

MEASUREMENT AND
EVALUATION OF
INTERDISCIPLINARY
RESEARCH AND **ED J. RINIA**
KNOWLEDGE TRANSFER

Measurement and evaluation of interdisciplinary research and knowledge transfer

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Promotor: Prof. Dr. A.F.J. van Raan

Referent: Prof. Dr. W. Glänzel (Universiteit Leuven)

Overige leden: Prof. Dr. R.R.P. de Vries

Prof. Dr. Ph. Spinhoven

Prof. Dr. M.R. Rutgers

In herinnering en dank aan mijn ouders

Preface

Interdisciplinary developments in science by definition cross existing boundaries and categories. This is true for both interdisciplinary research practice – researchers working at frontiers of disciplines– as for the flow of knowledge – knowledge that leads to developments and discoveries in other fields. This elusiveness forms a special challenge to efforts of developing methods by which interdisciplinary modes of science can be investigated empirically. Quantitative analyses are increasingly enhanced by development and advancement of bibliometric methods and techniques. The possibilities of these research methods, originally based on large scale analyses of available data in bibliographic databases and other media in which research results are manifested, have strongly increased recently by greater access to data on science and technology through ICT facilities and internet. Results of bibliometric analysis can support research policy by offering insight into the emergence of new fields and new applications, by making visible the networks between fields and the longer term effects and outcomes of research as well as factors playing a role in research assessment, and more especially in the proper evaluation of interdisciplinary research.

This thesis aims to offer a contribution by further analysis, application and development of these methods. This is done by investigating the coherence between science indicators based on bibliometric data and existing evaluation procedures in science, thereby facilitating the evaluation of these mechanisms, in particular peer review in science. Furthermore, this is done by application and further development of bibliometric methods in research on interdisciplinarity in science and the detection of knowledge transfer.

The work described in this thesis is the result of a growing interest in science both as a human endeavour and as a self-organizing system, in its role in society, and in processes of evaluation in science. This interest has been strengthened through my work at the Foundation for Fundamental Research on Matter (FOM - the physics division of the national research council NWO) which promotes, co-ordinates and finances basic physics research in the Netherlands. An important topic of research policy at FOM has always been the search for scientific methods for the evaluation of science and for objective measures of performance and quality in the fields concerned. My work at FOM increasingly involved the use, but also studies of the possibilities and limitations, of science indicators and science statistics in practical purposes in research policy. A large part of the research described in this thesis is related to projects in this context, part of which have been carried out in close cooperation with the Center for Science and Technology Studies (CWTS) at Leiden University. CWTS, as a world leading centre in the development of methods and standards in evaluative bibliometrics, has played a vital role, not only for the handling of large parts of the bibliometric data, but also for the construction of advanced indicators that have been applied in these studies.

I wish to thank the co-authors of articles included in this thesis. Firstly, (former) colleagues at FOM, Mark Brocken, Rudy Kouw, Eppo Bruins and Hendrik van Vuren.

They have stimulated me to pursue the research goals described in this thesis and they were always available for critical discussions. FOM in general should be acknowledged for creating an atmosphere in which it was possible to combine the search for policy relevant results with scientific curiosity.

I also wish to thank colleagues at CWTS for supplying and elaborating the relevant bibliometric information from their impressive data system, for their support and discussions. Especially, I would like to thank Thed van Leeuwen, who is a co-author of many articles in this thesis and who has been indispensable for obtaining large parts of the data used in these studies. I wish to thank my colleagues Ronald Rouseau and Leo Egghe and Henk Moed for their critical appraisal and discussions on parts of the topics described in this thesis.

All this work, however, could not have been done without the support and love of my family. I wish to thank Mona en Minke, who have allowed me to be absent, also while being at home, many days and evenings.

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Part 1 Framework of the thesis: background, context, research questions

1 Introduction

1.1 General Background

One of the most striking changes that are taking place in science in recent decades is the increasing influence of external demands for economic and social relevance of research and its results and, with that, the urge for interdisciplinarity. Examples of this influence can be found, for instance, in the strategy agendas of nearly all research councils and funding agencies in developed countries. Government science policy documents equally reflect these desires. Globally, the contribution of science to the knowledge economy and the enhancement of interdisciplinary research has become an important goal. In principle, the constraints for promoting societal relevance of research results have to be distinguished from those to pursue interdisciplinarity. In practice, though, there are presumed to be strong links between these two goals: inter- and multidisciplinary research is perceived to give important contributions to the solving of not only scientific but also societal and technological problems and innovation. These developments have a strong influence on the way science is being performed, organised, funded, managed and evaluated. Researchers may be confronted with these demands in their research practice by the selection of topics to be studied or by collaborations that are formed; universities and other institutions may change their organisational structures and research programs to meet these demands; research councils adapt their funding programs to stimulate application oriented research and interdisciplinary collaboration (Gibbons *et al* 1994, Etzkowitz and Leydesdorff 1997). Evaluations of science, in the broadest sense, also increasingly have to take into account the contribution of research to innovation and interdisciplinarity. Thereby the problem has to be faced how to properly investigate and assess the contribution of research to these goals. Especially the evaluation of interdisciplinary research poses specific problems. These problems are met at several levels: researchers may have to deal with additional criteria in peer reviewing the work of colleagues, expert committees have to cover a broader range of expertise, science management has to assess its contribution to scientific or technological progress, science policy has to incorporate interdisciplinary developments in setting priorities. As a consequence, demands for methods to analyse interdisciplinarity and to retrieve the consequences of it for evaluation practices, have become stronger.

At the background, with respect to interdisciplinary research several questions are interesting. For instance, from what does interdisciplinarity originate; To what extent does interdisciplinarity exist? In which areas is it emerging? Is there a science-intrinsic drive

and can it be stimulated by policy measures? Is interdisciplinary research of growing importance or has the emergence of e.g. environmental science, materials science, or biophysics in earlier decades been perceived similarly as a historical turn in the production of knowledge? How does interdisciplinary research function and, even more important, to what degree does it contribute to the advancement of knowledge? What is its influence or impact. An important question, also in a research policy context, is whether interdisciplinary research requires specific evaluation methods and procedures. These are, however, many and broad questions that cannot be addressed in a single study.

A survey of the literature learns that, though a lot is written on interdisciplinarity in science, empirical studies on this subject, and more specifically on the topic of evaluation of interdisciplinary research are scarce. In the studies presented in this book the evaluation and measurement of interdisciplinarity in science is the central topic. The work in this study starts from the premise that quantitative studies of science may offer further contributions to analysis and evaluation of interdisciplinary research. It is presumed that these may contribute to reducing the difference between growing emphasis on interdisciplinarity in science on the one side and the lagging behind of research on this subject on the other side. The field of quantitative science studies is also called scientometrics. For an important part of it is based on bibliometric methods. Bibliometric research focuses specifically on the analysis of published accounts of scientific research in order to reveal underlying processes in science¹. Scientometric methods have been developed and applied in an increasing number of studies on science and technology, both for explorative and for evaluative purposes. The central question in this study is to what degree scientometric and more especially bibliometric methods can contribute to a further analysis and evaluation of interdisciplinary research. More specifically we aim to assess and explore the use of these methods in evaluative practises in present day science policy.

1.2 The phenomenon of interdisciplinarity

The enormous growth of science in the past decades has been accompanied by ongoing differentiation and specialisation of fields of knowledge into an increasing number of disciplines and subfields, each showing a different degree of institutionalisation. The diversification of scientific specialties appears to be an autonomous and inevitable process in the development of knowledge production. However, there are counter forces that contribute to integration of specialised knowledge and to the bringing together of disciplinary approaches. This integration of disciplines and specialties is stimulated by several forces, whereby both internal scientific processes and external factors play a role. As an internal drive from within science there is a need to combine knowledge from different fields to cope with specific scientific problems. The emergence of *biochemistry*

¹ The terms *bibliometrics* and *scientometrics* are described in Section 3.2.

and *neurosciences* are examples. An essential factor is here that the knowledge and approaches from different specialties may cast new light on a subject and allow understanding of a problem in a more complete way. In the history of science many examples can be found of scientists who successfully combined different disciplinary approaches (e.g., Scerri 2000). Here specialisation itself may be seen as an incentive for 'recombination'. But also social or technical problems may ask for an integrated approach from different disciplines. Pressure for integration may become stronger as the relation between science and socio-economic welfare becomes more important. It even seems that in recent times societal demands for problem solving capacities in return for large investments in the scientific system seem to be the strongest push for joining disciplinary approaches.

The assumption that (socio/economic) problem orientation is an important incentive for more unifying interdisciplinary approaches of relevant problems and questions is quite generally accepted (e.g. van den Besselaar and Heimeriks 2001). It is partly based on historical evidence. An important drive to what has been called 'pragmatic interdisciplinarity' (Weingart 2000) was given in WOII, when new initiatives were developed which stimulated problem-focused and mission-oriented (military) research (e.g., Manhattan project). Since WOII, the combination of disciplinary approaches has been perceived firstly as a means to solve important technical problems and has been explicitly put into practise in originally mainly governmentally supported laboratories, for instance in areas like nuclear science, atomic physics, materials science or biophysics. In these initiatives to join disciplinary approaches, instrumentality is the central element (Thompson Klein 2000). The idea that interdisciplinarity should be promoted, gained a wider audience in the seventies, when the belief in the possibilities of planning in general were strong. A landmark was the *OECD* report on the blessings of interdisciplinarity (OECD 1972), of which it was admitted afterwards that the ideas had less impact than supposed.

At the end of the eighties, a request for a stronger emphasis in academic settings on application-oriented research in general came up. The push for so-called strategic research was not only strengthened because science budgets became more tight, but also because the role of research as an important factor in the (hampering) economic growth became more apparent. In that context, bringing together different disciplines to address socio-economic and technical questions was being more often considered as a way to enlarge the contribution of scientific research to these strategic goals. This might be attained by specific targeted projects, but also by means of opening up new directions within established specialties. In the case of physics the *US National Research Council* states in 1986 that almost all significant growth has occurred at interdisciplinary borderlands between established fields: biological physics, materials science, the physics-chemistry interface, geophysics, mathematical physics and computational physics (NRC

1986). In the eighties, worldwide also new large interdisciplinary initiatives were set up by which was tried to stimulate interdisciplinarity by a top-down approach. In the US several large programs were initiated by the National Science Foundation for funding interdisciplinary research in the field of engineering (*ERC-program, Science and Technology Centres* program), materials science (*Materials Research Science and Engineering Centres* program) and also specific centres were founded, in particular in the life sciences (e.g. *BPEC*, but also more recently *Bio-X*) (Pray 2003). In many European countries the same happened (AWT 2003). For instance in Germany the Research Council DFG and the Science Ministry (BMFB) started several specific interdisciplinary funding programs and centres.

Although from time to time the value of fundamental science, also for social and economic goals, is brought back to the attention (e.g. Lederman 1984), at present the notion of transforming scientific research into a more important factor in societal and economic innovation seems widespread. Often used concepts like 'knowledge economy' or 'valorisation of research', show the increasing awareness of this fact. This societal pressure is translated to the scientific system by among others funding mechanisms and appears to change the structure of science. At least, this is the way it seems. According to an influential school of thought the relatedness of science and social-economical context now even has lead to new modes of knowledge production. According to Gibbons this new mode is characterised by transdisciplinarity. In this 'Mode 2' agenda setting en validity are determined by problem contexts or contexts of application, rather than by traditional academic disciplinary approaches (Mode 1) (Gibbons *et al* 1994). This theory has been further elaborated in the so-called Triple Helix literature on the triple helix relationship between universities, governments and industry (Etzkowitz and Leydesdorff 2000).

Together with the growing emphasis on the contribution of research to knowledge economies, funding agencies and research councils, which traditionally supported disciplinary knowledge production, have started to stronger enhance interdisciplinary research. At present, there is hardly any national science policy strategy document that does not mention the necessity of encouraging or enhancing interdisciplinary research (Metzger and Zare 1999). For instance, in the Netherlands promotion of multidisciplinary research is an important element in the strategy of the *National Research Council* (NWO 2006). The *Royal Netherlands Academy of Arts and Sciences (KNAW)* created a special working group 'multidisciplinary research'. The *Dutch Advisory Council for Science and Technology Policy (AWT)* recently issued a special advice requested by the Minister of Education and Science entitled 'the promotion of multidisciplinary research' (AWT 2004). The situation in The Netherlands appears not to differ from that in many countries. Many examples of science policy initiatives promoting multidisciplinary research in a number of countries can be found. A recently issued extensive report by the *US National Academy of Sciences* mentions numerous initiatives in the US (COSEPUP 2004) and gives

recommendations to further develop interdisciplinary research. According to these reports it seems that we are at the point where an unprecedented change to interdisciplinary knowledge production is taking place.

A lead motive, central in most of the declarations and documents surrounding these initiatives is that scientific, societal and technological problems have become so complex that more and more often the activation of a diversity of disciplines is requested. In this context, topics like genomics, proteomics, bioinformatics, neuroscience, speech technology, nanotechnology, or climate research, are mentioned. A main feature thereby is the identification of and the link between interdisciplinary research and innovation. In many science policy documents, however, these concepts are used in a vague way. In this study we propose to make a further distinction between types of interdisciplinarity and types of innovation. In this chapter we will further elaborate a distinction between on the one side interdisciplinary activities developing within basic, curiosity driven research and on the other side the enhancement of interdisciplinary approaches by more large-scale projects aiming at the solving of urgent technological problems. The first type concerns border crossing interdisciplinary developments occurring at frontiers of disciplines and specialties and often originating from basic research within disciplines. It is often perceived as groundbreaking because breakthroughs are expected at the frontiers of specialties. This type of interdisciplinarity in this study is named 'small interdisciplinarity'. This is distinguished from the more classic type of interdisciplinarity, often separately organised in specific projects or institutions, with a relatively strong emphasis on the aim to contribute to technological and economic innovation. For this we apply the term 'big interdisciplinarity'. It should be noted however, that these are prototypes and mixed types of both forms will be found. In the literature the concepts of big and small interdisciplinarity have been used before in a slightly different way. *Morillo et al* (2003) take (categories of) journals in a field that are multi-assigned to several closely related subject categories as indicative of 'small interdisciplinarity' and those that are simultaneously classified to several more distant categories as representing 'big interdisciplinarity'. In their study, these concepts are not elaborated further. *Schmoch et al* (1994) appear to refer to both a proximity aspect and an organisational aspect when using these terms. According to their definition, 'big interdisciplinarity' aims at the integration of disciplines of high distance and is mostly carried out in an industrial research environment, whereas 'small interdisciplinarity' stands for 'the re-integration of specialized branches within a discipline' by smaller teams. This latter definition appears to resemble more closely our conception. However, in our view, small and big are not explicitly related to a 'distance' between disciplines involved, although in practice interdisciplinary developments emerging at the borders of disciplines most likely will establish links between more related disciplines. The main distinction between big and small, however, is related to differences with respect to the level of organisation and with respect to application orientation. This means also that 'big interdisciplinarity' more often will

involve a top-down approach whereas 'small interdisciplinarity' is characterised by bottom-up initiatives. Several drives for interdisciplinary research mentioned in the literature (Schmoch *et al* 1994; COSEPUP 2004) have been distinguished.

- solution of urgent (societal) problems of mankind (e.g. global warming);
- introduction of results from scientific research in technological applications (e.g. ITER);
- development of generative technologies (e.g. *ESRF*²);
- re-integration of specialized branches within a discipline;
- exploration of the interfaces of disciplines (e.g. biophysics);
- inherent complexity of nature and society (e.g. the *Human Genome Project*).

The first three motives can be related to 'big interdisciplinarity'; the next two are more specifically connected to 'small interdisciplinarity'. In the last drive a mix of both types of interdisciplinarity may be involved.

In the discussion on the relation between interdisciplinarity and innovation it also appears to be necessary to make a distinction between at least two types of innovation: innovation in the scientific context and innovation in a social, economic or technological sense. In the scientific context, it is often presumed that the crossing of borders of disciplinary fields is an almost necessary condition for progress in scientific research. At least, there is a widespread belief that the most dynamic developments occur at frontiers of disciplines (COSEPUP 2004; AWT 2003). This type of innovation appears to be more closely related to our concept of 'small interdisciplinarity', as distinguished above. Quite commonly, a relation between interdisciplinary research and societal and technological innovation is also presumed. This might partly be explained by the close connection between interdisciplinary research and applied science and problem solving established in the past (Turner 2000). Innovation in this respect, will be more often related to the second type of interdisciplinarity ('big interdisciplinarity') described above. Though in general this may be the case, it should be noted that big interdisciplinarity is not exclusively related to societal or technological innovation just as small interdisciplinarity is not restricted to innovation only in a scientific sense. For instance, big interdisciplinary projects may also contribute to scientific innovation (e.g. the *Human Genome Project*). On the other side, for instance, instruments that result from 'small' interdisciplinary research may find technical application (e.g. NMR), and may contribute to problem solving and innovation outside the scientific system. In general, however, a more close relation between small interdisciplinarity and scientific innovation on the one side, and big interdisciplinarity and non-scientific innovation on the other, may be expected. In Fig. 1.1 the distinction between these types is represented schematically and a typical example of each form is given. It is evident that for each box numerous examples can be mentioned. However, it is presumed that cases belonging to the upper left or lower right box will be more frequently found than those classified in the opposite way.

