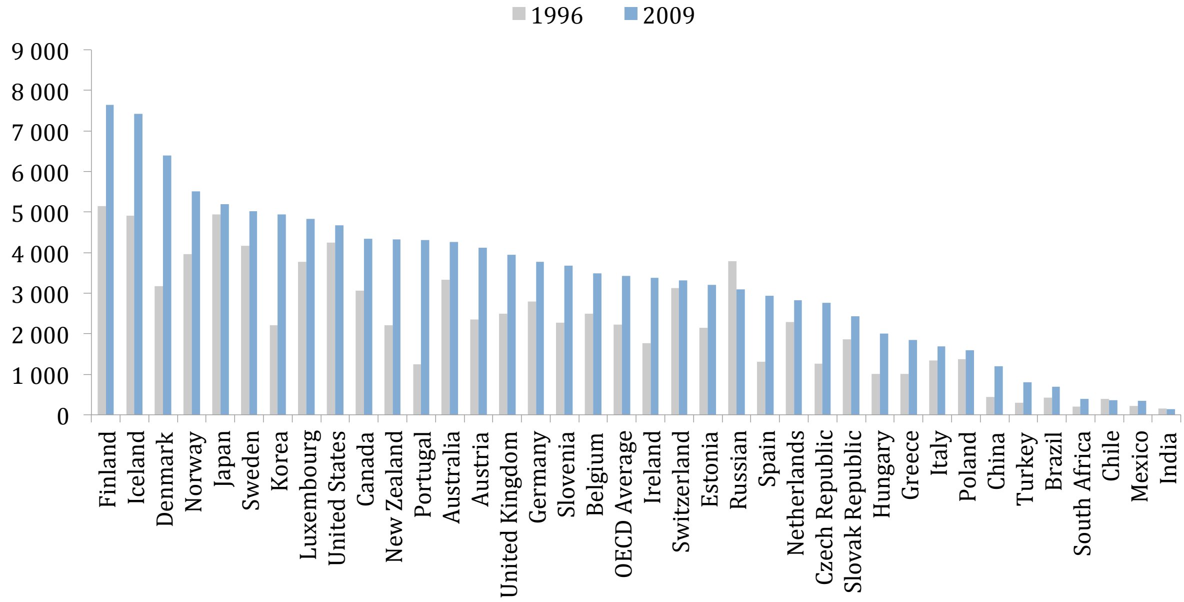

Fig. 2. Number of researchers per million people, in 1996 and 2009

Based on these considerations, it can be concluded that the science system has experienced a rapid increase in size over the last three decades. With this fact having been established, the transformation in the structure of scientific knowledge will be discussed in the next subsection.

2.2. Transformation in the structure of knowledge

The dynamic nature of science is also reflected in the transformation of its structure. As mentioned above, the structure of science refers to the classification of the science system into different disciplines according to the similarity of research. To elaborate this transformation in structure further, it will be useful to begin with a discussion of the emergence of disciplinary research. This subsection first reviews briefly how scientific knowledge evolved into such disciplines as mathematics, physics, and chemistry. The emergence of interdisciplinary research is then elaborated from cognitive, methodological, and practical perspectives. This subsection concludes with a focused analysis of the research field of biological science.

2.2.1. Emergence of disciplinary research

This subsection discusses how scientific knowledge evolved into disciplines from the cognitive, institutional, and social perspectives.

Cognitive perspective In the 1930s, Fleck considered scientific discipline formation to be a process in which “many developing strands of thought intersect and interact with one another” (1979, p. 14). He did not, however, provide an explicit explanation for how thoughts interact with or remain separate from one another. Fleck seems to imply that a boundary is formed by “thought style,” which is the pattern or the fundamental principles that a community of scientists shares and respects (1979, p. 159-161). A thought style constrains and determines the way in which a community of researchers thinks. The formation of a thought style is a long process, one that starts in the early stages of a discipline and undergoes an evolution of concepts as well as experiments, both successful and unsuccessful, as the discipline develops.

Thought style is similar to the famous concept of paradigm that was proposed by Kuhn (1962). A paradigm is a series of fundamental theories, methodologies, and technologies to which researchers within a scientific community adhere. Various disciplines (or what Kuhn called a disciplinary matrix) then develop according to their own paradigms.

It is obvious that knowledge production is a dynamic process. Fleck considered the development of a scientific fact a similarly continuous process, and in this sense thought style is relatively stable within a specific scientific community, and is tolerant to challenges and even compatible with changes. Kuhn’s theory, however, emphasized revolution as the main force behind scientific progress. Kuhn’s paradigm is incompatible with challenges or changes; according to him, revolution results from tensions existing in the current paradigm. A new paradigm is then established and replaces the original one. In other words, scientific progress is a discontinuous process (Chalmers, 1982). Tracing back the history of science, Fleck’s approach to the progress of science is better suited to the purposes of this thesis.

From a cognitive perspective, cognitive similarity is a significant criterion to differentiate scientific knowledge, since each scientific discipline has its own logic (Lenoir, 1997). Furthermore, a discipline may split into several sub-disciplines as scientific knowledge develops and becomes specialized.

Institutional perspective From an institutional perspective, the appearance of disciplines can be traced back to the eighteenth century in two German universities, Halle and Göttingen (Weingart, 2010). One of the explicit purposes for establishing disciplines or departments was to resist and deny traditional authorities.

As Clark (2006) has pointed out, traditional academic authority was reflected in clothing, books, chairs, titles, and other markers of position in a hierarchical society. However, in eighteenth-century Germany, rational authorities gradually replaced traditional authorities in academia. One signal of this shift was the establishment of a new lecture catalogue structure that was ordered in a scientific and systematic way. Along with this transformation, scholars were re-organized in accordance with their research disciplines, and this new structure gradually replaced the traditional seniority-based structure. In the process, a discipline-based classification system became the prevailing way in which academic labors were partitioned in nineteenth-century Western society (Clark, 2006). With the emergence of new lecture catalogues, departments and division structures were established that provided the framework for modern universities.

A further purpose of institutionalization was to address the increasing accumulation of scientific knowledge. With the institutionalization of knowledge, it became relatively easier for scholars to identify with a scientific discipline and in this way to perform their research. Later, academic institutions such as academic journals, conferences, and research funding agencies started to classify scientific articles and grant applications according to a disciplinary structure.

Another primary advantage of institutionalization is that scientific knowledge can thus better serve social functions, for instance by contributing to the education of young specialists and to the evaluation of research performance (Huutoniemi, 2012; Rinia, 2007; Turner, 2000). The development of society can also influence the evolution of scientific disciplines; thus the appearance or disappearance of a discipline may be the consequence of its historical and social contexts (Krishnan, 2009). For instance, environmental science has emerged as a discipline as a response to increasingly severe environmental problems.

Of course, the emergence of academic disciplines can be explained from other perspectives, such as philosophical or political. In this thesis, however, I focus on two closely related dimensions, namely cognitive and institutional, adopting the perspective that the nature of a scientific discipline lies in cognitive similarity within the boundary of the community. To be specific, specialists within the same discipline hold a similar understanding with regard to fundamental theories and techniques. As just discussed, the appearance of academic departments, divisions, journals, conferences, and so on was accompanied by the institutionalization of scientific knowledge. Meanwhile, the impulse to serve society also stimulates the emergence of scientific disciplines. It should, however, be noted that the boundaries of disciplines somewhat represent an arbitrary demarcation of knowledge according to cognitive similarity. In sum, scientific disciplines are the intellectual (cognitive) and social (institutional) structures by which modern knowledge is organized (Bordons et al., 2004).

2.2.2. Emergence of interdisciplinary research

As knowledge increases, scientific disciplines may be further subdivided, creating numerous specialties that, in general, have a narrow research scope compared to the disciplines from which they arose. This process is referred to as knowledge specialization. Further, in the process of knowledge specialization, the integration of scientific knowledge from various disciplines or specialties also takes place. Klein (1996) has described the process of knowledge specialization and knowledge integration,

> [a]s older fields have divided into smaller units through fissioning, they have confronted the fragments of other disciplines. The deeper specialization goes the greater the number of specialties, and the greater inevitability of specialists meeting at the boundaries of other disciplines…. Specialization produces narrower and narrower fields, nearly all of which correspond to the intersection of two disciplines…. Depending on the case, "interdisciplinarity" may be used as a symbol of crisis, the means of exploding an over rigid disciplines, or the foundation for a new discipline. (p. 45)

As Klein observes, along with the specialization of science, knowledge from various specialties or disciplines begins to undergo integration. The occurrence of knowledge integration has been interpreted from three perspectives: cognitive, methodological and practical.

Cognitive perspective As discussed above, scientific disciplines are partitioned on the basis of cognitive similarity. However, it should be noted that perception of cognitive similarity is inevitably limited by the development of science and technology at a given time. Thus the boundaries of disciplines are not absolutely strict and permanent, and are likely to fragment inherent relations of knowledge from different disciplines. In other words, while some studies belong to different scientific disciplines, they may in fact be closely related in certain important aspects.