² European Synchrotron Radiation Facility, Grenoble, France

INTERDISCIPLINARITY		
	small	big
INNOVATION	<i>biological physics</i>	<i>Human Genome Project</i>
social, economic, technological	<i>nuclear magnetic resonance</i>	<i>nuclear fusion research</i>

Figure 1.1 Schematic presentation of the relation between types of interdisciplinary and types of innovation. In each box a typical example is given.

The analytical distinction may be helpful because, as mentioned, the different elements of these concepts often are failed to be distinguished.

The rise of nanoscience and nanotechnology offers a recent example of the claims by both scientists and science managers that interdisciplinarity will lead to eventually both a new science field and new breakthroughs in science and to innovations in a range of technologies. Nanoscale research nowadays is generally seen as one of the most promising areas in science for future applications in physics, chemistry, life sciences, medicine, pharmacology and in technology. As a consequence, it is one of the fastest growing 'areas' in science, as is shown by exponentially growing investments worldwide. According to *Roco* (2003) the worldwide *nanotechnology* research and development (R&D) investment reported by government organisations has increased approximately seven-fold in the last six years from \$432 million in 1997 to about \$3,000 million in 2003. A more recent estimate by the EC mentions that the level of public funding for nanotechnology R&D in Europe has risen from around EUR 200 million in 1997 to the present level of around EUR 1 Billion (Research and Markets 2005).

The emergence of nanoscience is also demonstrated in several bibliometric studies (e.g. Braun *et al* 1997; Meyer and Persson 1998). It was shown that the number of articles in bibliographic databases containing the word *nano* in their title has been exponentially growing since 1985 at an average growth rate of about 34%. If this trend should continue all scientific papers would contain the prefix *nano* in the year 2022 (Schummer 2004). At the same time, the concept of nanoscience is very vague; in fact the only binding factor is the nanoscale size at which research is directed. Still, in most cases and in most countries, the promise of a newly emerging interdiscipline is surrounding many initiatives. Most policy documents and funding programs in this area consider nanoscience not only as an area with potential new technologies, but also as a new step towards integrating different disciplines and enhancing interdisciplinary collaboration. Also from the side of scientists many initiatives can be found which aim at interdisciplinary collaboration in this area.

However, in a study on interdisciplinary collaboration in nanoscience, it was found that in the newly emerging *nanoscience* journals indeed articles from a range of disciplines are included in the specific journals concerned: i.e. the journals showed high multidisciplinary. But it was also found that there was a low collaboration by authors from different disciplines in the same research article, i.e. there was apparently low interdisciplinary collaboration (Schummer 2004). Before, *Meyer and Persson*. (1998) observed no real growth of interdisciplinarity in this area. It still has to be proven whether the boost of *nano* will be more than just an increased appearance in titles of papers, journals, department names, projects applications and so on, and even more whether it is a leap towards growing interdisciplinarity. In this respect an earlier observation concerning interdisciplinary research programs in climate research comes to mind.

'The establishment of such overarching interdisciplines is primarily driven by political goals and needs of legitimation. Most programs are initiated by the scientific community in the first place, or at least they are the result of negotiations between scientists and policy makers. Under conditions of scarce resources and pressures of legitimation scientists will invent problem definitions and labels that appeal to the public and its representatives. The scientists relabel their research projects in order to fit in' (Weingart 2000).

This observation was inspired by the analysis of German interdisciplinary research centres and funding programs. In this analysis *Weingart* found that in spite of goals to stimulate interdisciplinary approaches, finally differentiation and the definition of specialised topics developed, also in these initiatives. Based on case studies in the areas of medical lasers and neural networks, also *Schmoch et al* (1994) conclude that a strong tendency towards a division of research according to traditional disciplines even in interdisciplinary areas can be observed. As an explanation of these contradictions between proclaimed interdisciplinarity and actual specialisation, *Weingart* points to an ambivalence of scientists by which on the one side values are adapted, which include openness to all relevant knowledge as crucial to innovation. However, on the other side they look for niches in uncharted territory, avoid contradicting knowledge by insisting on disciplinary competence and its boundaries, and denounce knowledge that is outside this realm as undisciplined.

'Thus, in the process of research new and ever finer structures are created as a result of this behaviour. This is the very essence of the innovation process but it takes place primarily within disciplines and is judged by disciplinary criteria for validation' (Weingart 2000).

Weingart's analysis further emphasises the importance of disciplinary knowledge organisation and structure (e.g. disciplinary organisation) in knowledge production.

'These structures may be variable over time, but will be necessary 'to maintain the activity, to give it direction for the future by providing the memory of past achievements'. 'Without such a structure ... there could be no such thing as knowledge' (Weingart 2000).

The conclusion is that for interdisciplinarity as an organisational principle leading to innovation, there may be a certain rationale: the diversity of approaches can influence the conditions of creativity. However, in terms of contents, the process of knowledge production is inevitably a process of specialisation and differentiation.

'Every new combination of bits of knowledge from previously different fields, if it is novel, is bound to be more specialised and to create new boundaries. Eventually, social organisation – training, communication, and certification – follow suit.

Therefore, interdisciplinarity and specialisation can be seen as parallel, mutually reinforcing strategies' (Weingart 2000).

This approach counterbalances views that state that only new interdisciplinary forms of science can deal with the complexity of present day problems, involving a more important role of non-scientists (users, stakeholders) in the production and validation of knowledge (Gibbons *et al* 1994). This may be the case in certain topics and areas, but, and this is an important conclusion, these views tend to overlook the fact that real problems are constituted by existing knowledge and its gatekeepers (Weingart 2000). In this context, also van Raan (2000) points to the fact that problem orientation has always been an important motive for science and scientists. However, they must be appealing scientific problems in order to contribute to scientific reputation.

'Though most socio-economic problems are interdisciplinary in nature, scientific appeal and reputation work predominantly disciplinary. This means that a specific discipline will mostly play the first violin in interdisciplinary work' (Van Raan 2000).

This is reinforced by the fact that 'scientific craftsmanship' is learnt on the basis of van disciplinary methods. These theoretical notions offer a basis for the analysis of the contradictions concerning theory and practice of interdisciplinary research. At the same time they throw a new light on efforts in present day science policy to enhance problem orientation and interdisciplinarity.

1.3 First observations

Some important elements for the approach of interdisciplinarity in science can be distinguished. Firstly, it can be concluded that though problem-driven research is an important source of interdisciplinarity, disciplinary structure and validation stay indispensable elements in the definition of scientific problems and the distinction between relevant and irrelevant. Secondly, we learn that interdisciplinary areas may arise, but that structures and the delineation of disciplines and specialties always will come back as essential elements in knowledge growth. It should also be noted that these structures are not per se inhibiting innovation in science, like sometimes appears to be overstated in reports promoting interdisciplinarity in science (e.g. AWT 2004).

Concerning the observed contradiction between interdisciplinarity and specialisation, the insight is fruitful that in science there is a continuing process whereby in spite of forces working towards combining disciplinary approaches and synthesis, inevitably specialisation will occur. However, comparable with processes in biological evolution, both elements should be seen as complementary and as two sides of scientific progress. This insight also counterbalances views on specialisation perceived in its negative connotation as fragmentation. Specialised branches of science then can be compared with the organs in a body, that each have a different task and are also specialised, but that are also indispensable for the functioning and evolution of the whole. So, specialisation can be seen as a necessary and unavoidable process in the evolution of each complex system (Van Raan 2005). Furthermore, in network theory and –research it has been found that the distance between each node in a complex network is never more than six steps. From this we may learn that growing complexity and differentiation does not automatically imply that parts more and more will grow apart.

An important notion from the above given analysis is that progress and innovation in science to a large degree appear to be a consequence of specialisation and differentiation within disciplines and within basic science. It may be concluded that innovation and interdisciplinarity are often enhanced by researchers who see a chance to open up new developments in neighbouring fields, by applying specific approaches from their disciplines and by doing so disclose new niches. This means that often, if not mostly, basic science performed in disciplines and specialised subfields is at the bottom of interdisciplinary developments (Morillo *et al* 2003). In Chapter 12 we address the role of basic areas as sources of knowledge for other disciplines. The *CWTS*³ research profiles, that are used to describe the scattering of publication output and citation impact of research units across disciplines (c.f. Section 3.3), also show that often 'disciplinary' research is in fact inherently interdisciplinary, i.e. it frequently appears to be related to a range of fields. In terms of the previously made distinction between 'big' and 'small' interdisciplinarity, this conclusion means that often 'small interdisciplinarity' will be at the basis of innovative developments in science. It may be concluded that in discussions on interdisciplinary of research it is often failed to differentiate between forms of interdisciplinarity and a neglect of the above given finding is rather widespread.

Furthermore, it is important to notice that technology and instruments, which play an important role in interdisciplinary developments, are often developed in a disciplinary context (Van Raan 2000). The bridging role of instruments between disciplines is discussed in several studies. Instruments are, for instance, seen as partly responsible for the flourishing of new disciplines such as astrophysics, or biochemistry (e.g. Scerri 2000). Many more examples can be found (COSEPUP 2004). *Van Raan* (2000) distinguishes a triangle of socio-economic problems, scientifically interesting problems and

³ Centre for Science and Technology Studies (CWTS), Leiden University, The Netherlands

interdisciplinarity at the basis of the interdisciplinary nature of science. Its dynamics is characterised by the domination of the knowledge of just one or two disciplines. This, in turn is reinforced by technology, mainly by creation of new instruments. As instruments often are typically disciplinary developed, they also further reinforce the role of a specific discipline in interdisciplinary work (Van Raan 2000). Signs of the importance of technology in interdisciplinary developments were also found in bibliometric studies. For instance, the 'bridging function' of work in the subfield of applied physics, as intermediate field between the discipline of physics and other areas, has been shown (Chapter 12).

Given these considerations and questions, it can be concluded that there is an increasing need for studies that empirically analyse interdisciplinarity. Based on the theoretical approaches discussed above, a number of research themes can be identified. Firstly, it appears to be necessary to develop more refined methods and measures to trace the *occurrence, nature, extent of non-disciplinary research* and developments. Studies on this subject often have been exemplary and were started from a historical or philosophical perspective. *Porter and Chubin* (1985) noticed that 'the absence of data on interdisciplinary research has been a bane to the study of this phenomenon. Since the observations by *Porter and Chubin*, a number of studies, especially in the field of scientometrics, have developed methods that contribute to our insight in interdisciplinary processes. In Section 3.3 these methods are discussed. It is concluded that further methodological improvements should be made. These may be helpful to better identify and analyse current models and practices of interdisciplinary research and the impact on research and education. Furthermore these methods will be instrumental in studying processes by which interdisciplinary research originates; to investigate practises and to determine the outcomes. In Chapter 10, 11 and 12 some new approaches to assess the occurrence and extent of interdisciplinary knowledge transfer are presented, based on the analysis of cross disciplinary citations in research literature published world wide.

The bibliometric methods, discussed in Section 3.3 and in Chapter 10, 11 and 12, eventually may contribute to further answers on e.g. the question what exactly the influence is of increasing pressures from science policy to enhance interdisciplinarity and thematic programming. Is it true that at an increasing extent 'the landscape of science is characterised by fashions of the political agenda' (Weingart 2000) or is it just the relabeling of autonomous developments in science. Do the numerous science policy initiatives contribute to a real growth of interdisciplinarity and by which ways? Is for instance nanoscience a buzz or a catalyst for many disciplines to engage in new forms of interdisciplinarity? (Schummer 2004).

A second theme concerns the *analysis of outcomes, impact and influence* of interdisciplinary research. Here too, studies based on empirical data appear to be scarce. E.g. *Steele and Stier* (2000) notes the absence of systematic evaluations on the products

and impact of interdisciplinarity in environmental research, while at the same time in this area interdisciplinary research has been fostered strongly. Combining several quantitative methods, they found a positive correlation between interdisciplinarity and impact in the field of forestry research. Studies like this yield interesting evidence (cf. Section 3.3), but their limited number does not allow for further going conclusions. In view of the increasing number of initiatives to stimulate interdisciplinarity in present day science policy, more extensive studies that empirically investigate its influence and outcomes appear to be necessary. In Chapter 9 we address an element necessary for such studies, namely the suitability of a number of bibliometric indicators as a measure of impact in interdisciplinary research .

Moreover, there is a need to obtain more insight in the *knowledge flows* between disciplines in science and from science to technology and vice versa. Mapping these flows gives a view on the relations between disciplines, the kind of knowledge that is transferred, by what means and with which impact. One of the first larger studies in this respect is the *TRACES* report, commissioned in 1968 by the *US National Science Foundation*. It studied the (disciplinary) origins of a number of breakthroughs in technology, like the oral contraceptive pill, the video tape recorder and the electron microscope. The study showed the important role of basic scientific research that was at the root of these products (Illinois Institute of Technology 1968). Likewise the project *Hindsight*, performed by the *US Defense Department* in the mid-1960s sought to identify the origins in science of significant innovations. It focussed, however, more on management factors and systems applications, which were vital for development of advanced systems. However, since then, few comparable studies of this kind have been performed. In the Netherlands some smaller studies have been conducted (Chapter 6). Problems encountered in studies tracing the influence of (basic) research on other fields, applied science and technology are the long incubation period from first discoveries to final applications and the many factors often involved in this process. In the field of scientometrics new quantitative methods for empirical research on cross disciplinary relations and relations between basic and applied science have been developed. The study of citation flows between disciplines appears to be a fruitful object of study and recently has found some interesting applications (e.g. Small 1999; van Raan and van Leeuwen 2002; NSB 2000). In Chapter 11 and 12 some new indicators on this subject are proposed and new results on interdisciplinary influence from research, in particular in physics, is presented.

A third theme is related to the specific problems in the qualitative and quantitative *evaluation of interdisciplinary research*, also compared to mono-disciplinary research. Evaluation is meant here in a broad sense, ranging from internal scientific validation to external assessments at the science policy level. Before, the specific function of disciplinary knowledge organisation in the validation of new knowledge, based on previously accumulated knowledge, specific methods and disciplinary standards, has been

discussed. In this context, peer review - the assessment of research contributions by colleagues working in the same field - plays an important role. There is a general belief that interdisciplinary work is inhibited by peer review, because of its disciplinary bias (e.g. Metzger and Zare 1999). Such views, for instance, were found in the opinions of British researchers on the *UK Research Assessment Exercise* (Evaluation Associates 1999). Though peer review in general has been studied extensively, there are, however, few studies addressing the topic of peer review in relation to interdisciplinary research (Thompson Klein 2000). The few studies performed up till now, show little empirical evidence for the above mentioned belief. In our studies, an extended validation of peer review by use of bibliometric indicators has been undertaken for the subfield of condensed matter physics (Chapter 7). The functioning of peer review in relation to interdisciplinarity is more specifically addressed in chapter 8 and 9. In chapter nine, furthermore, the validity of bibliometric indicators in case of interdisciplinarity is analysed. We may conclude that further empirical research will contribute to better insight in the functioning of peer review processes in the context of interdisciplinary developments in science. At the science policy level, the complexity in assessing interdisciplinary research is partly replicated, because here often is built further on disciplinary validation mechanisms, including peer review. At this level specific, or additional criteria and measures appear to be less developed in case of interdisciplinary research. In this context has been pointed to the problem of defining proper yardsticks, and perspectives (e.g. on fundamental merit) and to the failure of standard metrics (Hackett 2000). Here too, few studies are known that specifically address the evaluation of interdisciplinary research.

Summarising, it can be concluded that there is a strong need for studies directed at the evaluation of interdisciplinary research from several perspectives, studying the social processes at work (e.g., Laudel 2004), the epistemic dimensions, the development of criteria for judgement (Boix Mansilla and Gardner 2003) and existing and newly developed evaluation procedures. As mentioned, in this thesis we confine ourselves to empirical studies that may strengthen insight in these processes. In the field of quantitative science studies more refined methods already have been and should be further developed to obtain empirical evidence on the degree and kinds of interdisciplinary research, processes of knowledge transfer, indicators and measures of performance and outcomes. A key issue is to use quantitative indicators in ways that support the understanding of the general and specific nature of interactions between types of knowledge-creating and knowledge-utilising entities (Van Leeuwen and Tijssen 2000). In this study we further restrict ourselves to bibliometric methods that may offer valuable contributions to the study of these topics. In Section 3.3, therefore, the state of the art on bibliometric methods directed at the investigation of interdisciplinarity is described. First, however, in the next sections we address the basic elements of the concepts *discipline* and *interdisciplinarity*. Research themes mentioned in this chapter are summarised in Table 1.1.