As science and technologies develop, inherent connections among different disciplines may be recognized and revealed. In this case, new research fields that incorporate knowledge drawn from different existing scientific disciplines may appear. This new type of field is referred to as an interdisciplinary research field. Traditional or existing disciplines are used as benchmarks for measuring interdisciplinarity.

Thus, for example, tracing the emergence of biomedicine, it can be seen that the discovery of common patterning genes in all animal life including humans brings together the research fields of biology and medicine. Exploration of animal development using genetics also contributes to uncovering the causes of human diseases (Burggren et al., 2010). Although current biomedicine may no longer be considered an interdisciplinary research field, its emergence points to inherent connections between biology and medicine. Because of the limited cognition at the time before biomedicine emerged as a field, the underlying linkages have required time and effort to be uncovered. In other words, the demarcation of the science system is confined to the development of science and knowledge at a given time. The connections among certain research fields that are currently considered quite different, though they may in fact be closely associated, may thus take a long time to become apparent.

Methodological perspective The methodological dimension takes into account the fact that concepts, methods, techniques, and so on from different disciplines can be borrowed and integrated in order to solve research problems in a particular research field (Bruun et al., 2005; Klein, 2010). This pattern is quite common in current scientific research. For instance, statistical and mathematical methods have been adopted in various fields as important tools for conducting quantitative analysis. It is however obvious that not all such research patterns may be considered interdisciplinary. If an adopted methodology only functions as an auxiliary tool, the original field is unlikely to undergo significant change, and can therefore hardly be considered an interdisciplinary research field by virtue of the newly introduced technique or practice.

Bioinformatics is a useful example for explaining the emergence of interdisciplinary research from a methodological perspective. This field is concerned with combining knowledge “from the fields of experimental molecular biology and biochemistry, and from the artificial intelligence, database, pattern recognition and algorithms disciplines of computer science” (Doom et al., 2003, p. 387). The principal research problem of bioinformatics focuses on the representation, analysis, annotation, and mining of large databases of genome sequence information (Doom et al., 2003). This focus differs from the fundamental research questions of either computer science or molecular biology. In this case, computer technologies do not function merely as auxiliary tools; instead, researchers also develop bioinformatics algorithms to analyze biologically relevant data.

Societal perspective The societal dimension takes into account the fact that interdisciplinary research tends to be regarded as crucial for exploring and solving intricate problems that are not confined to a single discipline. Gibbons et al. (1994) argue that one characteristic of Mode 2 knowledge production is application-oriented, “knowledge is intended to be useful to someone whether in industry or government, or society more generally and this imperative is present from the beginning” (p. 4). The report on Facilitating Interdisciplinary Research that was published a decade after Gibbons et al. by the National Academies of Science in the US lists four drives of interdisciplinary research, the inherent complexity of nature and society, the desire to explore problems and questions that are not confined to a single discipline, the need to solve societal problems, and the power of new technologies (Committee on Facilitating Interdisciplinary Research, 2005). As can be seen, the latter three drives are all related to practical demands.

Some interdisciplinary research has emerged in response to complex problems. For instance, as mentioned, the increasingly serious environmental problems in some developing countries have fostered the rapid development and evolution of environmental science, which can now be conceived of as an application-oriented interdisciplinary research field.

Previous studies have also discussed the relationship between applied research and interdisciplinarity. For instance, Rinia et al. (2002) observes that applied research fields are likely to be interdisciplinary based on analyses using citation-based indicators, since applied fields largely depend on results and references from basic research. Similarly, Sandström et al. (2005) posit a connection between applicability and interdisciplinarity based on an investigation of the WoS journal classification system. However, some researchers conclude that while the interdisciplinary approach plays an important role in addressing practical and societal problems, this does not necessarily mean that all interdisciplinary research is practical and application-oriented (e.g., Morillo et al., 2003).

It can therefore be concluded that, on the one hand, the emergence of interdisciplinary research is inevitable as implicit and inherent connections among existing disciplines are gradually revealed. On the other hand, increasingly complicated research is also required in order to integrate knowledge drawn from different domains and to explore potential solutions to complex problems.

2.2.3. From disciplinary to interdisciplinary: A case of biological science

In the previous section, the evolution of academic disciplines has been discussed from a theoretical perspective. Here, the evolution of biological science is used as a concrete example. The origin of the modern biology can be traced back to the late eighteenth century. Treviranus (as cited in Richards, 2002) described early biology as follows,

> [t]he objects of our research will be the different forms and manifestations of life, the conditions and laws under which these phenomena occur, and the causes through which they have been effected. The science that concerns itself with these objects we will indicate by the name biology or the doctrine of life. (p. 4)

In other words, biological science takes life and living organisms as its research field. Because of the cognitive limitations, biological science in the eighteenth and nineteenth centuries was limited to the study of zoology and botany. However, the invention of advanced microscopes substantially accelerated the development of biological science, since researchers could now observe bacteria, fungi, and various other small organisms and structures. With the improvement in microscopy, biologists began observing the structure and function of cells, gradually establishing the field of cell biology.

Likewise, as chemistry advanced, the breakthrough represented by the discovery of the structure of DNA has accelerated the fragmentation of biological science. To be specific, the subfields of biological science can be roughly classified into two groups. One involves research on living organisms, and the other takes place at the molecular level, that is,

> [s]earching below the large-scale manifestations of classical biology for the corresponding molecular plan. It is concerned particularly with the forms of biological molecules and ... is predominantly three-dimensional and structural—which does not mean, however, that it is merely a refinement of morphology. It must at the same time inquire into genesis and function. (Astbury, 1961, p. 1124)

As can be seen, organismal biology in many ways continued research units of traditional biological science. However, studies at the molecular level differ from traditional biological studies.

Furthermore, Burggren et al. (2010) observe that "Biology and medicine – two distinct disciplines each with their own approaches, currencies, and outcomes – have nonetheless coexisted as intertwined disciplines for more than two millennia" (p. 120). They further explain that the knowledge obtained from biological science, especially from studies on animals, has been used to investigate medical problems for thousands of years. This fact suggests that knowledge integration between biological science and medicine began taking place at a very early stage in the development of both disciplines. Moreover, explorations of living organisms at the cellular and molecular levels further deepen knowledge integration between modern biological science and medical science. In other words, biological studies at the molecular level promote and accelerate the integration of medical and biological knowledge. The understanding of cells and molecules helps medical scientists to understand diseases in depth and thereby to explore possible therapies. Advances in modern medicine are thus connected to advances in biological studies.

In addition, biological science has also interacted with computer, mathematical, and statistical knowledge in the last half century. This integration has been of particular importance in terms of handling complex molecular biological data. Since most studies of molecular biology are quantitative, the emergence of bioinformatics is connected with the increasing challenges in analyzing large-scale data. Bioinformatics studies are conducted at the interface between molecular biology and computer science. It can be concluded that bioinformatics is an application-oriented interdisciplinary research field.

An in-depth study of the evolution of biochemistry and molecular biology can be found in Chen et al. (2014), who count the proportion of cited references to papers in the fields of biochemistry and molecular biology from 1900 to 2012 and propose that the integration of disciplines is likely to start from neighboring fields and then to extend to distant research fields. The field of biological science provides empirical evidence for this claim because its evolution began with the integration of such closely related research fields as medicine and has extended to fields that appear to be quite removed, such as computer science.

Apart from the examples mentioned above, biological science has also integrated with such research fields as environmental science, engineering, and physics, as can be seen in Fig. 3.

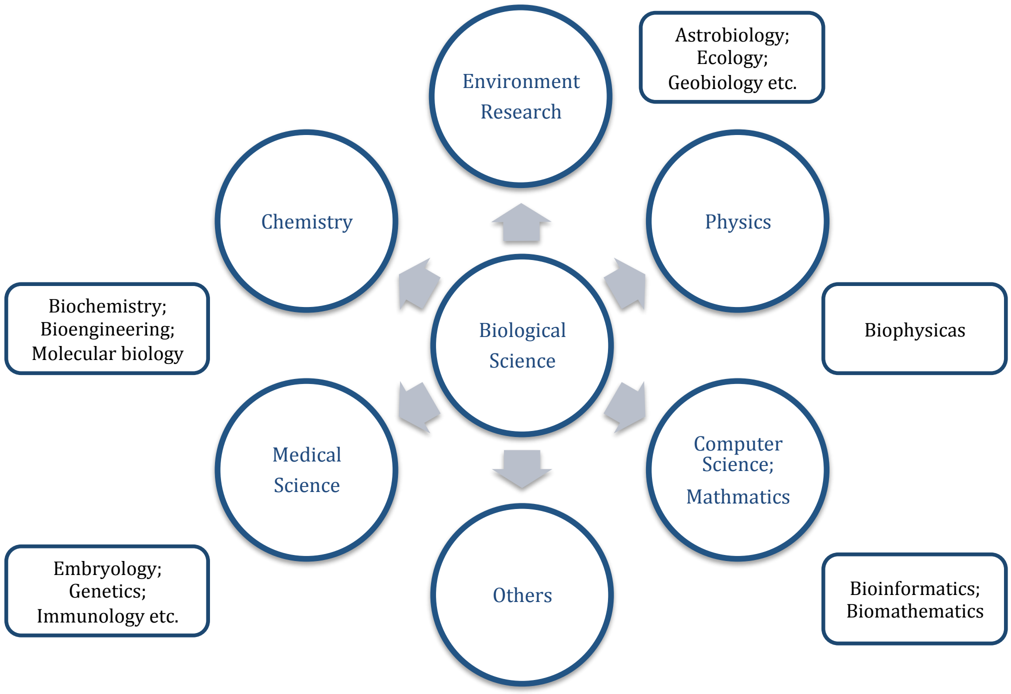

Fig. 3. Biological science and its branches

It should be stressed that I am not claiming here that biomedicine and biochemistry are interdisciplinary research fields; these fields, in the course of their development and maturation, have elaborated their own distinct languages, theories, and methodologies. Thus the boundaries between these and other disciplines have been established, for which reason they can no longer be considered interdisciplinary research fields. As Burggren et al. (2010) observe, biochemistry was recognized as being located at the interface between biology and chemistry in the early 20th century. Today, however, biochemists (or molecular biologists) seldom consider their research as inherently interdisciplinary, since they have already developed a language of their own that differs from that used in either biology or chemistry. This issue will be further elaborated presently; the aim here is merely to introduce the process of boundary crossing and knowledge integration.

I conclude this subsection with three remarks. First, academic disciplines can be considered as the structure of the science system, with the characteristic of being dynamic. This means that the scope and aims of a specific discipline may undergo changes and adjustments in order to keep pace with cognitive development and the shifting social demands to address emerging and urgent problems. Furthermore, a research field may be characterized as highly interdisciplinary at a certain point, but, after knowledge convergence, this field may in time construct its own particular language and logic, thus establishing the boundaries of a distinct discipline. In this sense, such a research field can no longer be considered interdisciplinary. This suggests that, when an interdisciplinary field reaches maturity, as is indicated by the establishment of a corresponding department in universities and by the development of its own journals, conferences, curriculum of study, and so on, this field should be perceived as a distinct discipline rather than an interdisciplinary one. Interdisciplinary research thus has the essential property of time variance.

Second, in the process of evolution, the specialization and integration of scientific knowledge proceed concurrently or alternatively. One point worth stressing is that specialization and integration are not contradictory concepts. Klein (1996) argues that "specialization produces narrower and narrower fields, nearly all of which correspond to the intersection of two disciplines" (p. 45). Fig. 4 illustrates this process of knowledge specialization and integration. In a sense, knowledge specialization can be seen as promoting the emergence of interdisciplinary research.

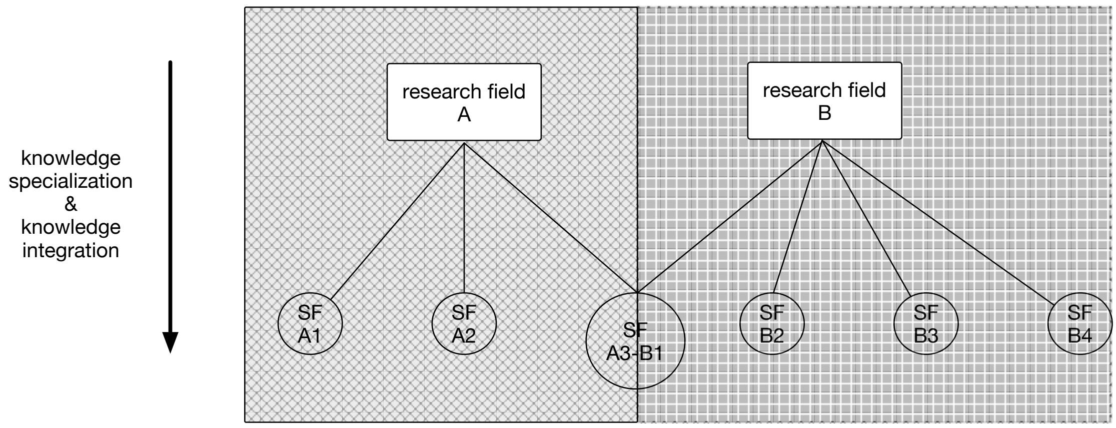

Fig. 4. Knowledge specialization and integration

The definition of an academic discipline can be discussed from various perspectives, such as cognitive or institutional. This dissertation focuses on the cognitive aspect to understand the transformation in the structure of science. I acknowledge that the information made available by academic institutions and organizations can also be used to analyze this transformation. In fact, previous studies have already investigated interdisciplinarity with regard to institutional information, for instance the use of research area codes from funding agencies (e.g., Sandström et al., 2005; Song, 2003) and the departments to which researchers belong (e.g., Morrison et al., 2003; Sanz-Menendez et al., 2001). However, shifts in academic institutions are always time-delayed; meanwhile, universities do not demarcate departments using the same criteria. These factors increase the obstacles to the investigation of the structural transformation of knowledge. Studies on interdisciplinarity from the institutional perspective are, thus, not within the scope of this thesis. Furthermore, from the cognitive perspective, disciplines are characterized by homogenous knowledge, whereas interdisciplinarity emphasizes heterogeneity and the integration of knowledge. This distinction is among the most significant between these two patterns of knowledge production.

2.3. Basic concepts

In previous subsections, terminology relevant to disciplinary and interdisciplinary research has been introduced. It is therefore important to clarify and distinguish these sometimes overlapping terms. This subsection introduces the concept of a discipline first, followed by a discussion of the concept of interdisciplinary research.

2.3.1. Concepts of disciplines

According to Stehr and Weingart (2000), “Disciplines are diffuse types of social organizations for the production of particular knowledge; they differ in size, in their orientation, and in their structure” (p. xiv). At the same time, academic disciplines are the basis on which the system of modern science is differentiated and organized (Bordons et al., 2004).

As discussed above, a scientific discipline is comprised of two dimensions, cognitive and institutional. From the cognitive (intellectual) perspective, a discipline is a branch of the science system in which a community of scientists uses a shared set of underlying theories, methodologies, instruments, and so on in order to address research questions that fall within a defined set of boundaries and constitute the norms for evaluation (Darden & Maull, 1977; Lamont, 2009). On the other hand, the institutional aspect of scientific disciplines takes into account such organizational structures in academic society as departments in universities and the subject categories of journals (Rinia, 2007). These two dimensions constitute the building blocks of a scientific discipline.

Disciplines play a vital role in many aspects of science. To begin with, disciplines define the boundaries of research fields; a discipline is the repository of accepted knowledge within its domain (Abbott, 2001; Huutoniemi, 2012). Second, disciplines have the functions of education and training, people who enter a discipline learn the accepted and shared principles, theories, and methods within this knowledge domain. As Turner (2000) observes, “disciplinary training creates a community or audience of persons who can understand what is said” (p. 52). Finally, the most important function of a discipline is its responsibility for knowledge validation and evaluation. Achievements within a discipline need to be validated by its experts and researchers according to shared norms.

It is, however, difficult to draw the boundaries of disciplines, which are not always clear and sometimes even arbitrary. In the words of Kuhn (as cited in Stokols et al., 2003), “the boundaries between specific disciplines and sub-disciplines are to some extent arbitrarily defined and generally agreed upon by communities of scholars” (p. S23). Furthermore, as discussed above, the boundaries may separate implicit connections among disciplines because of the cognitive limitations in a certain time period. Hence, the boundaries of scientific disciplines are dynamic, as is the development of science and technologies. In other words, the continuous specialization and integration of knowledge also contribute to the dynamism of disciplines, which are constantly changing in connotation and scope.

Furthermore, such terms as research fields, areas, topics, and specialties are often used interchangeably to denote scientific disciplines. These terms overlap to some extent, but still have nuances, especially in reference to the scope of a discipline. This thesis follows the terminology used by Rinia (2007), according to which discipline and research field are synonymous. The distinction between research fields and disciplines lies in the conception that research fields are more focused on the intellectual or cognitive dimension, whereas disciplines represent the combination of the intellectual and institutional perspectives. Furthermore, a research area is composed of several research fields, whereas research topics represent a fine-grained classification of a specific research field. Fig. 5 takes life science and its branches as an example to demonstrate the distinctions among these similar concepts.