Table 1.1: Themes and topics for investigation of interdisciplinary research

Theme	Topic	Chapter
1. Evaluation of interdisciplinary research: ranging from internal scientific evaluation to external assessments at science policy level.	<ul style="list-style-type: none"> • Functioning of peer review processes in relation to interdisciplinarity • Development of additional criteria and measures • Determination of outcomes and impact 	6, 7, 8, 9
2. Analysis of interdisciplinary developments in current research: development of methods and measures to trace its occurrence and extent	<ul style="list-style-type: none"> • Developing methods to identify interdisciplinary research • Determining the amount/growth 	8, 9, 10, 11, 12
3. Analysis of impact and influence of interdisciplinary research; mapping of knowledge flows between disciplines and between basic science and technology	<ul style="list-style-type: none"> • Tracing disciplinary origins of breakthroughs and significant innovations in science and technology • Tracing the influence of (basic) research on other fields, applied science and technology and vice versa 	10, 11, 12

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2 Basic concepts

2.1 Main elements of a scientific discipline

Before addressing the theoretical question what can be considered as interdisciplinarity, the main elements of the concept 'scientific discipline' have to be regarded. Disciplines can be conceived as diffuse types of social organisations for the production of particular knowledge (Weingart 2000). They are the intellectual and social structures through which modern knowledge is organised (Bordons *et al* 2004). Historically, disciplines have formed the traditional framework for research in universities and have been the basis of the internal structuring of most universities into departments and faculties (OECD 1999).

Looking at its constituents, the first thing that comes to mind is the cognitive aspect of a discipline. Disciplines comprise the codified stock of knowledge that serves as a baseline against which new knowledge claims are tested and validated. An important aspect of this cognitive dimension is the learning of accepted content and methods to new students who enter a discipline (Turner 2000). Part of the cognitive aspect is also the use of a common (technical) language, as an analytical tool. These elements come together in the description that a discipline provides a structure for research, which helps define the important problems, how they should be approached, by what methods, and what knowledge should be regarded as a contribution to the field (OECD 1999).

The function of knowledge validation by disciplinary organisation and the notion of a common language bring us close to the second aspect of disciplines: the social dimension. Elements from this dimension may range from clearly distinguishable organisational structures like departments for research and training/education at universities, professional organisations and their journals, to less visible, but equally important mechanisms like the allocation of reward and reputation. Merton pointed to the central role of reputation in science (Merton 1973). To a large degree these mechanisms fulfil this role at the disciplinary level. Precisely the less well functioning of this regulation mechanism is one of the problems in the evaluation of interdisciplinary research. Among the social aspects of a scientific discipline also other social characteristics can be distinguished, like 'shared attitudes', 'shared ambitions', or even 'disciplinary arrogance'. Turner (2000) even states that the social dimension is the most important characteristic of a discipline:

'Disciplinarity is a matter of identity and exchange. . . Disciplinary training creates a community or audience of persons who can understand what is said. . . . Notions of disciplinarity about common intellectual cores (i.e. about the nature of knowledge contents) are open to challenge'.

This denial of the importance of the cognitive aspect of a discipline, seems too one-sided. However, the importance of the social function of a discipline cannot be denied. The

above mentioned elements are reflected in the definition of discipline in *Websters New World Dictionary* (as mentioned in Weingart 2000):

- Branch of knowledge or learning
- Training that develops self-control, character, orderness and efficiency
- Acceptance of or submission to authority and control

Typically, this is also reflected in the classical organisation of universities. In the context of scientific disciplines, the latter aspect refers to the social side of the validation function of disciplinary knowledge organisation, which is exercised by a network of interlocking roles (peers, reviewers, gatekeepers) in charge of selecting among proposed variations in a domain (M. Csikszentmihalyi in Boix Mansilla and Gardner 2003).

Presently, it appears that disciplines have become less monolithic, and are more decentralised in smaller units, that are situated less clearly within conventionally defined boundaries (Thompson Klein 2000). Whether this is part of a shift from traditional single disciplinary research mainly located in universities, to new modes of knowledge production generated in new settings combining basic and applied research, has to be proven yet. Nevertheless, theories emphasising these latter aspects have been important for 'highlighting the breadth of disciplinary participation in many current research questions, the loosening and reshaping of many structures within the research environment, and the growing permeability of institutional boundaries' (OECD 1999).

A distinction has to be made between several concepts that are sometimes used as equivalent for the term discipline. Apart from discipline, the terms *research area*, *sub(field)* and *specialty* are often used for the delineation of a specific knowledge domain. The concepts *discipline* and *field* are often used in the same breath. There appears to be a gradual difference in size in social and organisational respect (societies, departments journals) and in a cognitive sense (knowledge domains) from a *discipline* (e.g. *chemistry*) via *field* and *subfield* (e.g. *organic chemistry*) to a *specialty* (e.g. *bio-organic photochemistry*). A *research area* is composed of several disciplines that are cognitively related (e.g. *life sciences*). However, it is not or to a much lesser degree characterised by corresponding social and organisational forms like is the case with disciplines. Furthermore, a *research sector* describes a division of research between different organisational and societal sectors but is not related to a distinct cognitive domain. For instance, the private research sector located in firms can be distinguished from the public research sector located in e.g. universities.

2.2 Concepts of non-disciplinarity

Scientific disciplines can be perceived as organised forms of gathering knowledge on subjects at which human curiosity is directed. An important element is the fact that these

subjects are divided into different areas with more or less clearly distinguished frontiers. In that perception, interdisciplinarity can be described as a development by which areas, which were formerly separated, are joined because the research subjects concerned appear to have tangent planes. For instance, in biological organisms chemical or physical processes are found to play a role, which gives rise to new fields like chemical biology or physical biology. This view includes that interdisciplinarity mainly emerges by advancement in understanding.

The concept interdisciplinarity is often used as generic or umbrella term, which stands for all forms of non-disciplinary research. It is described as a mode of research by teams or individuals that integrates, data, techniques, methodology, procedures, tools, terminology, concepts, and/or theories from two or more disciplines or bodies of specialised knowledge. Its aim is to advance understanding or to solve problems on topics that are beyond the scope of a single discipline (OECD 1998; COSEPUP 2004). This definition primarily describes traditional forms of 'big' interdisciplinarity but may cover as well forms of small interdisciplinarity", as described in a previous section. However, it appears to put less emphasis on interdisciplinarity as a process that may occur in daily research practice.

Much has been written about the elements included in the concept of interdisciplinarity (e.g. Thompson Klein 2000). However, the integration of terminology in interdisciplinarity research practice has obtained less attention. To our opinion, the notion of disciplines as entities using a common language, mentioned above, is also fruitful in the approach of interdisciplinarity. In this perception, interdisciplinarity means that scientifically interesting problems are being tackled by the combined effort of scientists speaking different languages or by the efforts of scientists mastering another language. By doing so they may open new views and approaches by using different words and concepts.¹ For example, the introduction of the concept of neural network, stemming from brain research, gave way to new views when applied to social and computer networks, the introduction of a concept like electrical conductivity in the study of DNA, or the (physics) concept of mechanical stress in the study of a cell (wall) opens new views in *biochemistry* and biology. Together with new words and concepts other analytical tools come along. For instance, in the latter cases, instruments developed in physics by which atomic forces can be measured or models and statistical methods from mathematics by which mechanical forces can be calculated enter into the biosciences.

Though interdisciplinarity is often used as generic concept, in the literature interdisciplinarity is more specifically described as one of a variety of forms of non-

¹ The important role of language in interdisciplinarity was recognised by Alan McDiarmid, who received the Nobel Prize Chemistry 2000 for the discovery and development of conductive polymers. He acknowledges the interdisciplinary efforts in this development and remarks: 'Alan Heeger and I found, however, you have to learn a different language – a different lingo – for a physicist to talk to a chemist and a chemist to talk to a physicist' (AWT, 2003).

disciplinary research. Quite generally, the following categories are distinguished, whereby a continuum in the coming together of two or more disciplinary approaches is supposed, according to the organisation, intensity and integration of the interdisciplinary cooperation (OECD 1998). Multi-disciplinarity is often distinguished as a first stage. By this, knowledge from different disciplines is directed simultaneously to a single problem, but research stays within disciplinary boundaries and retains to a large extent the approaches and methods of their respective disciplines. Interdisciplinarity is identified as a second stage. Here, to a much further degree than in multidisciplinary research, in teaching, learning, training and research the categories of more than one discipline are integrated (Gibbons *et al.* 1994). Central is the creation of an own theoretical, conceptual and methodological identity (van den Besselaar and Heimeriks 2001). Interdisciplinarity is mostly perceived as the interaction of closely neighbouring disciplines. However, more recently, the emergence of 'massive interdisciplinarity' is noted, in which more divergent disciplines come together from science, engineering, the social sciences and even 'arts and humanities' (PREST 2000). Examples are the joining of a wide diversity of approaches in specific projects in *cognitive science* or research on diseases².

In so-called Mode 2 theories (cf. Section 1.2) a development in science is predicted towards transdisciplinarity (Gibbons *et al.* 1994). According to these theories presently a historical turn in science is taking place. Postulated is an abandonment of established ways of knowledge production, that are characterised by traditional academic disciplinary work (Mode 1). They are replaced by a second mode of knowledge production, in which interdisciplinarity and a larger application orientation of research that is performed in a wider set of organisations are central elements. Thereby quality control is not only exercised by peer review processes, but is supplemented by criteria on utilisation. Finally Mode 2 may result in transdisciplinarity, which means the merging of two disciplines into a new discipline and thus is the most intensive form of interdisciplinarity (Schmoch *et al.* 1994). However, to our opinion the historical uniqueness of these processes, postulated in these theories, can be questioned and at least has not been proven yet. Though undoubtedly externally driven criteria have gained influence in setting scientific priorities, these theories tend to neglect the function of disciplinary knowledge organisation and validation in science (cf. Section 1.2).

Summarizing, a distinction can be made between various aspects of the concept of a discipline. It includes social (education, training, reputation), cognitive (stock of knowledge, methods, techniques, instruments) and socio-cognitive (language) elements. Interdisciplinarity concerns the integration of a part or of all these elements. Studies of interdisciplinarity will have to take into account these various aspects involved. In section

² An example is the combined effort to tackle Mosquito-Borne Diseases by remote sensing experts, virologists, biologists, mathematicians, entomologists, engineers, environmental scientists, economists, epidemiologists, historians, biophysicists, and specialists from the area of public health in an Exploratory Center for Interdisciplinary Research of the US National Institute of Health (NCRR).

3.3 we discuss the suitability of bibliometric methods to address these dimensions of interdisciplinarity.

A variety of forms has been distinguished, according to level and intensity of the interactions between and integration of formerly separated knowledge domains. In fact there a continuum can be found from 'strictly' monodisciplinary (e.g. pure mathematics) to 'interdisciplines' that that have turned into disciplines like biochemistry, chemical technology or molecular biology. In this chapter, we use of the term interdisciplinary research in its generic meaning, thereby not diversifying the various stages of disciplinary co-operation.

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3. Evaluation of interdisciplinary research

3.1 Problems with peer review

The evaluation of interdisciplinary work poses specific problems when compared to disciplinary research. These problems may occur in assessments at a more general level: e.g. how to determine whether strategic goals have been reached or what the output or outcomes are. They may also occur at the level of scientists which are faced with the problem how to validate interdisciplinary knowledge. It should be noted, however, that between these two levels there is not a clear demarcation. Experts involved in peer review may, apart from internal criteria, also consider e.g. publication output. On the other side, evaluations at a more aggregate level may build further on expert review (e.g. indicators based on number of grants obtained). In both cases, and in spite of the problems related to the assessment of interdisciplinary work, signalled in many reports and articles, few empirical studies can be found on the subject of evaluating interdisciplinary research (Thompson Klein 2000; COSEPUP 2004).

As is the case for the evaluation of interdisciplinarity in general, studies specifically addressing the topic of peer review in relation to interdisciplinary research are scarce. It has often been mentioned that more specifically peer review should not work well in case of interdisciplinary research. From the before mentioned it can be concluded that this would affect many parts and stages of the evaluation process. It has been mentioned that peer review in case of interdisciplinary research fails to capture the knowledge composition as a whole, because of the use of narrow disciplinary criteria (Boix Mansilla and Gardner 2003). Sometimes, disciplinary standards even may conflict. It has been suggested that in typical interdisciplinary research peers don't exist (Laudel 2004). Furthermore, a lack of conceptual clarity about the nature of interdisciplinary work is signalled and the need to develop validation criteria for innovative work in novel territories (Boix Mansilla and Gardner 2003). In an explanation on a new interdisciplinary award, the *UK Medical Research Council* states:

'One of the common complaints from people who have tried to develop interdisciplinary working is the uncompromising nature of the peer-review system. Typically a chemical referee will criticize the chemistry in an interdisciplinary project as not being novel and the life science referee will point out that many life scientists have been working on the problem for years. Both these points may be technically correct but they miss out on the novelty of the application and the potential impact of the collaboration' (O'Toole 2001).

In a plea for adaptation of the review system to better assess interdisciplinary research, *Metzger and Zare* (1999) state:

'Peer review by definition came to mean judgements by those from a single discipline, and often by those working in the same research area within a discipline. Judgements on research support, which are critical to an academic career, became increasingly more specialized and discipline-bounded.'

At the background of this discussion is the previously mentioned role of validation by existing knowledge and its gatekeepers as a *sine qua non* for scientific progress. Before, we discussed how new forms of validation cannot exist without these mechanisms and, whether old or new, there have to be specialised structures to fulfil this function and provide criteria for validation.

In spite of all complaints about impediments, in the few studies that have been performed on this topic, little empirical evidence is found which support the views of a bias in peer review of interdisciplinary research. Some evidence was found in an analysis of reviews of a small set of approved cross disciplinary proposals at the *National Science Foundation* (Porter and Rossini 1985). However, in several other studies less evidence for a bias is found. An example is a study on the assessment of interdisciplinary research in the context of the *Research Assessment Exercise (RAE)* in the United Kingdom. In this procedure, expert panels review the higher education sector in the UK every four to five years. There was found a wide belief among departments and scientists that the *RAE* hinders interdisciplinary research. One quarter believed that the *RAE* strongly inhibits interdisciplinary research. In a wide range study on the assessment of interdisciplinary research in the 1996 exercise, however, the main conclusion was that there is no evidence that the *RAE* systematically discriminates against interdisciplinary research (Evaluation Associates 1999)¹. In Chapter 8 we report results from a study on the assessment of interdisciplinary programmes in a nation wide survey of physics in the Netherlands. A preliminary conclusion is that the contradiction between empirical results and often-heard views of a peer review bias in case of interdisciplinary research is at least a challenge for future research.

In spite of this, presently several efforts are undertaken to adapt review systems in order to be able to address more specifically aspects of non-disciplinary research. A distinction can be made between adaptations to internal review criteria, to review procedures and to evaluations and metrics at a more aggregate level.

- At the level of so-called internal criteria used by scientists to assess the quality of (interdisciplinary) research, attempts are made to formulate additional criteria for reviewing interdisciplinary research. For instance, based on expert views, *Boix Mansilla* and *Gardner* (2003) suggest three core epistemic symptoms: consistency (with multiple separate antecedent disciplinary knowledge), balance (in weaving together perspectives) and effectiveness (in advancing understanding).

¹ 'This could be because fears about this are much overstated, or that there are counterbalances and institutions act despite perceptions about disadvantage'. (Evaluation Associates 1999).