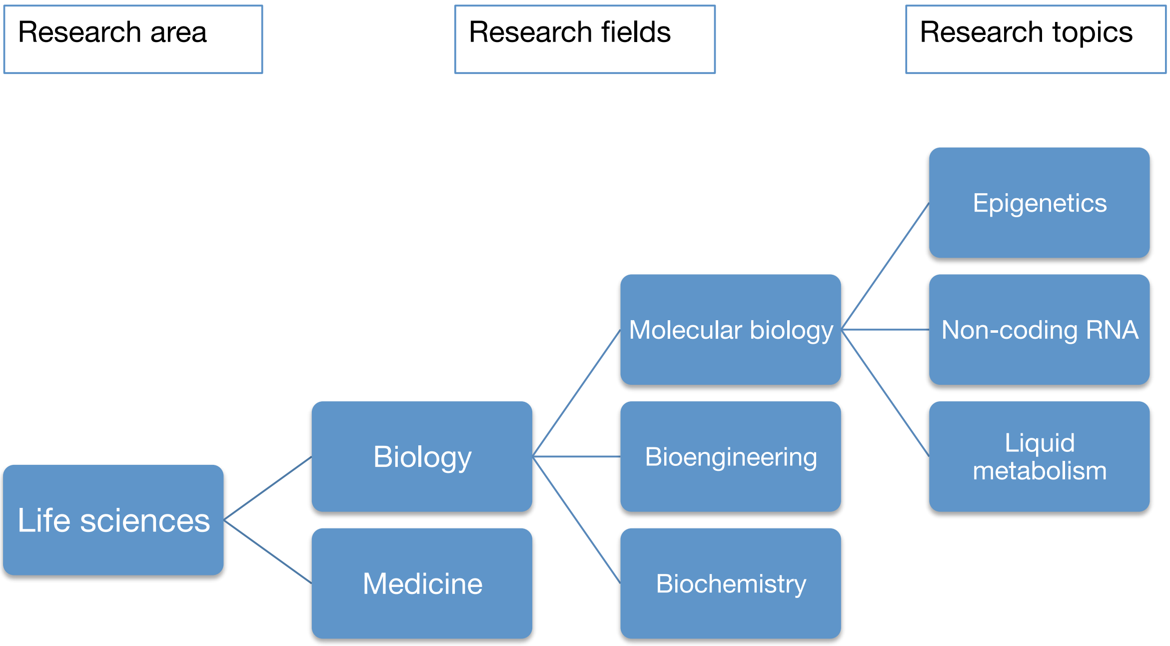

Fig. 5. Various aggregation levels of life science

2.3.2. Concepts of interdisciplinary research

Currently, a wide variety of analogous terms, such as multidisciplinary, transdisciplinary, and cross-disciplinary, is used to describe interdisciplinary research. While some studies aim to clarify the distinctions among these terms (e.g., OECD, 1972; Stember, 1991; Stokols et al., 2003), their definitions and unique characteristics remain ambiguous. There are also studies that attempt to categorize interdisciplinary research; Klein (2010), for instance, demarcates interdisciplinary research as methodological and theoretical interdisciplinary research. An exploration of the nuances of these similar terms will not be undertaken as part of this study. For in fact, all of these terms refer to a pattern of research that combines knowledge drawn from distinct traditional research fields. It should therefore be emphasized that, in this thesis, the term "interdisciplinary research topics" is used to cover all of the terms just mentioned, serving as an umbrella term that embraces interdisciplinary, multidisciplinary, transdisciplinary, and cross-disciplinary research.

Furthermore, this thesis follows the definition proposed in 2005 by the U.S. Committee on Facilitating Interdisciplinary Research,

> [i]nterdisciplinary research (IDR) is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or

> to solve problems whose solutions are beyond the scope of a single discipline or area of research practice. (p. 2)

For the purposes of this thesis, the two fundamental attributes of interdisciplinary research lie in knowledge integration and cognitive distance. It should also be stressed again that this dissertation is in particular focused on the cognitive dimension; as already mentioned, the measurement of interdisciplinarity from the institutional perspective is beyond its scope.

3. Research questions and the outline of the thesis

As discussed above, the dynamic nature of science is embodied in the growth of knowledge in magnitude and the transformation of knowledge in structure. Knowledge production in such a context creates challenges for the measurement of science. For instance, to identify the emergence of prominent research topics is rather difficult with such a background. Therefore, effective and flexible approaches for the measurement of science are increasingly demanded by various stakeholders, such as research assessment organisations and research funding agencies.

This thesis aims to develop flexible approaches in other to address some of the challenges to measuring science effectively. Under this framework, four specific research questions are raised:

Research question I	How to identify emerging research topics?
Research question II	How to assess the accuracy of journal classification systems?
Research question III	How to measure the interdisciplinarity of research topics?
Research question IV	What is the effect of cognitive distance on the peer review process and research output?

These questions have been explored in the five separate papers included within this thesis. Fig. 6 illustrates the overall framework of this thesis, in which the relations of research background, research questions and appended separate papers are described. As shown, research question I is related to knowledge increase in the magnitude, and is addressed in Paper I. Research question II concerns a disciplinary structure of science, which issue is tackled in Paper II. The remaining research questions are all concerned with interdisciplinary research, and have been explored in the other three papers. The following subsections of this chapter elaborate on the formation of these research questions in detail.

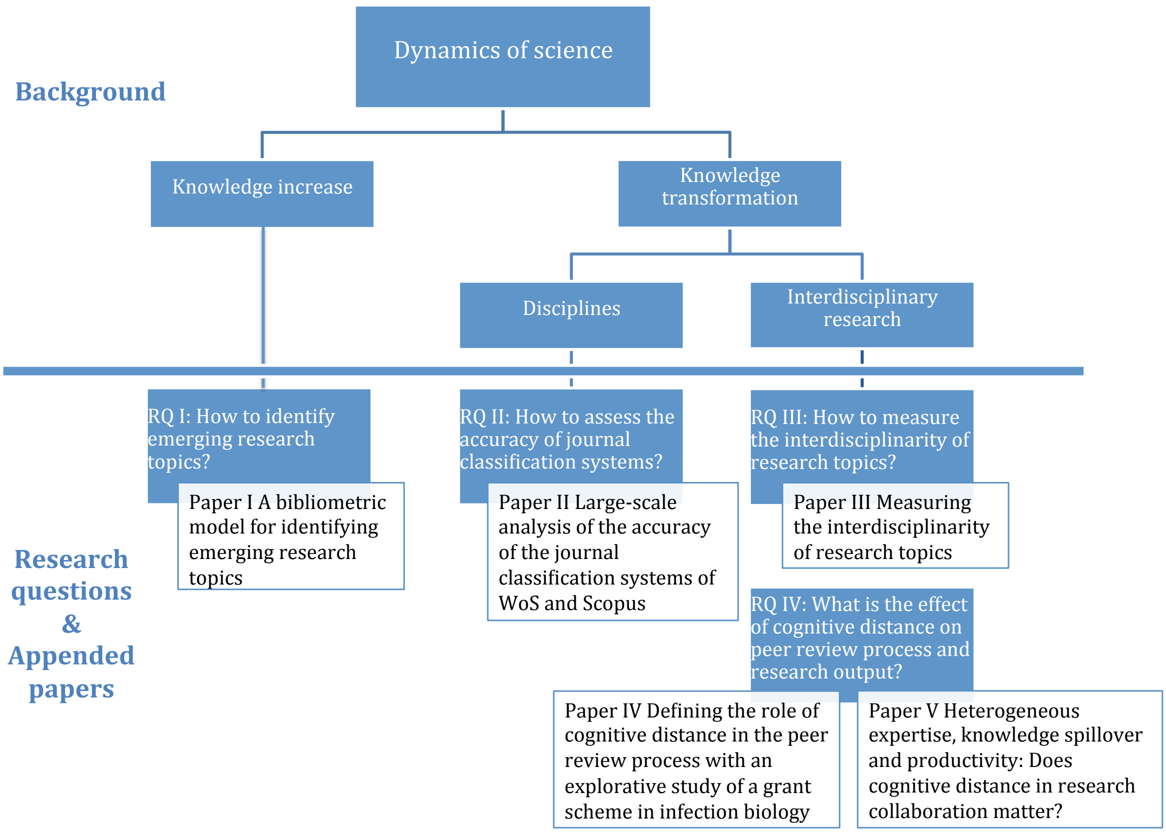

Fig. 6. The overall framework of this thesis

3.1. Importance of identifying emerging research fields

Identifying emerging research fields is useful for various stakeholders. First, it assists funding agencies and research policy makers to identify research topics of prominent scientific impact. Funding policies have a steering effect on the development of science (Braun, 1998). Currently research has become a capital-intensive industry and scholars need regular incoming grants to support their research. In other words, regular research grants are vital for most researchers to carry out their studies. Financing a certain research project could greatly accelerate its development. Thus, it is important for research funding agencies to support the research topics with prominent impact, and put these research topics on their priority list. According to the instruction of the U.S. National Science Foundation (NSF), its aim and responsibility are "to determine where the frontiers are, identify the leading U.S. pioneers in these fields and provide money and equipment to help them continue" (NSF, 2014). Funding agencies in other countries at the national level tend to have a similar responsibility. Hence in order to occupy the leading position of scientific research, funding agencies need to monitor the development of science and technologies and identify emerging research topics.