- At the level of procedures for peer review, there can be found numerous examples of recent adaptations to these procedures in order to better account for interdisciplinary research. For instance the German *DFG* announces that in 2004 it implemented a new system to replace the previous peer review system. One of the reasons is that 'fragmentation of disciplines could lead to a provincialisation of standards in the peer review process, which, for example, may not do sufficient justice to interdisciplinary proposals'. The UK Research Councils mentions it 'reformulated its peer review principles in order to better cope with multidisciplinary and interdisciplinary research proposals'. For instance, it is proposed to select a mixture of reviewers for proposals at the interface of the Research Councils to ensure sufficient coverage and assessment of different aspects of the proposal. And also the applicants is offered the opportunity to nominate referees. Similar modifications of procedures can be found in other countries. A 'modified peer review' model has been developed in the Scandinavian countries, 'where evaluation criteria, evaluators and specific procedures are open for negotiation', and the evaluation of research is based on a compromise between the universities and the Ministry of Education (Zellner 2003). Also in evaluations of German interdisciplinary *SFB*'s² a negotiation model, combined with extensive communication between reviewers and reviewed is applied (Laudel 2004).
- Adjustments to methods to evaluate of interdisciplinary research more scarcely are found in evaluations at higher aggregate levels. A recent report by the US National Academy of Sciences is one of few attempts to formulate more systematically approaches for evaluating outcomes of interdisciplinary research, additional to those for disciplinary research. A step forward appears to be the proposal to evaluate interdisciplinary research in the light of its four driving forces, distinguished.³ A distinction is made in this report between direct and indirect impacts of interdisciplinary research, which are amenable to evaluation. Among the first are: contributions in the form of new knowledge (e.g. the stimulation of understanding in multiple fields by the *Human Genome Project*); the creation of a new field (e.g. cognitive science); to add value to traditional fields of research (e.g. feed backs from nanoscience to physics) or to develop new technologies (e.g. drug delivery systems). As indirect outcomes are mentioned e.g. spin off's from technologies, quality of education or instrumentation that has multiple applications in different fields (e.g. synchrotron sources originally developed for physics research had impact on many fields). Among the proposed more specific measures

² SFB stands for Sonderforschungsbereich or Special Collaborative Research Centres in Germany. These are long-term university research centres in which scientists and researchers work together within a cross-disciplinary research programme.

³ For instance, by examining the extent to which researchers truly collaborate. Or to evaluate the stimulus of generative technologies by the degree to which new technologies are generated that enhance research in many fields through the development of new instrumentation (COSEPUP 2004).

for evaluation of interdisciplinary research some relatively new quantitative ones are:

- Surveys of emerging interdisciplinary fields to identify demographic information (e.g. numbers and characteristics of participants in various interdisciplinary fields, and/or the kinds of activities in which they engaged.)
- matrix evaluations to capture the activities and accomplishments of interdisciplinary researchers; a matrix approach is one that would consider interdisciplinary research as an integral part of the disciplines in which the researchers are 'embedded' and make visible the cross-departmental efforts of the researchers.
- Include as evaluation criteria the co-mentoring of doctoral students, the contributions of individuals to multiple departments, and publication criteria. Among the latter a number of indicators are suggested which have been developed more recently within bibliometrics and which are discussed in the following section (e.g indicators including the nature of the journal audiences for whom the work is published; citation analysis that reveals a broad, interdisciplinary interest in the work being cited; multiple-authorship patterns that reveal the disciplinary backgrounds of co-authors) (COSEPUP 2004).

Together with the future implementation of these proposed methods, a growing problem in science policy is to find a balance between guarding scientific quality and at the same time pursuing goals like interdisciplinarity and the contribution to economic innovation. In this context *Elzinga* (1997) introduced the term 'epistemic drift', that accounts for the shift from strictly internalist criteria and reputational control to externally driven criteria that are more open to regulation in the political arena. We may conclude that more empirical research on the functioning of peer review in relation to interdisciplinary research is necessary. This should give answers to questions like possible biases in the evaluation of interdisciplinary research or the effects of different review procedures. Bibliometric data may provide additional evidence, as is shown in the analysis described in Chapter 8. Furthermore, adaptations to peer review procedures to take into account the different aspects of non-disciplinary research, mentioned above, still appear to be developed. Depending on the kind of non-disciplinary research and the review processes concerned (e.g. publications, funding, ex ante or ex post evaluation), several approaches can be found. Most of these, however, are still in a developing stage. Further research might shed light on the question whether in the difficulties encountered in developing proper methods and procedures, it plays a role that scientific validation is inherently disciplinary or specialty bound, or whether new forms of assessment are really emerging.

3.2 Bibliometrics as an evaluation tool

Bibliometrics is the quantitative investigation of science on the basis of published results. It is part of the larger domain of scientometrics, which more broadly encloses all quantitative studies on science. Its main basis is information included in articles, patents, journals and the condensation of these in bibliographic and patent databases. The use of information made public by internet and web-sites is more recently explored. Apart from other applications, bibliometric data and indicators nowadays form an important part of analyses of research performance, in particular in the natural and life sciences.

Bibliometric studies are for an important part based on the assumption that an essential element in scientific progress is, that scientific results need to be made 'public', by whatever means. Publication is necessary in order to inform other researchers and by that it is 'submitted' to a process of permanent evaluation by international professional colleagues (Van Raan and van Leeuwen 2002). An important aspect is the analysis of references (citations) in and to publications and patents. References are a sign of acknowledgement to previous work that has served as building element of present work. Behind the study of citation processes are theoretical assumptions on the function of priority, reputation and the reward system in science (Merton 1973). In the analysis of citations and references it is assumed that particularities of 'reference behaviour' are singled out in large scale analyses, on the basis of statistical considerations (Van Raan and van Leeuwen 2002).

Citations might be defined as indicators of scientific influence. Influence can be seen as a specific component of scientific quality. However, quality is a concept with many dimensions.

As discussed before, the main instrument for determining the 'quality' of scientific contributions in science is the judgement by experts in a field. Quantitative measures can never replace peer review, but they may present fruitful additions to it. The more so since new sophisticated calculations of citation impact are developed, for instance by the construction of more specific reference standards (Van Leeuwen 2004). Furthermore, peer review is also not the absolute way to determine quality of research(ers) and also has drawbacks (Horrobin 1990; Jefferson *et al* 2004). For instance, peers may not always be perfectly informed in the subject matter involved, or peers may be biased for several reasons like the belonging to different schools. Apart from cognitive biases there may be institutional biases (Viner *et al* 2004). As peer review is performed at higher aggregate levels and the distance between reviewer and reviewed subject increases, disadvantages, like a lack of expertise in all the subject fields involved, become stronger. It might be stated that the greatest strength of peer review is at the lower aggregate level of research proposals, articles, projects or programs. This strength diminishes if larger units are to be

evaluated. For bibliometric indicators the reverse seems to be the case: they are most weak at the level of individual researchers and become stronger at higher aggregate levels.

Several studies show a slight, positive correlation between outcomes of bibliometric indicators and peer review based assessments (Martin and Irvine 1983; van Raan 1996). A more recent examination on this subject is presented in this study (Chapter 7). Presently, bibliometric methods have become a customary element in larger scale analyses of strengths and weaknesses of national science systems. As mentioned, the use of bibliometric indicators in the evaluation of interdisciplinary research in science policy, is still underdeveloped.

3.3 Quantitative methods and the study of interdisciplinarity

A number of scientometric and bibliometric methods have been developed to study various aspects of interdisciplinarity in science. These methods can be classified according to several dimensions,

Table 3.1: Levels and measurement items of interdisciplinarity in science

level	measurement item
discipline	disciplinary origine of scientists collaboration by researchers with other disciplines
department/faculty institute	collaboration with other departments in different disciplines composition of groups/scientists disciplinary background of students and staff
research group	collaboration with groups in other fields composition by scientists from different disciplines disciplinary background of staff
scientist	collaboration with scientists from other disciplines migration to other disciplines publishing in journals in other disciplines
journal	publishing articles from different disciplines publishing by authors (affiliations) from different disciplines classification/assignation to different disciplines citations by/references to journals in other disciplines
article	key-words from distinct disciplines classification to different disciplines authors/affiliations from different disciplines
patent	co-patenting by inventors from different disciplines referring/citing to literature from different disciplines
author	co-publishing with authors from other disciplines
citation	referring/citing to other disciplines co-citation of articles from distinct disciplines

like the level of aggregation at which interdisciplinarity is studied. Most analyses are directed at the characteristics of interdisciplinarity at higher aggregate levels of disciplines,

fields or institutes. Studies at this level often are of a historical or descriptive nature (e.g. Scerri, Maassen in Weingart 2000). Quantitative investigations of the interdisciplinary character of these entities are often relying on data obtained by questionnaire or survey. Empirical data used in these studies, furthermore, are often based on lower level elements like the interdisciplinary features of (the work of) scientists, instruments, journals or research articles. Here, we take the latter elements of analysis as a starting point for a classification of scientometric methods applied in studies on interdisciplinarity. The primary goal is to describe these analytical methods and give some examples of application. It is not the aim to give a comprehensive overview of all studies applying them, nor of their results. For the latter we can refer to a recent overview of the state of the art (Bordons *et al* 2004). At the end we will discuss strengths and weaknesses of each method. In Table 3.1 the most important levels at which interdisciplinarity in science can be quantitatively analysed, is represented, as well as items that may reveal interdisciplinary processes at each level.

It should be noted that lower level measurement items may be indicative also for interdisciplinarity at higher levels. For instance, citations to publications may be indicative for interdisciplinarity of not only papers, but also journals, scientists and eventually disciplines, just as interdisciplinary collaboration by authors may yield indications for interdisciplinarity of groups, departments and so on.

With respect to the first three levels mentioned in Table 3.1 ('discipline', 'department/faculty institute' and 'research group'), interdisciplinarity is mostly studied by making use of either survey methods or by scientometric methods based on lower level items. Therefore, our discussion of these latter methods starts at the level of scientists.

Scientist

At the level of scientists, several interdisciplinary features have been object of study, whereby the focus mostly has been on their disciplinary origin, training and research practise in order to identify shifts in professional careers. As signs of interdisciplinarity is studied the migration of scientists to other fields, collaboration with scientists from other disciplines or their publication behaviour. Often surveys are at the basis of data collection. *Sanz-Menéndez et al* (2001) measured by questionnaire in three fields in Spain the variety in disciplinary training (degree) and specialisation of scientists, the disciplinary composition of groups and external collaboration by scientists. An interesting finding in this study was that interdisciplinarity of fields as a whole may differ from that of groups within a field. For instance cardiology appeared to be relatively homogenous as a field, according to the diversity of the disciplinary background of its members, but the composition of the groups within cardiology is more diverse. The opposite is shown by materials science, often seen as a typical interdisciplinary field. Materials science as a field indeed appeared to be more diverse than e.g. cardiology, whereas groups within materials science were more homogenous, i.e. composed of scientists from more similar disciplines.

Apart from survey studies, information included in specific (mostly national) databases or census data have been used to study interdisciplinary activity of scientists. An assumption that has been investigated is that migration of scientists provides information on the knowledge flows between fields. *Pierce* (1999) defines this way of knowledge transfer as *boundary crossing*. An early example is a study on migration of scientists to other disciplines in the Netherlands (Le Pair 1980). Groups of scientists, moving to other disciplines than in which they received training, were used as an indicator of the interdisciplinary potential of the parent disciplines. *Hargens* (1986) also analysed migration patterns of researchers across disciplines. In the latter study symmetric relations between disciplines were found, whereas in the first study some fields, e.g. physics, appeared to be more fundamental and supplying more knowledge via migration than others, leading to a description of fields as donors or receivers (Bordons *et al* 2004).

In general, migration of scientists to other domains appears to be an interesting tool for studying knowledge transfer, not only between disciplines, but also between research sectors. -A research sector is characterised by the specific societal setting where research is performed, e.g. the private research sector in companies that can be distinguished from the public(ly funded) research sector. Migration by scientists from the private to the public sector has been studied as a means to trace knowledge exchange between private companies and universities (e.g. Zellner 2003). A problem is the availability of data, which often depends on national initiatives or data assembled by professional organisations. In the Nordic countries legislation allows collection of census data, which explains a larger number of studies in these countries on this subject (Zellner 2003).

Furthermore, collaboration by scientists from different disciplines, as shown by co-application for grants, has been analysed to evaluate a multidisciplinary research program at the Spanish UCM⁴ (Bordons *et al* 1999). Interdisciplinary activity or collaboration by scientists may also be revealed by their role as author of scientific articles. In the field of bibliometrics this topic has been used more extensively and, therefore, is discussed separately, hereafter.

Journal

Journals are an important tool for the analysis of interdisciplinarity in science. The contents of journals may be studied from an editorial point of view in order to analyse the interdisciplinary character of a specific journal. However, most studies start from the presumption that journals are a communication channel for a specific research community and as such reflect characteristics that are typical for such a community, specialty or discipline. Several approaches of interdisciplinarity by analysing journal characteristics can be distinguished.

⁴ Universidad Complutense de Madrid (UCM), Spain

Firstly, contributions to a specific journal may be analysed quantitatively to determine the interdisciplinary characteristics of a particular field. The degree of interdisciplinary collaboration by authors, their (disciplinary) affiliations, the range of specialties that are represented, or the fields that are drawn on by articles (references) have been studied here. (e.g. Schoepflin and Glänzel 2001).

Secondly, another approach defines the multiple attribution of journals, i.e. attribution of journals to more than one field or subfield, in prevailing classification systems, as a sign of interdisciplinarity. E.g., the classification scheme of *ISI's* Science Citation Index is used for this purpose. In this scheme (sub)fields are defined as journal categories based on a classification of scientific journals into categories developed by *ISI/Thomson Scientific*⁵. Although this classification is not perfect, it provides a clear and 'fixed' consistent field definition suitable for automated procedures in scientometric studies. The analysis of multiple attribution of journals is in fact a specific form of co-classification analysis (discussed hereafter). Instead of looking at the multiple attribution of individual articles, here the simultaneous classification of journals to more than one 'class' or subfields is considered and taken as an indicator of the rate of interdisciplinarity of the journal involved (Katz and Hicks 1995; Morillo 2001). In contrast to other forms of co-classification studies, by analyses of multiple attribution of journals, articles are classified journal-wise, not individually. The analysis of multiple attribution of journals in *ISI's* classification scheme, at a general level provides rather convergent results compared to other measures. However, it also appeared to be less sensitive than methods based on subject classification of individual articles or on citation analysis (Morillo 2001). Limitations especially concern the more general journal categories in the ISI scheme. Analysing the percentage and the diversity of multiple attribution of journals within disciplines and the strength of links between fields, a general typology of the interdisciplinary character of subfields and larger areas has been attained (Morillo *et al* 2003). Multiple attribution of journals appears to be an interesting method, especially for the analysis of larger areas, also because the data are relatively easy to obtain compared with other measures. For the analysis of specific sets of articles, the method appears to be not enough specific. In the next section, discussing methods at the article level, we further address this drawback. The method is also more static than other measures, as journal classification systems are rather stable and less subject to changes over time⁶. By analysing multiple attribution, also no distinction can be made between directions of knowledge flows, like is the case with citation based methods, discussed hereafter.

⁵ The former Institute for Scientific Information (ISI) in Philadelphia, now Thomson Scientific, is the producer and publisher of the Science Citation Index (SCI, extended version), the Social Science Citation Index (SSCI), and the Arts & Humanities Citation Index (AHCI), these databases are commercially accessible via the 'Web of Science'.

⁶ In the period 1981-1996 38 new journal categories have been added to the ISI-classification; 112 remained unchanged. The number of journals increased on average by 90%. Interestingly, new categories showed a higher interdisciplinarity (Morillo 2003).

A third approach of (inter)disciplinary structures in science at the level of journals is based on the analysis of the relations between journals, as revealed by journal-to-journal citation patterns. By this method, the sciences are considered to be organised in dynamic sets of journals representing specific fields, which are identified on the basis of a quantitative analysis of their citation environment (Leydesdorff 1993, 2005; McCain 1991). Here, not conventional classifications of research in (sub)disciplines are taken as starting point for looking at (non) disciplinary forms of science, but the communication patterns as revealed by actual citation relations. The latter serves as a means for the structuring of the scientific landscape. Clusters of journals showing similar citation patterns, can be perceived to constitute a field. Characteristics of the communication patterns, e.g. the presence or absence of the dominance of a specialty in the communication network, and the stability of communication patterns, can be taken as indicators of the disciplinary or interdisciplinary behaviour of the field under study (Van den Besselaar and Heimeriks 2001). An advantage of this method is obviously the approach of the dynamic structuring of science. However, notions of prevailing disciplines or fields, sooner or later always enter the analysis, e.g. at the start when selecting core journals, or afterwards when explaining results.

Article

A significant part of the studies on the interdisciplinary character of research are based on variables that can be derived from elements of scientific articles. Most important elements in this respect are title words, keywords, classification codes or terms, author affiliations, references and citations. The study of these items is discussed separately in the next paragraphs.

Several measures, addressing interdisciplinarity of research articles, are making use of the method to classify articles to subfields, according to the subfield classification of the journal in which is published. As discussed before, a more global measure to assess interdisciplinarity of articles, that is based on this method, goes on from the multiple attribution of journals in classification systems. It defines articles as interdisciplinary when being published in journals that are classified to more than one subfield. This approach has been applied in e.g. an analysis of interdisciplinarity of research in nanotechnology (Meyer and Persson 1998). Hereby, a classification scheme of journals developed by *Katz and Hicks* (1996) was used, in which several multidisciplinary subfields (journal categories), between natural sciences, life sciences and engineering are distinguished. A large number of nano-articles was found to be published in journals in these multidisciplinary subfields and therefore a high degree of interdisciplinarity in nanotechnology was concluded upon. The method, however, seems too crude to allow for far reaching conclusions on the interdisciplinary character of research in a field. A weakness of the method is that a paper is not necessarily multidisciplinary if it is published in a multidisciplinary journal.