Second, for universities, it is important for managers of universities to understand the dynamics of science, as it contributes to formulating strategic development planning. To be specific, understanding the emergence of novel and prominent scientific research topics assists in the decision of whether to start a new research unit and to recruit researchers in order to promote the advance of an emerging field.

In addition, it is worth noticing that the methodology regarding the identification of emerging topics can also be built into a software tool, and therefore provides some business potential. In doing so, the approach could be made available to researchers beyond the bibliometric research field. However, detecting emerging research topics, especially in the entire science system, is challenging. Given the increase of science in magnitude, it is difficult to reveal emerging research topics. Bibliometric approaches can address this limitation by analysing large-scale data.

A paper of Rotolo et al. (2015) systematically reviews various relevant definitions and major empirical approaches for the measurement and identification of emerging technologies. These researchers acknowledge that, although many concepts exist, the fundamental attributes of an emerging technology remain ambiguous, and the connections between definitions and the approaches that have been created are fragile. They further indicated that, while a wide variety of bibliometric indicators have been developed, bibliometric methods for the identification of emerging technologies generally “lack strong connections to well thought out concepts that one is attempting to measure” (p. 1827). This lack of clarity is in fact a general limitation of studies that intend to identify emerging research topics. In this case, a study with a carefully defined concept and well-elaborated linkages between concepts and created indicators for detecting methods is urgently required.

3.2. Accuracy of journal classification systems

A classification system can assist with various problems; for instance, it can be used to demarcate research areas (e.g., Glänzel & Schubert, 2003; Waltman & Van Eck, 2012), to evaluate and compare the impact of research across scientific fields (e.g., Leydesdorff & Bornmann, 2015; Van Eck et al., 2013), and to study the interdisciplinarity of research (e.g., Porter & Rafols, 2009; Porter et al., 2008).

WoS, produced by Thomson Reuters, and Scopus, produced by Elsevier, are the two most important multidisciplinary bibliographic databases. They both include various types of sources, such as journals, conference proceedings, and books. Moreover, they both provide a classification system at the level of journals, and they both allow journals to have multiple classifications. Both WoS and Scopus journal classification systems are frequently used in bibliometric studies, especially the WoS system. However, while many studies have compare the two databases (for more details, please see Waltman, 2016), no study has systematically compared WoS and Scopus in terms of the accuracy of their journal classification systems.

Moreover, knowledge about the accuracy of the WoS and Scopus classification systems is very limited. Pudovkin and Garfield (2002, p. 1113) acknowledge that in the WoS classification system “journals are assigned to categories by subjective, heuristic methods. In many fields these categories are sufficient but in many areas of research these ‘classifications’ are crude and do not permit the user to quickly learn which journals are most closely related.” Similarly, Garfield (2006, p. 92) state that “the heuristic methods used by Thomson Scientific ... for categorizing journals are by no means perfect, even though citation analysis informs their decisions.” However, the accuracy of a classification system can seriously influence bibliometric studies. For instance, Leydesdorff and Bornmann (2015) investigated the use of the WoS categories for calculating field-normalised citation impact indicators. They focused specifically on two research areas, namely Library and Information Science and Science and Technology Studies. Their conclusion was that “normalizations using (the WoS) categories might seriously harm the quality of the evaluation” (p. 712). A similar conclusion was reached by Van Eck et al. (2013) in a study on the use of the WoS categories for calculating field-normalised citation impact indicators in medical research areas.

Given the importance of journal classification systems both in bibliometric research and in applied bibliometric work, a study of the accuracy of the classification systems is necessary and urgent.

3.3. Difficulties of measuring interdisciplinarity

As already mentioned, the emergence of interdisciplinary research is the inevitable result of the advancement of scientific research and the requirement of addressing complicated problems encountered in practice. The importance of interdisciplinary research has been widely recognized that it can assist in solving complex problems and promoting scientific developments and innovations.

The empirical evidence of the interdisciplinary tendency has been observed in the work of Porter and Rafols (2009), where they conclude that science is becoming more interdisciplinary in small steps. Moreover, the interdisciplinary tendency is also reflected in science policies, for funding agencies in many developed countries are considering enhancing interdisciplinary research as a topic of priority (Bordons et al. 2004; Rinia, 2007). For instance, research-funding agencies like NSF, Research Councils UK (RCUK), NSFC, and Swedish Research Council (VR) take the promotion of interdisciplinary research an essential task. However, as interdisciplinary research is taken seriously, the term interdisciplinary and its synonyms become buzzwords. Many researchers have attempted to include these terms in publications and research applications in other to attract more attention.

Previous explorations assessing the degree of interdisciplinarity have been conducted at different levels of analyses. More specifically, interdisciplinarity can be measured at the level of single papers (e.g., Uzzi et al., 2013), individual researchers (e.g., Gowanlock & Gazan, 2013; Porter et al., 2007), journals (e.g., Leydestorff, 2007; Leydestorff & Rafols, 2011; Rafols et al., 2012; Zhang et al., 2015), research topics (e.g., Rafols & Meyer, 2010; Morooka et al., 2014), and macro research fields (Porter & Rafols, 2009; Morillo et al., 2001, 2003).

In fact, on-going interdisciplinary practices are more likely to take place at a meso level, namely research topics. On the one hand, Colliander (2014) indicate "(u)nits in science larger than specialties, i.e., disciplines and fields, primarily perform infrastructure functions such as teaching, funding, and the institutional provision of libraries and laboratories (Morris & Van der Veer Martens, 2008), and it is generally not very meaningful to talk about research contributions being made to the advancement of knowledge in a discipline (Chubin, 1973)" (p. 23). On the other hand, measuring interdisciplinarity at a lower level, for instance that of individual researchers and journals, might be useful for editors, potential contributors, university managers, and other stakeholders, these individuals are not in a position to suggest the formation of an interdisciplinary research topic. Thus, ongoing interdisciplinary practices are more likely to take place at a meso level. However, to my knowledge, most investigations of this type are case studies, which can only examine the interdisciplinarity of a given research topic, and are not suited to identifying ongoing interdisciplinary practices.

With such a background, a systematic and comprehensive study for revealing interdisciplinary research topics that already exist and are gradually emerging is a matter of considerable significance.

3.4. Cognitive distance in research evaluation and outcomes

To elaborate the background of this research question, it is better to start with the term cognitive distance. In this thesis, cognitive distance refers to the difference of respective knowledge bases. As already mentioned, this thesis considers that the two fundamental characteristics are knowledge integration and cognitive distance. This research question is related to one dimension of interdisciplinary, that is cognitive distance.

Cognitive distance in grant decisions Nowadays, research evaluation is an essential tool for enhancing quality control in science (Luukkonen, 2002), and preventing low quality research from taking place. From the perspective of sociology of science, scientific communities play an important role in the evaluation of academic contributions (Cole, 1992). A scientific community is an invisible organisation, where its researchers hold a certain paradigm and are committed to the shared concepts, theories, instruments and methodologies. New contributions tend to be assessed according to the criteria of whether they fit the existing paradigm. In other words, knowledge production should follow the criteria of a certain paradigm. It implies that scientists within a specific research area should learn its specific appropriate theories, methods, and techniques, which forms a highly structured set of modern science (Gibbons et al., 1994).

Moreover, as indicated by Chubin and Hackett (1990), "[r]esearch evaluation is on the world science policy agenda because quantitative analyses of science can inform the resource allocation decisions faced by policymakers" (p. 183). In order to receive research grants, researchers have to formulate their research proposals according to the norm of a certain research area. In doing so, their applications may be supported and approved by the peers. Therefore, innovation of applications should be built on the existing knowledge of the corresponding research area, and also keep in line with peers' comprehension (Whitley, 2000). However, for interdisciplinary and front research topics, they cannot fit in any existing paradigm and their scientific communities may be still under development, as they are likely to break the boundaries and paradigms of existing research fields. Knowledge production in such a contest creates challenges for appropriately evaluating the performance of interdisciplinary also emerging research topics.

Nowadays peer review and bibliometric approaches are the two most frequently used methods to assess research performance. In general, peer review is often used for ex-ante evaluation, for instance research funding institutions apply it for selecting potential prominent research applications. Bibliometric approaches are likely to be applied for post evaluation, for instance funding agencies evaluate the research output of a funded project on the basis of some bibliometric data like publications, patents, and citations. In this dissertation, I am focused on peer review.

While peer review is intended to improve the credibility of the decision-making process for research funding agencies, its procedures do not always function as expected. While bias in peer review is a crucial issue that has generated many discussions (Bornmann, 2011; Bornmann & Daniel, 2005; Wesseley, 1998), cognitive bias is often ignored. Cognitive bias indicates a situation where scientists with a mainstream view of their respective fields could jeopardise a fair review process of new and alternative research strategies. It is obvious that cognitive bias is more easily generated in the boundaries between and even within disciplines (Travis & Collins, 1991; Whitley, 2000). Therefore, cognitive bias may serious affect the evaluation of interdisciplinary research proposals. However, this issue has not systematically examined yet.