Another indicator of interdisciplinarity has been found by looking at the share of articles by e.g. a research group or institute, published outside its main field (Bordons and Barrigón 1992; Bourke and Butler 1998). In Chapters 8 and 9, we apply this method to determine the degree of interdisciplinarity of research programmes in physics in the Netherlands. Elsewhere, the same method has been used in studies on the relation between research collaboration and interdisciplinarity, for which some evidence was found (Qin *et al* 1997), or on the investigation of determinants of interdisciplinary research (Carayol and Thuc Uyen 2004). In the latter study, using data on 900 researchers at the *Université Louis Pasteur* in *Strasbourg*, interesting evidence was found for a correlation between several individual and laboratory variables and interdisciplinarity, as defined by bibliometric data⁷. This measure of interdisciplinarity is also at the basis of the construction of so-called research activity profiles, developed in studies by *CWTS* (e.g. van Raan 2000). In these profiles, a breakdown of the publication output of a specific unit of analysis into research fields is made, based on journal classification. The scattering of the output over subfields offers an indication of the interdisciplinarity of the research performed and the interdisciplinary nature of the journal audiences that are reached. In the same way, also a citation profile or research influence profile has been constructed. It analyses the breakdown over subfields of scientific articles citing a specific set of publications and gives a picture of the interdisciplinary interest in the work being cited (Palmer 1999; van Raan and van Leeuwen 2002). A further discussion of citation analysis as a tool to study interdisciplinary research is given below.

Author and affiliation

Authorship of articles is analysed frequently as a means to obtain specific information on interdisciplinary characteristics of research. Thereby, often use is made of information on the departmental and institutional addresses of the authors concerned.

Firstly, analysis of co-authorship in scientific articles by authors from different disciplines has been used as a means to obtain information on interdisciplinary collaboration and hence as a sign of knowledge transfer between disciplines (Bordons *et al* 1999; Pierce 1999; Schummer 2004; Qiu 1992; Bourke and Butler 1998). By looking at co-authorship the main focus is on the collaborative input in interdisciplinary research processes (Steele and Stier 2000). Studies applying this method reveal large differences in the interdisciplinary character of fields. For instance, it was found that in the field of autoimmune diseases more than 50% of the articles show collaboration by authors from different disciplines (Hinze 1999). *Schummer* (2004) found for nanoscale research a percentage of 36%. However, the breadth of a discipline and the classification scheme that has been applied, are important factors in these figures and put restrictions to comparisons.

⁷ E.g. variables like (fulltime) appointment of scientists and their collaboration with industry correlated significantly with the degree of interdisciplinarity of research. Also of influence appeared to be the way a laboratory is funded: contract funding affects the propensity to perform interdisciplinary research more often than public funding.

Apart from the analysis of interdisciplinary *collaboration*, Pierce (1999) shows another element of interdisciplinarity that can be detected by authorship analysis. This element is defined as *boundary crossing*, which is the export of theories or methods to other disciplines. It has been studied by looking at e.g. migration of scientists to other disciplines, discussed before. In the context of authorship analyses, *boundary crossing* or export of theories or methods is the case when researchers publish in journals from other disciplines. In the study by Pierce, the latter was taken to be the case when disciplinary affiliations of first authors differed from the disciplines to which journals in which they publish belong (Pierce 1999). In a study on political science and sociology this latter practice of interdisciplinary knowledge transfer was found not to happen frequently⁸.

Keyword and classification term and -code

Analysis of the contents or subject matter diversity of scientific articles offers a direct means to obtain insight in the scope of interdisciplinary research efforts. Such analyses may be based on laborious reviews of titles, abstracts or even complete reviews of texts (Steele and Stier 2000). In larger scale bibliometric studies, more often methods are applied that derive information on interdisciplinarity from keywords attributed to research articles. These keywords may be directly derived from titles or abstracts (uncontrolled keywords) or from subject classification systems or thesauri (controlled keywords). Keywords may be given by authors themselves or by others, e.g. Abstract Services. In contrast to the use of uncontrolled keywords, the larger scale use of controlled keywords or terms is restricted to information enclosed in field specific databases in which such classification systems are applied. In general, methods to analyse the co-occurrence of keywords or terms in scientific publications have been developed to describe the structure of research domains. In recent years this method has been further elaborated to allow for mapping of specific fields of research (Noyons 1999).

The co-occurrence of several discipline specific keywords in a set of papers may be indicative for interdisciplinarity of research, because the simultaneous assignation of different subject terms or codes to an article reveals the relatedness of subjects and fields (e.g. Palmer 1999). At larger aggregate levels, the analysis of the network of co-occurrences between all subject terms or codes may reveal the structure and interdisciplinary relations. E.g. in the case of energy research, the analysis of co-classification of articles in the database *Energy Science & Technology* was found to be useful to identify characteristics of multidisciplinary areas in energy research (Tijssen 1992). *Morillo et al* (2001) analysed co-occurrence of *Chemical Abstract* classification codes, attributed to articles, as a sign of interdisciplinarity in a study of chemistry subfields. It revealed a high interdisciplinarity, particularly in the subfield of applied

⁸ As a third way of knowledge transfer Pierce distinguishes *borrowing*, which is the drawing on theories or methods from other disciplines, importing them to one's own discipline. It can be detected by e.g. citation analysis.

chemistry. Compared to methods based on journal classification, co-word and co-classification analyses are less dependent on the *Science Citation Index* as a data source. They have the advantage that other, more specialised databases can be used, that may better reflect specific subfields, for instance in areas of applied science and technology output (Tijssen 1992). Moreover, by this method field specific publications in more general journals, e.g., *Nature*, can be attributed more properly to a field or discipline than by journal wise classification. A disadvantage of the method is that interdisciplinary relations in a particular area with fields outside the scope of the database concerned are not well accessible.

Citation

Citations are an important element in the study of interdisciplinarity in science. Central presumption underlying this method is that references to articles in other subject fields are indicative of knowledge transfer between different fields. One of the first larger studies exploring this method has been carried out by *Porter and Chubin* (1985). Their study was groundbreaking in that it first investigated empirically the value of citation-based indicators for measuring interdisciplinary research processes. It also was one of the first studies addressing the difference in the direction of knowledge transfer reflected by references to other fields and citations by other fields. In their study, they defined fields as subject categories in the ISI journal classification system. Citations crossing the borders – i.e., which were given to articles in other categories - were labelled as *Citations Outside Category (COC)*. These were analysed for the subject categories of toxicology, demography and operations research/management science. In the study two important conclusions were drawn. Firstly, that the results were indicative of the potential in using *COC* as a cross-disciplinary indicator. Secondly, that relatively few citations were found, crossing the borders of one of four broad fields by which science was distinguished (Porter and Chubin 1985). Furthermore, they analysed differences between numbers of references to other categories, compared with numbers of citation by other categories. It led to the conclusion that these may shed light on differences between ‘who draws on a field versus on whom the field draws. E.g., the field of *toxicology*, as applied research area, was found to draw more heavily on other research areas than they do on it. This notion is further elaborated in our investigation on the so-called ‘citation balance’ of disciplines presented in Chapter 12. Restrictions of the study by *Porter and Chubin* are that *COC* was analysed for either narrow subfields (*ISI* journal categories like demography, toxicology) or broad research areas (e.g. life sciences, social sciences). As will be shown, a more intermediate level of disciplines appears to be more informative (Chapter 11). Further drawbacks of *Porter and Chubin*’s analysis are that citations were gathered for only the second year after publication, and that because of lack of available data due to restrictions of the *JCR*, for about two third of the citations *COC* could not be determined. Nonetheless, it can be concluded that it has been a pioneering study for many later applications. For instance, in

the biennial *Science & Engineering Indicators* reports in the *US*, their method has been applied at the macro level of the total output of the *US* research system (NSB 2000).

Further adaptations of *COC* measures of interdisciplinarity have been proposed. *Tomov et al* (1996) suggested the simultaneous inclusion of both references to and citations by articles from other fields in an interdisciplinarity index. This index was applied to the subfields of andrology and reproduction⁹. It was also proposed to exclude the (sub)fields (i.e., ISI journal categories) of general and miscellaneous journals. The method was further elaborated in a study on the impact of research institutes in elementary particle physics - *CERN*, *SLAC* and *DESY* - to other disciplines than physics. A new element was introduced here by addressing specifically the transfer of knowledge to application-oriented work, by among others examination of the affiliations involved in the citing papers from other fields. Another new element was the calibration of results by a world standard, in this case constructed by calculating all non-physics citations obtained by all physics publications world wide (Davidse and van Raan 1997). Presently, the scattering of references and citations across fields is becoming a more often used indicator in the analysis of interdisciplinary research. The more so because large-scale data analysis of *COC* has become technically feasible and allows for more sophisticated indicators (e.g. NSB 2000, van Raan and van Leeuwen 2002).

A different approach to analyse interdisciplinarity as revealed by references and citations is offered by co-citation analysis. It takes documents that are frequently cited together as signals of the cognitive relationship between subjects and hence fields concerned. The method has originally been developed for identification of research fronts in science. However, it is also possible to look at frequently co-cited documents that belong to different subfields, as a sign of interdisciplinary knowledge flow. In an interesting study, Small shows that by following these links, it is possible to (cognitively) leap from one (sub)field to another. In this way a fascinating journey through science was made, on a path starting in economics and ending in astrophysics (Small 1999). Interestingly, some of the key papers found in the study of Small, are also found in our analyses of the citation balance between disciplines. More particularly, some of the papers detected by Small, were also found to be highly cited papers that are responsible for considerable knowledge transfer between the subfields of physics and chemistry (Chapter 12). The study of *Small* is one of very few examples using co-citation analysis as a method to investigate interdisciplinarity. More recently studies are undertaken in which co-citation analysis is used to analyse the links between newly emerging (co-citation) clusters in current research and existing classifications of research in disciplines and subfields. Clusters, overlapping several traditional areas may point to interdisciplinary developments (Von Ins 2005).

⁹ In the present ISI classification the latter ISI category is named *reproductive biology*.

In this thesis the analysis of citations in studying interdisciplinarity is an important tool. A main reason is that citations give an indication of the actual use and impact or influence of research outside its own field. Furthermore, citation analysis offers the possibility to investigate knowledge flows, i.e. a giving and a receiving side can be distinguished. This makes it different from the analysis of the interdisciplinary content of research (by e.g. keyword analysis) or the collaborative input of interdisciplinary research (by e.g. co-authorship analysis). The value of this method to analyse knowledge flows between disciplines, as revealed by *COC*, is more particularly investigated in Chapters 10 to 12.

Patent

Patent information, more especially the link, found in patent applications, to previous research expressed by references to non-patent literature, more generally has been used to evaluate the science base of economically and technologically competitive knowledge. This has been found to be indicative for strong links between applied science and basic research in a number of fields (e.g. *Narin et al 1997*). Few studies are known investigating specifically the interdisciplinary character of research leading to patents. In one of the rare studies on this subject, *Hinze (1999)* retrieved citations in patents to analyse the cross disciplinary background of technological developments in *autoimmune diseases*. Looking at the disciplinary background of cited articles, it was found that a majority of patents draws on knowledge, i.e. refers to articles, from more than one discipline. In general a wide range of subfields was found to be relevant for technological developments in this field. In general, it appears that in studies on interdisciplinarity, the analysis of patents is informative and deserves more attention than it has obtained up till now.

Comparison of methods

The methods to analyse interdisciplinary research discussed above, each appear to have their strong and weak points. It depends on the specific subjects to be analysed and questions to be answered, which method may be preferred. A central problem, to be addressed by all methods, is how to distinguish (sub)disciplines. One approach is to focus on established disciplines in education, training, schools, or research organisations to identify disciplinary identity. These more institutionalised forms are characterised by rather stable patterns, although presently well known distinctions appear to change more rapidly. A second approach is offered by relying on existing categorisations of science into disciplines and (sub)fields, among which classification systems developed by bibliographic databases. A distinction can be made here between classifications spanning the full breadth of scientific research (e.g. *Ulrich's International Periodicals Directory* or *ISI/Thomson Scientific*) and those directed at specific fields (e.g. *Chemical Abstracts*). Also, the method underlying these classification systems may differ. For instance, ISI classifies articles to subfields journal-wise. Field-specific bibliographic databases like *INSPEC* classify each article separately, based on specific subject classification systems. A more dynamical approach to distinguish disciplines is based on bibliometric methods

like co-word, co-classification or co-citation analysis. Subject demarcation arises here from the actual content and cognitive development of scientific research that can be represented by a specific clustering of related research publications. Especially in the case of co-word and co-citation analysis, the lack of stable demarcations of fields puts restrictions to the possibilities of studying interdisciplinarity. As noted, for validation of results by these latter methods and putting them in context, it is often inevitable to refer to prevailing categories or on expert opinion.

Among the methods to classify research and investigate interdisciplinary activity, discussed above, those using disciplinary background or research settings of scientists have the advantage that indicators are based on more or less established fields. This is especially the case for fields of education and training. It has to be noted, that institutional designations do not always necessarily correspond with the actual research of scientists. For instance, a physicist appointed in a department of biology may still be a physicist, i.e. apply physical methods or address physical research questions. This problem has also been signalled in a study on Australian research departments. Here, the correspondence between departmental designation and the designation of fields to which members of these departments contribute (by publishing), was found to be diverse (Bourke and Butler 1999)¹⁰. These figures show that there is a significant part of research for which it is not clear which of both methods – either based on departmental assignment or on field of publication - is most appropriate to define the field of research. A disadvantage of methods based on disciplinary background of scientists, is that readily available data on disciplinary training or specialisation are often lacking, except those based on author addresses in publications. Surveys to collect these data are laborious and mostly have to be restricted to a small population. According to *Schummer* (2004), an advantage of the use of departmental affiliation names is that these correspond to disciplines as a combined cognitive and social category. It would make co-author analysis more suited to analyse interdisciplinarity in ambiguous fields like nanoscale research than paper and journal classifications. It should be noted, however, that this feature is not restricted to co-author analysis alone. Also journals may be related to both cognitive and social features of disciplines, as is the case for e.g. journals related to professional societies.

Bourke and Butler (1999) report that a 'collaboration' approach, based on departmental addresses in publications, was more accurate in reflecting cross-disciplinary activities than analyses of publications and citations outside the core field. The details of this analysis, however, could not be investigated. This finding has not yet been supported by other

¹⁰ For instance researchers in physics or chemistry departments appeared to publish predominantly in their own field, i.e. in physics or chemistry journals (70% and 71% respectively). For mathematicians this percentage is only 37%. In applied science and engineering departments, this share is even lower. Observed from the opposite side, publications in e.g. physics, chemistry or mathematics (as defined by journal category), predominantly come from scientists in departments with the same designations; however still about one quarter comes from scientists in other departments.

studies. It can be stated that bibliometric analyses that are based on elements of research output other than authors affiliations, have the advantage that a more direct access to cognitive aspects of interdisciplinary research is obtained. Among these, methods based on characteristics of journals in which research is published, like multiple attribution, form the most global approach. As mentioned, an obvious advantage of this method is that data are relatively easy to obtain. The global approach, however, puts restrictions and makes the method more suited for analysis at larger aggregate levels. Compared to that, analysis of keywords offers the most direct access to the interdisciplinary content of research articles, but is also the least standardised form. Especially in less homogeneous fields the lack of a broader frame of reference is a disadvantage in distinguishing interdisciplinary research. An additional problem is to reach consensus among scientists about the delineation of a field (Noyons 1999).

Co-classification analysis is closely related to keyword analysis. An advantage, however, is that subject terms or codes are obtained from a more systematic classification system which offers a reference frame. A disadvantage is the restricted scope of field specific classification systems, which hinders the analysis of research activities beyond the fields concerned. Classification systems also may lag behind new developments in science.

Finally, the analysis of citations to discover interdisciplinarity can be applied at both lower and higher aggregate levels. Like other bibliometric methods, it has the advantage that actual use of knowledge is analysed. More than the other methods, it allows for the analysis of the direction of knowledge flows between disciplines or subfields and the identification of fields or other entities as 'donors' and 'receivers'. It has to be kept in mind, however, that citation analysis is dependent on other methods or systems to classify the citing or cited articles concerned. Also, the period between the publication of research and its subsequent citing causes some time lag for analyses and prevents analysis of the most recent research.