Cognitive distance in research output. As an extension of the discussion on cognitive distance, the effect of cognitive distance between collaborators on research output is further examined in this thesis.

Previous studies have analysed the relations of interdisciplinarity with research output (e.g., Larivière et al., 2015; Yegros-Yegros et al., 2015). For instance, Yegros Yegros et al. (2015) use an inverted U-shape to describe relationship between interdisciplinary research, which is assessed using disciplinary diversity in the references of a publication and citation impact. However, few studies have measured the interdisciplinarity between collaborators, and explored its effect on research output.

Nowadays collaboration plays an increasing important function in modern knowledge production. Wuchty et al. (2007) indicate that research is increasingly done with collaborations among scientists instead of solo work. Also, teamwork is positively associated with producing high impact research, and leads to higher individual academic productivity (Ductor, 2015). Furthermore, Jones (2009) points out that individuals are likely to face an increasing burden of knowledge, and thus choose narrower expertise, which forces them to work in teams. Indeed, there are some studies that have investigated the relation of certain attributes between collaborators and their research impact. For instance, Freeman and Huang (2015) conclude that diversity in ethnicity, location, and references of a paper between collaborators are positively associated with publishing in higher impact journals and receiving more citations compared with papers with less diversity in these respects.

However, there are still no systematic investigations on the cognitive distance between collaborators and its effect on research output. This is probably because of the lack of individual-level data and the difficulties of addressing the endogeneity and selection issues in a collaborative relation. With such a background, as an extended discussion on the cognitive distance between collaborators and the effect of cognitive distance on research output is explored in this thesis.

4. Data and research methodology

4.1. Data

The WoS database is the primary one used in the appended papers. The Scopus database is also used in one study, that is Paper II. In practice, the appended papers are based on the data from the in-house WoS and Scopus databases of the Centre for Science and Technology Studies (CWTS) of Leiden University.

The two bibliographic databases include academic publications and such relevant information as authors, authors' institutions, journals, and references. Fig. 7 illustrates these bibliographic features.

Fig. 7. Bibliographic features

4.2. Research units of bibliometric analyses

The appended papers in this thesis address different research units of bibliometric analysis. Table 1 classifies research units according to the levels and dimensions. Since not all the research units are discussed in the appended papers, the following subsections are focused on those that are.

Table 1. Research units of bibliometric analyses

	Aggregation	Research output	Institutional aspects
Micro level	Research topic	Publication	Researcher
Meso level	Research field	Journal	Research agency & university
Macro level	Research area	Subject category	Country

4.2.1 Research units from an aggregate perspective

Research units that are demarcated from various aggregated levels have already been introduced in section 2.3.1. In practice, the appended papers are primarily conducted at the level of research topics.

In this thesis, research topics were constructed based on the direct citation relations of individual publications. The reason for choosing a direct, citation-based clustering method is that "a co-citation or bibliographic coupling relation requires two direct citation relations" (Waltman & Van Eck, 2012, p. 2380). This means that "co-citations and bibliographic coupling are more indirect mechanisms than direct citations, and direct citations may therefore be expected to provide a stronger indication of the relatedness of publications" (p. 2380). The use of direct citation relations is also supported by Klavans and Boyack (2015), who have studied the algorithmic construction of classification systems at the level of individual publications. They conclude that the use of direct citation relations yields more accurate results than bibliographic coupling or co-citation relations.

The research topics were established mainly based on the clustering method of Waltman and Van Eck (2012; 2013). It should be noted that Papers I and III conduct at the same aggregation level, which contains around 10,000 research topics over a 10-year time period. The level of research topics is a suitable tier to observe a current emerging and interdisciplinary research topic. As already explained, high aggregated levels of the science system are not suitable for observing the dynamics of science. In this thesis, research topics are at a fine-grained level of the science system.

4.2.2 Research units from the perspective of research output

Scientific publications are widely recognized as carriers of knowledge that function as channels for exchanging and diffusing novel thoughts and empirical results. Various bibliographic characteristics can be retrieved from a publication. For instance, one can find author(s), author affiliation(s), references, and such information about particular publications as titles, abstracts, and keywords, as shown in Fig. 7. The information regarding publications, especially references and citations, is frequently used in this thesis. Citation relations of publications are the basis for clustering research topics, evaluating research impact, measuring interdisciplinarity, and so on. Section 4.3 provides a concrete discussion of citation analyses.

Furthermore, academic journals are important subjects of bibliometric studies. "Journals are a communication channel for a specific research community and as such reflect characteristics that are typical for such as community, specialty or discipline" (Rinia, 2007, p. 32). Some bibliographic databases, like the WoS and Scopus, provide journal classification systems that assign journals with similar research topic to categories, as discussed above. This thesis uses journals and journal classification systems to evaluate the impact of research and to study the interdisciplinarity of research topics. More specifically, the relationship of journals and their assigned categories is systematically examined in Paper II, and Paper III employs the WoS systems to capture interdisciplinary research topics.

4.2.3 Research units from an institutional perspective

From the institutional perspective, research units can be classified as researchers, research agencies, and countries. Papers IV and V are focused on the cognitive distance of researchers.

The performance of an individual researcher can be measured using various indicators, such as the number of publications, received citations, and the impact of the journals in which his or her articles have been published. Nowadays, the most widely recognized indicator for assessing the performance of an individual researcher is the H-index, which was proposed by Jorge E. Hirsch in 2005. This indicator balances a researcher's production (the number of publications) and influence (the number of citations). Because of its simplicity and straightforwardness, the H-index has attracted a great deal of attention. As Waltman and Van Eck (2012) observe, however, the algorithm that the H-index uses to integrate publications and citations could lead to inconsistencies when ranking scientists.

For this reason, Papers IV and V primarily investigate the research performance of an individual researcher using publications, citations, and combined indexes of publications together with citations or the journal impact factor. Other information relevant to a researcher is also included for the purpose of the analyses; thus, for instance, Paper V uses institutional information about researchers to examine whether geographic proximity has an effect on the productivity of coauthors. This thesis does not include analysis at the level of research agencies and countries.

4.3. Citation analyses

This subsection introduces the most important methodology used in the appended papers, namely citation analysis. I begin with the term "citation indexing." According to Garfield (as cited in Moed, 2006),

> [t]he concept of citation indexing is simple. Almost all the papers, notes, reviews, corrections and correspondence published in scientific journals contain citations, they cite —— generally by title, author and where and when published —— documents that support, provide evidence for, illustrate, or elaborate on what author has to say. Citations are the formal, explicit linkages between papers that have particular points in common. A citation index is built around these linkages. It lists publications that have been cited and identifies the sources of the citations. Anyone conducting a literature search can find from one to dozens of additional papers on a subject just by knowing one that has been cited. And every paper that is found provides a list of new citations with which to continue the search. (p. 11)

It can be seen that a citation index includes cited and citing references. Individual publications are connected by their citation relations. The citation behavior according to which articles refer to earlier publications is "supposed to identify those earlier researchers whose concepts, methods, equipment, etc. inspired or were used by the author in developing his or her own article" (Egghe & Rousseau, 1990, p. 203). Cronin (1981) speaks of citations as "frozen footprints on the landscape of scholarly achievement; footprints which bear witness to the passage of ideas" (p. 16). An article may also be cited for other purposes, for instance in order to correct or criticize the work of others (Egghe & Rousseau,1990).

There are three types of citation relations, namely direct citation, bibliographic coupling, and co-citation, as shown in Fig. 8. Direct citation is straightforward and easy to understand; for instance, in the figure, P3 shares direct citations with the other four publications. When two publications are citing the same publication, they have a bibliographic coupling relation (Kessler, 1963); conversely, when two publications are cited by the same publication, they are co-citations (Small, 1973). In Fig. 8, P1 and P2 are co-citations, whereas P4 and P5 are bibliographically coupled.

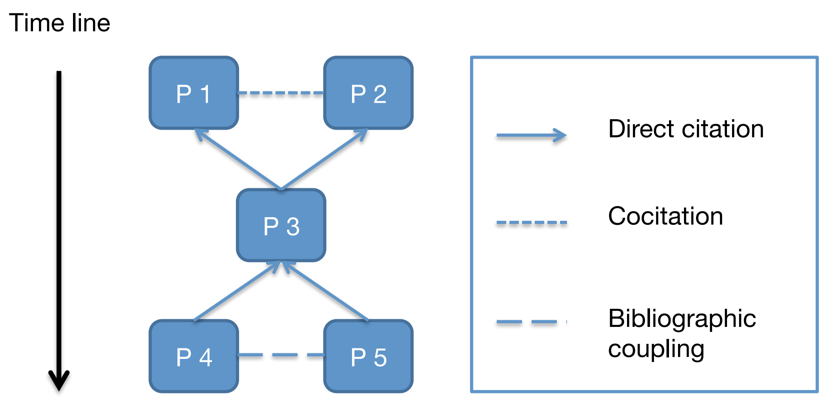

Fig. 8. Three types of citation relations

(Note that the figure has been revised based on Shibata et al., 2009)

The three types of citation relations have been frequently used to conduct various bibliometric studies. For instance, Waltman and Van Eck (2012) construct research fields based on direct citation relations; Small et al. (2014) identify emerging research topics using a combination of co-citation based clustering methods and a direct citation based clustering method; and Glänzel and Czerwon (1996) use bibliographic coupling relations to identify core documents and front topics.