The value of citation analysis as a tool for investigating interdisciplinary research has been corroborated by several studies. It was found that cross-disciplinary citations correlated with judgement by peers on the interdisciplinary character of research papers (Porter and Chubin 1985). More recently *Morillo et al* (2001) carried out a comparative analysis in a study on the interdisciplinary character of chemistry subfields. Compared were outcomes based on citation analysis, with those investigating multiple attribution of journals to different *ISI*-categories and those based on co-classification of separate documents to different *Chemical Abstract* sections. In general a convergence between the results of these methods was found. For instance, all three measures showed that research in Applied Chemistry was more interdisciplinary than in Polymer Science. It was also concluded that the usefulness of methods was related to level of study. Indicators based on *ISI*-multiple attribution of journals appeared to be most appropriate at the disciplinary level and less

sensitive at the subfield level. In the latter case citation analysis and co-classification analysis appeared to be more sensitive. At the journal level multiple attribution over *Chemical Abstract* classifications appeared to yield most valid results.

Two different studies on the interdisciplinary characteristics of disciplines worldwide (Morillo 2003) and our study that is presented in Chapter 11, allow for a comparison of results obtained by citation analysis with those obtained by analysis of ISI-multiple attribution (Bordons et al 2004). This comparison shows for a number of disciplines a rather converging picture. On the relation between applied science and interdisciplinarity, however, both studies offer a different picture. For the broad field of engineering as a whole, multiple attribution analysis shows a high interdisciplinarity. Citation analyses revealed a low interdisciplinary character for the field as a whole, based on the observation of a high import from but low export of knowledge to neighbouring disciplines; i.e. engineering is a 'large 'receiver of knowledge (c.f. Chapter 11 and 12). An explanation of the differences found, may be that in the first study several variables are combined that measure different aspects of interdisciplinarity. Splitting these up, it appears that the field of engineering shows high interdisciplinarity according to variables that address multiple attribution between subfields within this area. However, there is little multiple attribution of journals in this field to more distant subfields of different areas. Furthermore multiple attribution does not diversify between directions of knowledge flows and so this may be another explanation of differences found when globally comparing results (Bordons et al 2004). At the level of subfields, to a large degree identical results are obtained by the two studies. E.g. the subfield of applied physics belongs to the cluster with highest interdisciplinarity according to both multi-assignment based indicators and citation-based indicators. For the subfield of applied chemistry, an analysis of citation flows learns that applied chemistry cites to and is cited relatively often (around 60%) by other fields outside chemistry, which is consistent with conclusions based on multiple attribution analysis (Morillo et al 2001). However, the citation balance shows that applied chemistry is a net-importing subfield, suggesting that it 'uses' relatively more knowledge from other fields than vice versa.

Summarising, a range of bibliometric methods and tools are available for the analysis of interdisciplinarity in science. Differences exist in the specific elements of interdisciplinarity that are addressed by these methods. Depending also on level of analysis and the scale of the research to be studied, some methods have to be preferred above others. The analysis of the different elements that are playing a role in interdisciplinary research may require a combination of several methods. For instance, *Steele et al* (2000) applied a combination of citation and reference analysis, author analysis and subject analysis in an evaluation of interdisciplinarity research and its impact in the field of forestry. In Table 3.2 the main characteristics of the bibliometric elements discussed above, are summarised.

Table 3.2: Main characteristics of bibliometric elements for analysis of interdisciplinary research

element	analysis directed at	pro	con
scientist/author	border crossing; collaborative input; research practice	includes social and cognitive aspects	poor availability of data
affiliation	border crossing; collaborative input; research practice	includes social and cognitive aspects	not fully identical to actual research
journal classification	Scope of research; information/content	less elaborate; feasible	rough measure; general level
subject classification	Scope of research; information/content	stable basis; systematic and broad schemes	limited reach; conservative
keyword	Scope of research; information/content	direct link to content	dynamic/restricted frame of reference
citation	influence (borrowing); knowledge flows between disciplines	multi level; actual usage	less applicable to most recent research; elaborate

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4. First conclusions and bridge to Part 2

In this part, theoretical approaches of interdisciplinarity have been discussed in order to obtain a better view on the elements that play a role in determining what is exactly interdisciplinary research and which are the topics and problems involved in the evaluation of it. Based on an analysis of the debates in science studies and policy documents and on the results of earlier empirical studies some tentative conclusions are drawn. They act as a bridge to Part 2, in which we will address the topics in the context of these tentative conclusions with our own empirical work.

- Behind the push for interdisciplinarity in science two main drives have been distinguished. One factor is a science-intrinsic one, the drive of scientists to discover new areas in search for answers to basic questions. Another main drive is externally motivated and concerns the expectation that collaborative approaches by different disciplines will contribute to innovation and problem solving in non-scientific areas. Historical evidence learns that the presently often expressed view that a historical development towards interdisciplinarity in science is taking place, is not new. On the other side, however, demands for *the contribution of science to innovation* in other societal sectors and to 'knowledge economies' is becoming ever larger. This latter force can be presumed to be a main cause for increasing demands for interdisciplinarity in science. One of the consequences of these demands is a growing entanglement of science policy stimulating (societal) problem orientation and scientists who seize opportunities to get their research funded.
- In the analysis of interdisciplinarity it appeared to be clarifying to make a distinction between at least two forms. On the one side we distinguished 'small interdisciplinarity' as research that originates from primarily curiosity driven basic research in specialties at the frontiers of disciplines that crosses existing boundaries of vested disciplines. On the other side there is a more planned and organised form, stimulating combined approaches by scientists from different disciplines, whereby relatively more often is aimed at societal and technological goals and applications ('big interdisciplinarity'). Based on the latter form, the relation between application-oriented research and interdisciplinarity is often presumed. Theoretical analyses in so called Mode 2 theories appear to refer more to this second form of 'big interdisciplinarity', when pointing to e.g. a larger role of non-scientific stakeholders in *evaluation and validation of scientific results*. It has been argued that these theories appear to deny the role of (disciplinary) structure in science, which are found to be indispensable for knowledge growth and validation. In many pleas for enhancement of interdisciplinarity, 'small interdisciplinarity' often appears to be undervalued or mixed up with 'big interdisciplinarity' in the sense that it can be organised and directed and planned in order to contribute to economic or technological innovation.

- In projects or programs aiming at the *enhancement of interdisciplinary research* often specialisation and demarcation appears to be the practice. Examples are described in e.g. *De Mey's* (2000) analysis of the program in Cognitive Science at the University of California or in *Weingart's* analysis of interdisciplinary research organisations that have been set up in Germany. Though examples of successful 'big' interdisciplinary research projects can as well be found, results from a variety of analyses seem to support the conclusion that 'enforced' interdisciplinary research does not attract the best researchers, because real challenges are always within the area of a discipline (Baltes 2004). In a noteworthy analysis of the contradiction between specialisation and interdisciplinarity, *Weingart* (2000) explains how both may be seen as two sides of scientific progress.
- The assumption of (increasing) *problem-driven research* as a source of (increasing) interdisciplinarity should be considered balanced. External social, economic or technical problems may well be incentives for joining disciplinary approaches. However, disciplinary structures (though their delineation may vary over time) stay indispensable for scientific problem definition and validation and for scientific progress and eventually innovation and interdisciplinary developments. This view is supported by the insight that finally problems must be scientifically interesting and appealing in order to attract the interest of scientists.
- A leading conclusion is that *basic research* performed within disciplines and specialist topics may have important contributions to interdisciplinary developments. Insisting on disciplinary 'rigour', pursuit of specialist research interests, 'niche seeking', may lead to groundbreaking work at the frontiers of disciplines that often appears to lead to relations with other disciplinary or specialist approaches. Numerous examples can be found of small interdisciplinarity that is most important for scientific innovation and that eventually may also lead to *application in other societal sectors*¹.

From the above, two central research questions are derived, that will be addressed in the next chapters. A first more general problem concerns the *validity* of standard evaluation methods in case of shifts towards application oriented and interdisciplinary research. We address the emerging awareness of this topic in research policy in the past decades in Chapter 6. This led to improvements in peer and panel review procedures at Dutch research councils and explorations of possibilities and limitations of bibliometric indicators. It can be wondered then to what degree bibliometric data may support or add information to peer assessment, especially in case of strategic or interdisciplinary research. An answer is sought in our study reported in Chapter 7. A slightly significant general correspondence between bibliometric indicators and peer review, also in case of basic

¹ An example is the research on nuclear spin in the field of physics, starting around sixty years ago, that together with the further development of these techniques in chemistry, has contributed to (N)MR observational techniques that are now generally used in medical sciences.

research with a strategic component, found in this study, shows the additional value of quantitative measures. It gives further evidence on the correlation between specific criteria in peer review and specific types of bibliometric indicators. Disagreements in individual cases point to the necessity of complementary use of both methods. In this study, interdisciplinary programs were not specifically included. Their evaluation, however, became a more urgent topic in larger scale research assessments in the Netherlands, performed more recently. From the above discussed findings that problem definition, knowledge validation and reputational control in science in essence are essentially disciplinary based, in case of interdisciplinary research specific tensions in standard evaluation methods may be expected. It was questioned, therefore, how these mechanisms, that are vital in evaluation processes of scientific research function when work calling on expertise from several disciplines is involved. As reported, apart from general 'feelings' that 'traditional' forms of scientific validation and evaluation hinder interdisciplinary research, few empirical studies on this subject are known. In this thesis we address the question, whether interdisciplinarity is of influence on outcomes of evaluations in Chapter 8 and 9. Before we can focus on this problem, it is necessary to empirically establish what interdisciplinary research is. In general, experts in fields involved will be most qualified to determine whether specific research in an area is spanning several disciplines. But we assume that bibliometric data may offer fruitful additional information on interdisciplinarity of research and their use is especially attractive when such information is required at a larger scale. In Section 3.3 a variety of these methods have been discussed. For the analyses in Chapters 8 and 9, where research at a national scale is the topic, we take the share of publications by research units on subjects outside their main field, as an indicator of their degree of interdisciplinarity. Examining peer review assessments on the same units, their (dis)agreement with the rate of interdisciplinary research could be investigated (Chapter 8). In the same way outcomes on a range of bibliometric indicators of research performance for these units could be analysed against the background of their extent of interdisciplinarity, in Chapter 9. In this specific study we find that the rate of interdisciplinarity did not correlate with either peer review judgements nor with outcomes of advanced bibliometric indicators. In Chapter 9, elementary bibliometric indicators, like the citation average, are found to correspond with interdisciplinarity. Here probably it takes a longer period before (published) results get known outside their own discipline. Therefore, we analyse so-called age-distributions of cross disciplinary citations in Chapter 10. The comparison of citation flows within and between disciplines shows that interdisciplinary knowledge exchange often proceeds slightly slower than within a discipline. Typical differences between disciplines are found.

A second research question, that emerges from the theoretical notions discussed in the previous chapter, is to what degree basic research in disciplines, and specialisation and differentiation within disciplinary settings, contributes to *successful interdisciplinary developments*. The second part of the work in this thesis is directed at the

operationalisation of this question. More specifically we investigate whether empirical data may give further evidence for the role of basic science in interdisciplinary advancements. Several literature based methods are available (Table 3.2). In our studies we confine ourselves to the analysis of interdisciplinary influence and the contribution from one discipline to (new) developments in others and we restrict to methods based on citation analysis. At the macro level, we find that between disciplines significant differences exist in the amount at which research is of influence on work in other disciplines (Chapter 11 and 12). At a more micro level, citation analysis reveals typical cases of important breakthroughs at frontiers of disciplines with large interdisciplinary impact. For instance, new methods for the calculation of electronic structure developed by physicists working at the frontier of physics and chemistry, are found to have large impact in chemistry. Bibliometric methods, applied in Chapters 7-12, are found to offer useful empirical evidence for the analysis of several research questions raised in this chapter. Their further development, therefore, appears to be fruitful for more extended analyses of the role and functioning of interdisciplinarity in science.

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Part 2: Published articles

5. Summary of the themes addressed by the published articles

In this Part 2 of the thesis, which essentially consists of published articles, we discuss empirical approaches to the (dis)agreement between bibliometric indicators and peer review in the evaluation of research performance in basic and strategic research (Chapter 7); possible biases in the assessment and peer reviewing of interdisciplinary work Chapter 8); the validity of impact factors as indicators of research performance in interdisciplinary research (Chapter 9); the possible influence of a time delay in citation processes in interdisciplinary research (Chapter 10); knowledge exchange between disciplines of science and the measurement of interdisciplinary influence (Chapter 11 and 12). In the articles a specific development can be traced. In the first studies (Chapters 6-7) the confrontation of established methods applied in the evaluation and assessment of scientific research – peer review and quantitative indicators - with application oriented criteria and the occurrence of interdisciplinary research is gradually becoming a topic. In the following studies (Chapters 8-9) we address more particularly the applicability and validity of both peer review and quantitative methods in the evaluation of interdisciplinary research. In the last chapters (Chapters 10-12) interdisciplinary processes and the exchange of knowledge between disciplines as such become the central item.

Chapter 6 presents a review of scientometric methods and studies applied by research councils in the field of physics and technical sciences in the Netherlands. At the same time it introduces some of the problems encountered in the application of these methods in evaluation practises. Starting in the seventies, by the councils concerned, insights from the emerging field of science studies were explored and applied in research policy. Topics are the development of evaluation methods of outcomes of research in specific fields in the Netherlands, (DELPHI-)procedures for research evaluation, the functioning of peer review, and the application of bibliometric and other science indicators. The incorporation of results from science studies in research policy, by that time was groundbreaking in the Netherlands (Wouters 1999). It lead to e.g. the application of (DELPHI) insights in procedures for the assessment of grant applications in research involving utilisation, used up till present. Several studies were also carried out which showed that bibliometric indicators can supply useful additional information to other methods, especially in fields of basic research. Also, studies on e.g. the Dutch scientific contributions to the development of the electron microscope revealed that the impact of technical innovations was not fully reflected by citations to the authors involved and that application of standard bibliometric indicators may be limited in specific fields of applied science and interdisciplinary research, like research on fusion energy. This led the way to further research on the applicability of bibliometric indicators.

In Chapter 7 different methods to evaluate research performance, in both basic and strategic research, are compared. It aims at the confrontation of the results of an evaluation of condensed matter physics programs obtained by peer review with those obtained by bibliometric indicators. The latter are the result of a complicated effort to compile bibliometric indicators on physics research in the Netherlands. It is based on the publication output of the programs included in this evaluation, and makes use of the large amount of data stored in the SCI, as well as the advanced routines developed at CWTS. Basic indicators, like the average number of citations and more advanced indicators like the citation averages normalised to world averages in corresponding fields and journals were calculated. On the other side the results are used of an expert panel review of the same programs. In this assessment, expert judgements on several criteria have been distinguished. Moreover programs were split up in a category containing basic physics research programs and another category containing strategic and application oriented programs. The outcomes give insight in the degree to which both methods show corresponding results. For instance, the highest correlation between both assessments was found between the past performance of groups in basic physics research and bibliometric indicators comparing citation impact with world averages in a field. The study gives further evidence on the correlation between specific criteria in peer review and specific types of bibliometric indicators. A conclusion is that in this field bibliometric methods offer interesting benchmarks for outcomes of peer evaluations and panel reviews, both for 'basic' programs as for basic programs with a strategic character. It was concluded too that, due to the different strengths of both instruments, related to among others the level of aggregation, comparisons between bibliometric analysis and peer review outcomes have to be considered with care. Complementary use may strengthen the reliability of outcomes of performance evaluations (c.f. also Aksnes and Taxt 2004).

In Chapter 8 we describe how bibliometric data are used in a 'double way' in an evaluation of physics research programs in the Netherlands. In this research assessment, bibliometric data were used both as supporting tool in the assessment by an expert panel *and* as a means of determining the degree of interdisciplinarity of research programs. As part of a national system of assessment of academic research per discipline, a review of physics research in the Netherlands was held in which judgements of an expert panel were supported with outcomes of bibliometric analyses. The combined use of expert review and bibliometric data offered the possibility to further analyse the agreement between both ways of assessing performance. For some cases, showing contradictory results, a presumption was that the interdisciplinary character of programs might have played a role in either panel outcomes or in the bibliometric results. Therefore, the results of this evaluation were examined specifically with respect to the degree of interdisciplinarity of the programs concerned. We developed specific bibliometric methods to determine the degree of interdisciplinarity of the research programs that had been evaluated. There was no correlation found between rates of interdisciplinarity

and outcomes of expert reviews. Neither, a correspondence was found between advanced bibliometric performance indicators used in the expert evaluation and degree of interdisciplinarity. The quite often expressed assumption that interdisciplinary research is impeded by peer review, because peers have a disciplinary bias, was not supported by the outcomes of this analysis.

In Chapter 9, more particularly is focussed on the relation between several kinds of bibliometric indicators and interdisciplinarity. Data from a survey of about 200 research programs in physics research were used to analyse the correspondence between a range of specific bibliometric indicators and the rate of interdisciplinarity of the programs concerned. It was found that a number of elementary bibliometric indicators correlate slightly but significantly with the degree of interdisciplinarity. More advanced indicators showed no significant correlation. Highest correlation was found between interdisciplinarity and the average citation rates of journals in which is published by programs. The results of this study show that the uninformed use of elementary bibliometric indicators in research evaluation may yield biased results. For instance, this may be the case when applying *ISI/Thomson Scientific* journal impact factors, originally developed as a bibliographic tool, as a proxy for the citation impact of specific articles. Several objections can be raised against this use of journal impact factors (Moed *et al* 1996, 1999; Moed 2002; Van Leeuwen 2004). The correlation found between the average citation rates of journals and interdisciplinarity in case of the programs in this assessment on physics research, give further support for warnings in using journal impact as a substitute for article impact. As a second topic, in this chapter the slight difference found between degree of interdisciplinarity and citation rates normalised by journal and field averages, respectively, are discussed.

In Chapter 10 till 12, interdisciplinary processes as such are the central item. In Chapter 10, a link can be found between the previous chapter on possible biases of bibliometric indicators in case of interdisciplinary research – and the next two chapters where the main topics are the processes of knowledge exchange between disciplines. In this chapter the speed of knowledge transfer between fields of science is studied, based on an analysis of the age distribution of references in three large datasets, covering the publication output of Germany, the United Kingdom and the world total. A motivation behind this investigation is that possible differences in the speed at which knowledge is exchanged between different disciplines or subfields, might be of influence on outcomes of citation based indicators. The analysis shows how age distributions of references significantly differ between fields, with strikingly converging patterns in all three datasets. A distinction made between references to articles in the same field and to articles in other fields show several interesting features. A general tendency is found, by which publications in the same field are cited faster than those from other fields. It shows that knowledge exchange across disciplinary borders proceeds slower than within a field and therefore might be less

'visible' in the short term. Typical differences between fields in this respect could be detected, with again strikingly converging patterns in all three datasets. These processes are to a large degree typical for a discipline. A tendency to refer faster to literature originating from research in the same discipline was not found to occur in e.g. Mathematics and Clinical Life Sciences. A new indicator is proposed which gives a more refined measure to express differences in citation distributions.

In Chapter 11 and 12 a large scale analysis has been performed of knowledge exchange between fields of science by studying citation flows between disciplines. First a general typology of disciplines is searched for, based on rates of knowledge exchange with other disciplines at a global level. In Chapter 11 the main emphasis is laid on developing measures that express the rate of knowledge transfer between fields of science. Two indicators are proposed that appear to properly assess interdisciplinary impact. The analysis demonstrates the important role of basic areas, e.g. basic life sciences and physics, as sources of knowledge for other disciplines. In Chapter 12 we further elaborate a separate measure for interdisciplinary impact, which appears to better cope with some limitations of the dataset used. It calculates a citation balance of disciplines, based on numbers of citations received from articles in other disciplines and numbers of references given to other disciplines. This method to compare import and export of knowledge yields interesting results, both at a macro level on relations between disciplines as at the meso level of subfields. The results of knowledge balances offer a global picture of structural relations between disciplines. In Chapter 12 a more in depth investigation of citation relations between disciplines also reveals key papers in physics that are responsible for large interdisciplinary impact. According to these cases, this impact is not primarily related with sudden breakthroughs in research, like the discovery of high temperature (HT_c) superconductivity, but more to new methods and techniques that inspire research in other fields.

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Scientometric studies and their role in research policy

6 Scientometric studies and their role in research policy of two research councils in the Netherlands

E.J. Rinia

Foundation for Fundamental Research on Matter (FOM),
P.O. Box 3021, 3502 GA Utrecht, The Netherlands

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Scientometric studies and their role in research policy of two research councils in the Netherlands

Abstract

In the past 30 years a variety of scientometric analyses have provided input data for research policy objectives of research institutions in the Netherlands. In this article we discuss several pioneering studies performed on behalf of the research councils for physics (FOM) and technical sciences (STW), which have played an important role in the early development of scientometrics in this country. The motives for these studies, the results and the influence on research policy are discussed. Relations to present themes in scientometric investigations are drawn.

6.1 Introduction

Since the end of the 60's, when around the world and especially in the USA, the study of science started to flourish, the Netherlands have participated actively in this development. After a long period of increase in the level of science funding, budgets started to decrease - or at best stabilise - in the Netherlands as well as in many other countries. This development asked for a solid basis for science policy. Urgent questions to be answered were: 'why should science be funded', 'what are the benefits of science' and, given the scarcity of funds, 'what should be funded and how it is to be selected'. Also more general questions were posed about how the scientific system works and what the structure and function of the research enterprise are. In the development of early science studies also other factors were involved, as for instance the discoveries of De Solla Price on the exponential growth of science. At the same time, the availability of a wealth of data by the creation of the Science Citation Index (SCI) since 1961, led to a growing awareness that science could be studied quantitatively. This fact was well noticed by those involved in science policy and facing the above mentioned new demands.

In the Netherlands some of the first efforts to give science policy a scientific basis were taking place at the physics research council, the Foundation for Fundamental Research on Matter (FOM). Here too, setting priorities was a necessity due to the stagnating budgets. It was realised that for a well founded science policy it was necessary to be informed about the state of affairs of science studies elsewhere, especially those concerned with the evaluation of R&D. For this purpose, other research councils like the US National Science Foundation (NSF) were visited and cooperation with foreign experts, for instance De Solla Price, was started. It was realised that it was necessary to study science itself, to gain

insight into e.g., important contributions to a field, factors involved in research performance, or limitations of citation analyses. A series of studies were initiated, inspired by FOM director *Le Pair* and member of the FOM-council *Volger*, having mainly physics as the object of study and mathematical methods borrowed from physics as a tool for analysis (Wouters 1999). An extensive range of quantitative data on citations, manpower, careers, scientists, students, publications, patents were used.

In subsequent studies several topics were investigated, e.g., comparison of evaluation methods, factors determining scientific excellence, knowledge transfer by field mobility of scientists, migration of researchers, performance indicators or expansion and stabilisation of scientific fields. Originating from a FOM programme for technical physics and innovation, in 1981 a separate research council for technical research in all disciplines was established, the Technology Foundation (STW). Already soon new themes were added to the science studies agenda, like the measuring of utilisation of research and the evaluation of applied and technological science.

Partly the results of these pioneering studies have been published in the public literature, partly they were made available only in special reports. These activities, which started in the early 70's were the 'locus of the first scientometric activities in the Netherlands'. A more extensive description of these early developments is given by *Wouters* (1999). Some of these studies still have relevance for present day topics in the field of scientometrics, as will be described hereafter. Besides, one can describe what the role of these studies has been in the development of science policy of the two research councils. In this article, the main emphasis is laid on this latter aspect: the results of the principal investigations and the impact they have (had) on the research policy of the organisations involved.

6.2 What was studied

Beginning of the 70's a large project was initiated aiming at the evaluation of the achievements of Dutch post war physics. It consisted of several (sub)studies and was completed in 1982 with the issue of two large volumes containing a survey of achievements in all physics subfields in the Netherlands (Broeder *et al* 1982). The main goal was to gain insight in the results of Dutch efforts in this field and the response it had received from abroad. Already from the start, however, additional questions were simultaneously addressed, e.g., about the validity of evaluation methods in different subfields. At that time the use of citation analyses for evaluation purposes was gaining interest in science policy, but also scepticism about its equal applicability in all subfields existed. For instance it was found that in subfields like engineering or thermonuclear research, bibliometric analysis yielded an incomplete picture.

The evaluation project consisted of two components, one directed at internal factors as for instance evaluation and developments of subfields and another directed at external factors as for instance the contributions of science to society.

6.3 Comparing evaluation methods in basic science

One of the pilot projects was a study of research efforts in the field of (nuclear)magnetic resonance and relaxation (Chang *et al* 1977). Aim of the study was twofold: a first goal was to survey and evaluate Dutch contributions in this subfield i.e. trace important contributions which were stimuli for further work. A second goal was to compare outcomes of different evaluation methods. The study examined the subfield extensively. Apart from a quantitative description of the subfield, a survey of magnetic resonance and relaxation physics itself was outlined with the assistance of experts. Finally the impact of the research activities was evaluated by means of several aspects: textbooks, awards, patents, foreign expert interviews and citations.

The evaluation study showed that the various methods and techniques applied, were consistent in determining the most important Dutch contributions. Citation analysis proved to be an effective evaluation technique in this subfield. Agreement was found between various refined citation measures and expert opinion. Among citation measures an interesting distinction was made between numbers of citations, numbers of citers, foreign citers (useful to identify incrowds in science) and citing journals. An interesting side effect of this study was the development of a Citation Index Activity (CIA). This index takes into account the ageing of publications (citations given to an older paper are weighted heavier than those given shortly after publication) and is based on a model of citing as a stochastic process described by a Poisson distribution (see also Dieks and Chang 1976).

The study of this physics subfield showed that a combination of various methods is useful. It supported the insight that evaluation of R&D was best performed by applying different techniques simultaneously, which became also apparent in other science studies at that time (Martin and Irvine 1983). Moreover it was shown that citation analysis in this basic science field was useful and reliable: it even brought to light work that would otherwise would have gone unnoticed (Van Els *et al* 1989). The report evaluating the field of nuclear magnetic resonance was well received in the physics community. Furthermore, the results of the study helped gaining acceptance for citation analyses as a reliable tool in future evaluation studies of basic science.

In the following period the comparison of methods for evaluating basic science has been a recurring theme in science studies by FOM. A more recent example of such a comparison is an investigation of the correlation between peer review and bibliometric indicators in the subfield of condensed matter physics. Results of an expert evaluation of projects were compared afterwards with several citation based indicators. The latter were calculated in cooperation with the Center for Science and Technology Studies (CWTS) in Leiden. It showed that there is correspondence between the two methods. The highest correlation was found between peer judgements on competence of a team and the relative citation rate. Correlation was higher for more basically oriented projects than for more application oriented ones (Rinia *et al* 1998). The results confirmed earlier findings that citation

analysis is a fair evaluation tool in fields of basic science where publication in the serial literature is the main vehicle of communication. Case studies like these not only give insight in the reliability of several kinds of indicators, they also have a function in the process of following critically the review procedures used, to see whether improvements can be made.

6.4 Comparing evaluation methods in applied science

In another pilot project in which evaluation methods were compared, the research and development of the electron microscope was studied (Bakker 1977). Research in this subfield is mainly technical physics by nature and aimed at the development of an instrument. The study gave a thorough survey and evaluation of the Dutch R&D in this subfield, where some important contributions by Dutch scientists have been at the root of a commercial successful exploitation of the electron microscope by Philips Inc. The evaluation part of the study consisted of expert interviews, a review of international textbooks, (citation)analysis of publications and an analysis of patents and patent citations. It appeared that all measures used in this study provided valuable and complementary indications. Most of the Dutch contributions which were placed at a premium by experts, also showed up in the combined analysis of textbooks, publications and patents. Citation analysis of publications alone gave no complete picture, but provided complementary information to the analysis of textbooks.¹ Interestingly, it was found that the agreement between findings from textbooks and citation analysis of publications increases when the age distribution of citations is taken into account. However, a citation analysis of patents was indispensable for a more complete picture. The report showed again that for evaluation purposes a combination of various methods is useful and that one should best compare similar groups and similar types of research.

From a methodological perspective it is interesting to note that the study gave a first and early example of patent citation analysis, based on a study of all 490 US patents concerning electron microscopes in the period 1930-1977 and the citations therein. It was never credited for this pioneering effort, at least not in the public literature, probably because the report was written only in Dutch and not published elsewhere. In that way the study illustrated a phenomenon observed in the (Dutch) subfield of electron microscopes it studied itself. There too, for the scientists involved in developing this instrument, international journals were not the most important means of communication and their key publications were written only in Dutch language. It may be concluded that the study had a lasting impact on science policy by showing restrictions of citation analyses in fields of technical sciences, where publication in the serial literature is not a main source of

¹ It should be considered that almost half of the Dutch publication output studied here is published in conference proceedings and that the most important publications (as identified by experts) are written in the Dutch language. Moreover, for some important contributors, their number of publications equals their number of patents, indicating the commercial interests in this subfield.

communication. Related to that, it brought to mind that scientific ‘artefacts’ like instruments and technical products often do not show up in the ‘normal scientific literature’.

The different forms of communication and dissemination of results in fields of applied science were subject of further study at the Technology Foundation STW. A special topic that was studied was the bibliometric invisibility of scientific advances incorporated in instruments and applied technology. Basically, this study extended the analysis of the development of the electron microscopes discussed above. In a new approach the topic of the electron microscope was further elaborated by interpreting the mentioning of the trademark or model of this instrument in publications as a ‘citation’. The number of these instrument ‘citations’ were compared with citation rates of publications of the main scientists involved in the making of these instruments. Found was a so-called citation gap, with large differences between the ‘citing’ of instruments and the citing of publications (Le Pair 1988; Van Els 1989). The study gave further indications that for designers of instruments ‘their most essential contributions to science are not recognised’ when only looking at the public journal literature. The results were discussed in several follow up studies in which further examples of citation gaps of technological innovations were given (Le Pair 1993; Jansz and Le Pair 1992) (see also *Jansz*, this issue). The studies were effective as an eye opener for the bibliometric invisibility of instrumental science and for the fact that results of applied research may be incorporated in several forms, for which alternative ways of evaluation are necessary.

The comparison of evaluation methods in applied science was a more explicit subject of research in a further study. Analysed was a sample of 75 projects relating to application oriented research which had been submitted to the peer review procedure at the Technology Foundation STW. A discrepancy was found between jury scores for originality and the relative citation impact. It was concluded that although citation rates may be valuable indicators of the impact of a team’s past performance, they are not necessarily reliable indicators of the originality of research proposals, particularly in case of application oriented research (Van den Beemt 1995). The case study confirmed earlier findings on restricted applicability of bibliometrics in fields of technology where publication in international journals is not the standard.

6.5 Knowledge transfer between disciplines

Another part of the larger physics evaluation project aimed at unravelling the significance of the different science fields for society and their contribution to progress in other disciplines. This topic can be well understood if one considers the changing budget ‘climate’ since the end of the 60’s, in which benefits of science and disciplines and their ‘external’ merits had to be demonstrated more than before. At the same time ‘criteria for

scientific choice' were intensively discussed, among which those stating that fields which contribute most heavily to neighbouring scientific disciplines have the most scientific merit (Weinberg 1963). A further incentive for a study of this subject was that in 1975 for the second time a Nobelprize in Economy was awarded to a Dutch economist who was by origin a physicist. This supported the assumption that physicists are employable in a large variety of disciplines. Quantitative evidence for this assumption, however, was lacking. A scientometric analysis was carried out to investigate this, by analysing the mutual influencing of different disciplines in Dutch science. A novel aspect in this study was the use of data on the changing of disciplines of scientists, also called migration. Migration from field *A* in which often education had taken place, to a position in field *B* was interpreted as an indicator of the significance of the first discipline for the other (Le Pair 1977; 1980). Migration, also called field mobility, of doctoral scientists in the US had been studied by the US National Research Council in 1975 (NAS 1975).

Statistical data of the field migration of all academic staff employed at universities in the Netherlands in the period 1945-1970 were analysed. Several measures were calculated to enable the comparison between fields, among which a normalised parameter expressing 'Interdisciplinary Merit', taking into account the distribution of migrants of a distinct discipline across other disciplines. An interesting picture of the enabling character of all disciplines was obtained. Indications were found that scientists who shift their attention to other fields are an important factor for the emergence of new specialties and even new fields. The study led to the general conclusion that field migration had to be taken more into consideration both in policy concerning science and concerning science education.

The study underpinned that physics, like biology, contributed relatively much to other disciplines, when migration of academic workforce was considered. Therefore, it was a logical step to undertake a follow-up study which focused more narrowly on the migrated physicists and the ways in which they contribute to neighbouring disciplines (Van Houten 1982; 1983). A survey was held among all migrated physicists about motives for migration, characteristics of their careers and the nature of the work done and expertise used in the new environment. The results of the study showed many different aspects of the influence of physics on other fields. One of the findings was that migrants in general show a greater mobility than non-migrants.

These 'migration' studies helped to draw attention to the phenomenon of the movement of scientists from one field to another and to see that this is an important way of transferring knowledge between fields, which influences developments in existing and new disciplines.

The studies particularly gave evidence that those graduated in physics and related areas were not only employable in a large number of disciplines of science, but also occupied a variety of positions in society. This became an important topic in the 80's, when Western European economies stagnated and unemployment, also of university graduates, increased. The demonstrated facts about the employability of physics graduates in many directions and fields, played a role in successfully maintaining the capacity for physics grades in several European countries in this period.