There are several ongoing discussions regarding the accuracy of various types of citation relations in conducting bibliometric analyses. For instance, Ahlgren and Colliander (2009) compare the accuracy of different approaches for measuring document-document similarity and suggest that a linear combination of bibliographic coupling and text-based approaches performs best for first-order similarity measurement. Waltman and Van Eck (2012), however, argue that "a co-citation or bibliographic coupling relation requires two direct citation relations" (p. 2380), which would mean that bibliographic coupling and co-citation relations are less direct measures than direct citation relations. The use of direct citation relations is also supported by Klavans and Boyack (2015), who have studied the algorithmic construction of classification systems at the level of individual publications. They conclude that direct citation relations yield more accurate results than bibliographic coupling or co-citation relations.

There are, however, drawbacks to the use of direct citations. For instance, two publications may both cite the same document that is for some reason not included in the selection of publications, and therefore cannot be linked according to direct citation relations (Waltman & Van Eck, 2012). It may lead to a loss of information.

The appended studies primarily use direct citation relations to conduct analyses; bibliographic coupling relations are also used in Paper IV. Concrete reasons for choosing certain citation relations are provided in the appended papers.

Apart from citation analyses, other methodologies are also applied in the appended studies to achieve various research purposes, for instance text analysis, econometric methodologies, and visualization tools.

5. Summary of the appended papers

The overall theme of this thesis is to measure science effectively under a dynamic background. To achieve this purpose, four specific research questions have been proposed, as discussed in Section 3. Table 2 presents an overview of the appended papers, in which the level of analyses and research methodology of each paper are concisely summarised. The following subsections present primary research findings from the appended papers.

Table 2. Overview of the appended papers

Research question	Paper	Level of analyses	Methodology
RQ I How to identify emerging research topics?	Paper I A bibliometric model for identifying emerging research topics	Research topics	Bibliometric approaches
RQ II How to assess the accuracy of journal classification systems?	Paper II Large-scale comparison between the journal classification systems of Web of Science and Scopus	Journals and subject categories	Bibliometric approaches
RQ III How to measure the interdisciplinarity of research topics?	Paper III Measure the interdisciplinarity of research topics	Research topics	Bibliometric approaches
RQ IV What is the effect of cognitive distance on the peer review process and research output?	Paper IV Defining the role of cognitive distance in the peer review process with an explorative study of a grant scheme in infection biology.	Researchers	Bibliometric approaches and text analyses
	Paper V Heterogeneous expertise, knowledge spillover and productivity: Does cognitive distance in research collaboration matter?		Bibliometric approaches and econometric analyses

5.1. Detecting emerging research topics

Article I addresses the first research question by developing a novel method for the identification of emerging research topics. As discussed in Section 3, identifying emerging research topics is an essential subject, which is useful for various research agencies including for instance universities, publishing institutions and research funding agencies.

Paper I starts by contemplating the definition and attributes of an emerging research topic. The concept that Article I uses carefully adjusts the definition of an emerging technology that Rotolo et al. (2015) proposed. In Paper I, An emerging research topic is expressed as,

> a radically novel and relatively fast growing research topic characterized by a certain degree of coherence persisting over time and with a considerable scientific impact.

Accordingly, the four attributes of an emerging research topic are radical novelty, relatively fast growth, coherence, and scientific impact.

Furthermore, based on the attributes of emergence, a set of indicators for the identification of emerging research topics are created. The linkage between each attribute and each indicator has been well elaborated. In short, the growth and novelty of a research topic is measured with the annual number of publications. The number of citations that publications within a cluster have received is used for evaluating scientific impact. Coherence is assessed using the total number of within cluster citations divided by the total number of publications. A research topic can be considered as emerging only if it satisfies all criteria, namely the research topic should have a rapid growth, show radical novelty at the early stage of its emergence, present a prominent scientific impact, and be coherent.

The proposed approach was applied to research topics that were constructed based on the direct citation relations of individual publications. Using two sets of parameter values, several emerging research topics were identified. Finally, evaluation tests are conducted by the demonstration of the proposed approach and comparison with previous studies. The strength of the present methodology lies in the fact that it is fully transparent, straightforward, and flexible.

5.2. Examining the accuracy of journal classification systems

Paper II answers the second research question by examining and comparing the accuracy of the WoS and Scopus journal classification systems. Criteria to examine the category assignments of journals are based on direct citation relations between journals and categories. Criterion I is used to identify journals that in terms of citations have weak connections with their assigned categories, and Criterion II is used to identify journals that are not assigned to categories with which they have strong connections. If a journal satisfies either of these two criteria, it can be concluded that the classification of the journal is questionable.

Furthermore, the combination of Criteria I and II is also used to identify journals that have weak connections with all their assigned categories while they have a strong connection with a category to which they are not assigned. These can be seen as the journals with the most questionable classification.

The most important findings regarding the accuracy of the WoS and Scopus journal classification systems can be summarized as follows. First, WoS performs much better than Scopus according to Criterion I. Scopus journals are assigned to categories with which they are only weakly connected much more frequently than in WoS. Second, based on Criterion II, WoS and Scopus both perform reasonably well, with WoS having a somewhat better performance than Scopus. In other words, if a journal is strongly connected to a category, WoS and Scopus typically assign the journal to that category. Third, WoS also presents a significantly better result than Scopus based on the combined Criteria I and II. The results suggest that WoS and especially Scopus tend to be too lenient in assigning journals to categories. A significant share of the journals in both databases, but especially in Scopus, seem to have assignments to too many categories. The databases could adopt a stricter policy in assigning journals to categories. Such a policy could be supported by the use of citation analysis.

5.3. Measuring the interdisciplinarity of research topics

Paper III answers the third research question by providing an approach to measure the interdisciplinarity and conducting analyses at a fine-grained aggregation level. It aims to provide a systematic and comprehensive study on identifying interdisciplinary research topics from recent scientific literature of all research fields.

This work follows the definition proposed by the U.S. Committee on Facilitating Interdisciplinary Research in 2005. Taking it as a starting point, cognitive distance and knowledge integration are considered the two fundamental features of interdisciplinary research. To be specific, Paper III first constructs research topics based on direct citation relations among publications. A publication within a research topic may belong to one or several WoS subject categories on the basis of the journal in which it appears. Hence, an established research topic might belong to one or several of WoS categories according to the classification of within cluster publications. The WoS classification system can be considered a traditional perspective on scientific disciplines. Accordingly, a created research topic may represent a combination of traditional disciplines.

If a research topic could be considered as interdisciplinary, it should satisfy two criteria. The research topic should contain publications that belong to distant

WoS categories, and simultaneously publications in different categories should have intensive citation relations. The indicator used in this paper combines the two dimensions. Using this indicator, the degree of interdisciplinarity of research topics are obtained. This paper randomly selects high interdisciplinarity research topics for in-depth analyses. Finally, evaluation tests are conducted by mapping the citation relations of with-cluster WoS subject categories.

5.4. Cognitive distance in research evaluation and outcomes

Papers IV and V explore the last research question, that is the effect of cognitive distance on grant decisions and on researchers' research output. As discussed above, cognitive distance is one important dimension for interdisciplinary research.

Specifically, Paper IV aims to provide a method for measuring cognitive distance between applicants and reviewers, and to explore the role of cognitive distance on the results of the peer review process. Paper IV works on the level of individual researchers. Cited references and the content of articles are used to represent researchers' respective scientific knowledge bases. Furthermore, Paper IV adopts an author bibliographic coupling method and an author-topic modelling to capture cognitive distance. The research design is applied to a competition for grants in infection biology from the Swedish Foundation for Strategic Research (SSF).

The research findings of Paper IV are as follows. First, the results from this case study show that cognitive distance is a neglected dimension when the SSF selected referees for reviewing the research proposals. Moreover, Hick et al. (2015) acknowledged that some Nordic universities allocate research funding or bonuses on the basis of a number, for instance, by calculating individual impact scores to allocate performance resources or by giving researchers a bonus for a publication in a journal with a high impact factor. The research findings from Paper V somewhat confirm this statement in that the review results in the first round of peer review are largely influenced by the research outcomes of applicants, in particular the impact factor of journals where they have published their work.

Second, regarding the relations of cognitive distance and peer review results, the initial hypothesis of Paper IV is that reviewers are likely to support the applicants who are most similar to them. However, based on the second round peer review of the case, reviewers are actually more likely to approve applications with which they are familiar, and the same applies for applications with which they are relatively unfamiliar.

To explain this rather complicated result, the concept of 'optimal cognitive distance' is borrowed from the research field of knowledge management, which emphasises inverted U-shaped relations between cognitive distance and absorptive capacity (Nooteboom et al., 2007). For this case, to avoid cognitive bias, reviewers should be selected in the range of optimal cognitive distances with corresponding applicants.

Following Paper IV, Paper V explores the effect of cognitive distance between collaborators on peer effects and research output. In this study, cognitive distance is measured using a combined indicator, in which a researcher's publication history and the similarity of journals in which researchers have published are both taken into consideration. To address the endogeneity and selection issues, some prominent and productive researchers are identified, who passed away unexpectedly in the field of life sciences. Furthermore, Paper V applies a difference-in-differences strategy to estimate the changes in research output of researchers who have collaborated with these identified deceased scientists to determine if the changes differ in the cognitive distance between them, after the death of the prominent coauthors.

The results show that, following the death of an active and prominent life scientist, coauthors with close cognitive distance from the deceased scientist are more likely to experience a lasting decrease in productivity. While the cognitive distance between a coauthor and a deceased scientist attenuates the negative shock, the relationship appears to be non-linear for different measures of productivity. For measures of the quantity of research, the impact of cognitive distance on the magnitude of spillovers seems to approximate an inverted-U-shaped relationship. That is, the research output of coauthors at the close or distant level of cognitive distance statistically significant decreases after the loss of an active collaborator, compared with coauthors of middle cognitive distance in relation to the deceased scientist. However, for measures that place more stress on the quality of research, only cognitively close coauthors experience a severe decrease in research productivity.

This study assumes that knowledge spillover is more likely to exist between collaborators with a close cognitive distance (Azoulay et al. 2010). On the other hand, collaborators with a greater cognitive distance may be the result of a complement of different skills. In this case, the findings suggest that, after losing a preeminent collaborator, the loss of an irreplaceable source of ideas causes a more adverse impact on a survivor's productivity than the potentially imperfect skill substitution. The former may have impacts on both quantity and quality of the research productivity, while the latter mainly affects the research quantity.

Finally, it should be explained that Papers IV and V both estimate the cognitive distance among researchers, but different strategies are used for the measurement. To be specific, Paper IV uses an author bibliographic coupling method and an author-topic modelling to capture cognitive distance, whereas Paper V combines the researchers' publication history with the similarity of journals in which researchers have published. The main reason is that, in Paper IV, if researchers (referees and applicants) are not active in the same time frame, there is very little overlap of used references, especially when the research field has a very rapid knowledge renewal speed. Moreover, Paper V is focused on the research field of life science, which tends to present a quick knowledge production speed. For instance, if two researchers are not active in the same time period, they are less likely to reference the same publications. In this case, using author bibliographic coupling relations to estimate the cognitive distance among researchers may not be an optimal solution. Therefore, Paper V applies a new approach combining the similarity of journals and the distribution of publications across journals to reflect the cognitive distance of researchers.

6. Contribution and limitations

This dissertation begins with a consideration of practical problems in the measurement of science in the context of a dynamic environment. Given the increase in the magnitude of knowledge and the transformation of its structure, measuring science effectively and accurately is fraught with challenges. This thesis aims to develop approaches to address certain problems in current methods of research measurement. To achieve this purpose, it explores the identification of emerging research topics, the accuracy of the frequently used journal classification systems, the measurement of interdisciplinarity, and the effect of cognitive distance among researchers on grants decisions and on research output and impact. This section presents the contributions and limitations of the work presented here.

6.1. Contribution

This thesis primarily offers methodological contributions. Specifically, a series of methodologies concerning the measurement of science is proposed to tackle the challenges created by the dynamics of science. Paper I proposes a novel methodology for identifying emerging research topics that highlights the transparency of the definition as well as the connection between the definition that is used and the constructed indicators. The proposed methodology is rather flexible, which could make it useful for researchers with different goals. Paper II defines criteria for examining the accuracy of the WoS and Scopus journal classification systems that could also be employed to investigate other academic journal classification systems. Paper III presents a flexible methodology for measuring the interdisciplinarity of research topics. Papers IV and V offer proposals for the measurement of cognitive distance between researchers.

While the major contribution of this dissertation lies in the improvement of bibliometric approaches, it also offers insight into the current science system. For instance, Papers I and III identify current emerging research topics and interdisciplinary research topics, respectively. Unlike previous work, these two studies approach the construction of research topics using citation relations among publications. This bottom-up strategy can reveal recent and ongoing emerging or interdisciplinary research topics. Moreover, the results from Paper II provide insights into the accuracy of the frequently used journal classification system that have implications for future bibliometric studies. Paper IV explores the role of cognitive distance in grant decisions, thereby complementing investigations of latent biases in peer review processes, which can enhance the fairness of grant peer review. Furthermore, Paper V investigates the effect of the cognitive distance between collaborators on academic publications on their research output and research impact. Empirical evidence is provided for interpreting the relations of collaboration and knowledge production from the perspective of cognitive distance.

This thesis has implications for various stakeholders. For publishing organizations and database producers, the methodology for scrutinizing the accuracy of journal classification systems could be adopted as a basis for inspecting their own classification systems, and thereby improving the quality of such systems. Moreover, since a journal classification system can assist with various problems, such as evaluating and comparing the impact of research across scientific fields (e.g., Leydesdorff & Bornmann, 2015; Van Eck et al., 2013), advancing the quality of a system could also contribute to research in these fields. The identification of emerging research topics is also valuable for publishing institutions, for they can use the results when considering whether to launch new journals on novel research topics.

For policymakers and research-funding agencies, the identification of currently emerging and interdisciplinary research topics is helpful for observing and monitoring the dynamics of science and for detecting potentially prominent research themes. Furthermore, the exploration of the role that cognitive distance plays in grant decisions may help to start discussion on how to avoid or reduce cognitive biases in the peer review process, including how to select appropriate reviewers.

For universities, it is important to understand the dynamics of science, for the understanding aids in the formulation of development strategies. In addition, the investigation of the effect of the cognitive distance between collaborators on research output and impact might provide insight into personnel recruitment.

Finally, it is worth mentioning that the approaches proposed in this thesis, for instance the methodology regarding the detection of emerging topics, have market potential, since they could be built into a software tool and thereby made available to researchers beyond the field of bibliometric research.

6.2. Limitations

The primary limitation of this thesis lies in validation. While numerous studies have proposed bibliometric methods to measure the performance of science, the efforts to validate these approaches have been limited (Colliander, 2014). This is because of the difficulties inherent in justifying the effectiveness of bibliometric methods. As discussed by Klavans and Boyack (2015),

> [i]n most fields of science, accuracy is of paramount concern. Admittedly, some fields lend themselves more to accuracy than others. This is particularly true for those fields where physical properties can be measured, those for which gold standards exist, and those where a great deal of research is replicated. Unfortunately, none of these conditions are extant when it comes to the delineation of topics, or the creation of taxonomies of the scientific literature; there is nothing physical to measure, there are no gold standards, and very little research is replicated. (p. 8).

The absence of “gold standards” for these types of bibliometric studies increases the difficulties of conducting a validity test. Furthermore, while expert opinions could theoretically be used as an alternative means of justifying the accuracy of results, doing so is problematic. To begin with, the studies compiled in this thesis cover the entire science system. As a consequence, it would be difficult to identify and organize experts who could assess results obtained from such a broad context. Furthermore, experts may have various understandings of a certain definition, such as the definition of an emerging research topic, which may be also differ from the definition used in the appended study, in which case the criteria that experts use to identify a research topic as emerging would differ from those used in the study. Therefore, while expert opinions are indeed an essential channel for laymen to gain insight into an unfamiliar research topic, this means of assessment remains controversial regarding the flexibility of using it to validate the results of some types of bibliometric studies. For this reason, validity strategies should be investigated in future studies.

Moreover, the indicator used in this study to measure the interdisciplinarity of research topics is based on the WoS classification system. As Wagner (2011) observes,

> [m]ost current bibliometric-based measures of IDR output rely largely on journal categories established by ISI. However, we note limitation in the use of journal categories for measuring IDR because of the dependence upon a pre-defined taxonomy or category structure. Studies using journal categories are often viewed as biased due to a lack of consensus around the accuracy of any particular journal category system. (p. 23)

As proposed in Paper II, while the WoS performs much better than Scopus in general, it still has some problematic journal-category assignments. Thus, novel approaches for measuring interdisciplinarity without using any journal classification systems are worth investigating further. For instance, it might be feasible to use the citation relations of research topics to analyze interdisciplinarity; thus topics could be constructed by individual publications using their citation and text relations.

Finally, the analysis of cognitive distance and peer review results suggest that cognitive bias may have a substantial effect on interdisciplinary research proposals, since this type of research is often located at the boundaries of traditional disciplines. Funding agencies should therefore consider taking cognitive distance into account when selecting referees for reviewing research applications. This investigation, however, was conducted based on a relatively small number of cases, which limits the statistical significance, so more empirical tests on the relationship between cognitive distance and peer review are required to support this conclusion.

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