6.6 Position of physicists in society and at the labour market - career mobility

Related to the foregoing subject are a number of studies focusing more thoroughly on the position of physicists in society. A role played too that in the beginning of the 70's the future labour market for physicists became a subject of concern. In cooperation between FOM and the professional association of Dutch physicists (NNV), in 1973 a study was made of the supply side of physics graduates, in which forecasts were calculated, based on student numbers, success rates of courses in the past years and estimates of future demands (Miedema 1973). Though uncertainty about the demand side had to be taken for granted, the study gave supporting evidence that in the coming period a surplus of physicists might become real. The report also calculated estimates of the future supply of physicists in case a *numerus clausus* would be introduced. However, in the physics community a policy was preferred to attune supply and demand by public information. Therefore, a second study was devoted to the motives of first and second year students to choose a study in the field of physics and more especially to the degree in which labour market prospects played a role. Among others it appeared that labour market prospects were more central for students at technical universities than at general universities (Foekema 1974).

At the same time a more large scale investigation was held on the positions and physicists have in society. Based on a survey among 4000 physicists, graduated in the period 1920-1971, a statistical description was given of distributions across employers, positions, jobs, etcetera and differences therein between age groups or specialties. Part of the study was devoted to the career mobility of the scientists involved. To measure this, a sophisticated mathematical model was developed, the n^{th} partial Mobility Index, which allowed to get insight in the flexibility of the labour market position of scientists (Koeze 1974).

To cast some light on future and longer term developments in the societal demand for physics, a separate foresight study was done (De Laat 1975). A DELPHI-panel, consisting of representatives of relevant societal sectors, made forecasts of expected developments and future demands for researchers in sectors and identified growth areas.² Apart from gaining insight in expected trends per sector, a main outcome of the forecasts was too that a surplus of scientists in general and physicists in particular at the longer term could be expected. The study presented quantitative estimations of these forecasts which were seen as a necessary basis for employment policy and policy concerning the contents of academic studies.

These studies of the labour market and employment of physicists, and the prospects of stagnation, had several effects on the science policy of the two research councils. Among

² By a Delphi-procedure a panel is consulted in several rounds about information supplied to it and asked to arrive at a consensus about a forecast. Members of the panel do not directly interact and are anonymous, to avoid the interference of psychological factors. In each round, however, members of the panel are given feed back by means of a summary of the results of the foregoing round. Basically, the method is an opinion poll, organised in a scientific way.

others the results assisted in arguing for an active employment policy of the government and in finding ways to create new positions. Also, in the following period, a number of measures were taken to improve prospects for university graduates at the labour market. Foregoing studies had pointed out that physics graduates were employable in numerous fields. Therefore, efforts were undertaken to further capitalise on this, for instance by presenting courses to broaden the skills of graduates. Another effort was to shorten the period for graduation, because it was found that there is a correlation between the length of this period and future prospects at the labour market.

From a methodological point of view the DELPHI-method, used in the last study, was seen as a necessary complement to statistical and social-economic analyses of the science system.

Statistics and forecasts of the number of physics students and physics graduates have been studied by FOM also more recently (Maessen 1990). Statistics of the labour market situation for physicists are studied in the Netherlands on a regular basis now by the association of physicists (NNV), as is done for instance in the US by the Education and Employment Statistics Division of the American Institute of Physics. These statistical data provide input for the policy of the several organisations involved in research and education in this field.

6.7 Assessing research quality

Criteria to set priorities were intensively discussed at the end of the 60's by those involved in establishing a rational basis for science policy. At the root of these efforts was the idea that with the aid of universally accepted criteria research policy could be developed on which priorities could be based. Especially the criteria formulated by *Weinberg* (1963) were subject of debates. A part of the science study programme at FOM mentioned before, was devoted to an analysis of the application of Weinberg's criteria to the discovery of electromagnetic induction by *Faraday* in 1831 (De Konink 1971). The conclusion of this study was that Faraday's work would have been given low priority, because during the first 20 years after his discovery there were low 'external' merits for other fields and for technology. High so-called 'internal' scientific merit only, was according to Weinberg not enough reason to pursue a particular science. The study concluded that Weinberg's criteria undervalue the significance of basic research exploring new frontiers for future developments within a field. Moreover it showed an example of basic research with important applications on the long term which were (apparently) hard to foresee at that time. It learned that it is hard to develop a (simple) set of universally accepted criteria on which a research policy can be based to set priorities between fields. The discussions and studies about criteria led to the important conclusion that a more fruitful way was not to compare (sub)fields, but to assess individual research projects and to use scientific quality as the only criterion for comparison of projects. This was taken as leading motive in the new project selection process which was an important element of the emerging science

policy at FOM. It led among others to the introduction of a separate selection procedure for proposals from all subfields of physics, to be selected on the basis of their quality (ranking) only, a procedure which is still in use today. Similar procedures based on this principle were developed for project evaluation within a number of larger subfields in physics.

A second element of the new evaluation procedures, which started in the the 70's, was based on findings of studies of the DELPHI-procedure, mentioned before. This procedure was intensively studied and played an important role too in the shaping of a review system of research proposals at FOM. Reshaping of the review process became more urgent when the freezing of budgets made selections inevitable (Le Pair 1980). An element of the DELPHI-procedure which was incorporated in the peer review process was the introduction of juries of which members act independently and not as a committee in which social and psychological factors play a role. Main elements of the DELPHI-procedure, in some variations, are still at the basis of review procedures at the research councils involved. From the beginning, citation analyses were used in this review procedure as supporting tool in finding the right experts in a field.

In the peer review process criteria about for instance the team, the goal or the method are presented to the members of the jury. They have a function to draw their attention to several aspects of scientific quality before giving a final judgement. From the start of these newly introduced review procedures, around 1976, also experiments started in subfields, like metals research, to add 'external' criteria to the assessment procedure. They were included to do justice to the application oriented character of research in this field. After 1981 this was further extended by the incorporation of criteria concerning possible applications in the procedures of the Technology Foundation STW. Up till present selection is taking place here by open competition between proposals from all disciplines. An essential addition is that juries are asked to give a grade, not only for 'scientific' quality, but also for the 'utilisation potential' of a project (Le Pair 1980).

It can be concluded that the studies of and experiments with the DELPHI-method have resulted in a number of improvements of review procedures for grant applications. The use of quantitative data in these procedures for project selection is restricted. In this context, citation analyses mainly have a function to find experts in certain areas and get insight in the existence of invisible colleges. This may, however, be useful in order to find the right examiners for review procedures within and without established networks.

Review procedures and criteria as described above are rather universally applied nowadays in review procedures of research councils all around the world. The nature of these criteria has only slightly evolved since then, though, especially in the last decade, criteria concerning possible applications of research generally have been given more weight in these procedures.

6.8 National science indicators

As part of the project to evaluate the achievements of Dutch post war work in physics, also a first study was made of the Dutch contribution to world output in physics in comparison with the performance of other industrial nations (Chang 1976). The study was inspired by the publication of the first Science Indicators report by NSF in 1973. It was felt that 'quantitative data about the Dutch output constitute part of the information necessary to formulate a science policy', or in other words, 'are we keeping up with the Jones?'. The study also addressed the relative size of subfields of physics in the Dutch output compared to World figures. For some subfields the deviations from the World average were identified. In general, however, 'a striking consensus among the various countries on the allocation of resources to the subdisciplines in physics' was observed. The study, based on Physics Abstracts, was a first effort to gather bibliometric information about a Dutch science field at a macro scale. Reports containing physics indicators at macro and meso scale were continued afterwards by several updates (Rinia 1991; Glänzel 1994). In the latter studies also information based on large scale citation analyses and comparisons with several countries were included. Furthermore, the impact of physics research based on international cooperation was analysed.

On behalf of the Technology Foundation STW a first study on the Dutch publication indicators in engineering sciences compared with those of other countries was performed in 1996 (Vlachy 1992).

A main function of these field specific indicator studies is to compare developments and performance in fields, subfields and specialties with those in competing countries and as such showing (lack of) competitive capacity compared with other industrial nations. Outcomes of these studies have contributed to create pictures of the national performance in subdisciplines and strengths and weaknesses therein. Specific effects, however, are often hard to trace, as research policy measures are often inspired by multiple causes. For instance, in the first study in 1976 it was found that the subfield 'quantum electronics and quantum optics' deviates negatively from World figures. According to the report 'probably due to the lack of governmental support, which in some countries boosted the development of superpower lasers' (Chang 1976). Since then this subfield has grown considerably in the Netherlands. It received increasing support by FOM, and the subfield became also part of a 'research community'. However, apart from science indicators, various factors have played a role here, most important of which are the internal developments in a field. The particular contribution of each factor is often hard to unravel.

In the Netherlands, a first report of a series of nation-wide science indicators reports was produced by the Advisory Council for Science Policy (RAWB, presently AWT) in 1984. This first study was partly financed by the Technology Foundation STW (Van Heeringen 1984). Of special bibliometric interest was the inclusion of a large scale co-citation analysis concerning Dutch science. It was the first time that this technique, developed in 1974

(Small 1974), was applied to an analysis of a science system at a national scale. The resulting maps showed the important topics in a number of areas along with the participation and shares of the Netherlands. Apart from showing a general strong position of Dutch science, a conclusion from the study was that in a number of young, fast developing research-themes little (Dutch) activity is shown. The maps of science, based on co-citation analysis, were used for further discussions with researchers and research managers. It appeared that these alternative ways of considering their fields provided fruitful discussions about developments taking place. In a separate follow up study of this report, also the potential of patent statistics as technology indicators were further explored (Mommers 1985). These early studies at the RAWB in the beginning of the 80's finally resulted in a further integration of science indicators in Dutch science policy. Nowadays these national reports are jointly produced by the Centre for Science and Technology Studies (CWTS) and the Maastricht Economic Research Unit (MERIT). They contain a large number of bibliometric and economic indicators and other statistics of the Dutch science system in comparison with other countries (NOWT 1998).

6.10 Assessment of research performance of programmes and groups

Scientometric analyses at the micro level have been playing a minor role in science policy concerning Dutch physics and technical sciences. Restrictions mentioned before are more severe at this low aggregate level. A well known fact is too, that applying bibliometric techniques to small numbers of publications has serious doubts (King 1987).

Bibliometric data at the meso level of larger research groups or institutes formed part of the information used by an expert committee evaluating Dutch physics in 1984 (VCNO 1984). In the final report of this committee, bibliometric data were part of the analyses of several topics. Among others bibliometric performance differentiated per age group and per category of faculty at universities and institutes were investigated. Final results of this study among others played a role in decisions to build a new accelerator facility for nuclear physics in the Netherlands.

A scientometric study at the meso level of research programmes in academic physics was recently performed in collaboration between CWTS and FOM in 1996 (Van Leeuwen 1996). At CWTS an advanced datasystem and bibliometric indicators have been developed, which allow for comparison of average citation rates of groups with the world average of journals and fields involved (Moed 1995). Requirements, formulated in earlier studies mentioned before, to compare similar groups and similar types of research, can be fulfilled by these new bibliometric tools.

The results of this recent analysis of physics were among others made available to a committee of foreign experts, evaluating the state of affairs in this academic discipline at universities in the Netherlands. Together with other information, based on visits, presentations and with the opinions of experts, they were at the basis of a judgement on

quality, productivity and relevance of the evaluated programmes. The final results of this assessment exercise played a role in research policy at the level of the universities and faculties. Effects, for instance on the future support of programmes, however, may differ from place to place. As far as the research policy of FOM is concerned, in some cases the results were occasion to focus more thoroughly on circumstances in specific programmes and situations.

6.11 Conclusions

Above a number of scientometric studies were discussed, performed on behalf of the research councils for physics and technical sciences in the Netherlands. In this paper not a complete overview of all scientometric activities at these councils is given. Apart from the studies discussed, other smaller projects and activities, carried out by own means or by others, were not mentioned. We concentrated especially on a number of pioneering studies which yielded new or special methods or results, or which were of special interest for science policy. These studies all together had a certain influence on the science policy of both organisations and sometimes beyond. Sometimes the outcomes of the studies supported existing policy, sometimes they initiated smaller or larger changes in this policy. Part of the effects described above are products of their age or restricted to a particular area. For another part they also had a more lasting impact on developments in science policy and on the topics analysed in science studies in the Netherlands. Among others, the early developments and studies of science have helped, together with other circumstances, to create a climate in the Netherlands in which scientometric studies are accepted as a useful tool for science policy. The studies demonstrated the possibilities to give a scientific and quantitative basis to science policy, based on statistical description and analysis.

No doubt, future scientometric analyses will be partly directed on subjects which are relevant for contemporary topics in science policy. One of these topics gaining relevance is the evaluation of interdisciplinary research. The growing importance of research at the boundaries of existing disciplines asks for further validation of existing methods and the development of new methods for studying and evaluating interdisciplinary fields. Another topic, partly related to the foregoing, is the enabling character of disciplines. It will be interesting to develop methods to trace the ways in which outcomes of research in one discipline is felt in another discipline or in further applications. New methods for the evaluation of applied science will also be a main topic of present day and future research policy.

Effects of international cooperation in science are already a central theme in scientometric analyses and will certainly be also central in the near future. New methods for studying and evaluating developments in fields involving large collaborations e.g., elementary particle physics or molecular biology, will become necessary. The existence of large international collaborations, in which individual, group or even national contributions can hardly be

identified, poses questions about the applicability of existing scientometric methods in these fields. Finally the monitoring and forecasting of new developments in science will become an increasingly important issue in science policy.

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Scientometric studies and their role in research policy

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7 Comparative analysis of a set of bibliometric indicators and central peer review criteria: evaluation of condensed matter physics in the Netherlands

E.J. Rinia*, Th.N. Van Leeuwen**, H.G. Van Vuren* and A.F.J. Van Raan**

* Foundation for Fundamental Research on Matter (FOM) P.O. Box 3021, 3502 GA Utrecht, The Netherlands

** Centre for Science and Technology Studies (CWTS), University of Leiden, Wassenaarseweg 52, P.O. Box 9555, 2300 RB Leiden, The Netherlands

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Comparative analysis of a set of bibliometric indicators and central peer review criteria: evaluation of condensed matter physics in the Netherlands

Abstract

In this paper first results are presented of a study on the correlation between bibliometric indicators and the outcomes of peer judgements made by expert committees of physics in The Netherlands. As a first step to study these outcomes in more detail, we focus on the results of an evaluation of 56 research programmes in condensed matter physics in The Netherlands, a subfield which accounts for roughly one third of the total of Dutch physics. This set of research programmes is represented by a volume of more than 5,000 publications and nearly 50,000 citations. The study shows varying correlations between different bibliometric indicators and the outcomes of a peer evaluation procedure. Also a breakdown of correlations to the level of different peer review criteria has been made. We found that the peer review criterium '*team*' shows generally the strongest correlation with bibliometric indicators.

Correlations prove to be higher for groups which are involved in basic science than for groups which are more application oriented.

7.1 Introduction

In an increasing amount and variety of studies bibliometric data have been used to assess research performance, particularly in the natural and life (medical, biological) sciences. The assumption underlying these analyses is that bibliometric indicators provide a reliable 'image' of (at least substantial parts of) scientific activity. For instance, number and type of publications are considered to be indications of scientific production. Citation-based indicators are regarded as measures of impact or international visibility of research (Narin 1976; Garfield 1979; Martin & Irvine 1983; Moed et al. 1985).

In this context of research evaluation one distinguishes between the concepts 'impact' and 'quality' of scientific research (e.g., Martin & Irvine 1983; Martin 1996; Moed et al. 1985). Quality is perceived of as a broad concept with different aspects. For example, cognitive and methodological quality are distinguished. Impact is assumed to point to another specific quality aspect. Because of the multi-dimensional character of the concept quality, an assessment of quality is in practice always based on the application of a 'mix' of different criteria (Van Raan & Van Leeuwen 1995).

In peer review, the main assessment mechanism in science by which programmes, proposals or manuscripts are critically judged by professional colleagues, this is often

recognised by the inclusion of several criteria which reviewers are asked to address. The number and the nature of these criteria in the evaluation of research proposals are currently issue of extensive discussions (see for instance NSF 1996).

It seems to be more generally assumed now that advanced bibliometric methods offer crucial information about research performance that can be seen as complementary to peer opinion (Van Raan 1996, NSTC 1996). This is particularly important, as peer review also has serious drawbacks (Cole et al. 1978, Horrobin 1990).

In several earlier bibliometric studies comparisons are made between bibliometric results and the judgement of scholars or experts on the quality of research. (Anderson et al. 1978; Bayer & Fulger 1966; Chang 1975; Cole & Cole 1967; Martin & Irvine 1983; Nederhof 1988; Nederhof and Van Raan 1987, 1989). These studies revealed a reasonable correspondence between the results of bibliometric analyses on the one hand, and judgements of scientific quality by peers on the other. This is an important basis for the applicability of bibliometric indicators.

The correlations found are significant, but not perfect as can be expected. It is important to know whether more general or systematic patterns can be found for cases where judgements on the basis of bibliometric results do correspond and where - and why - they do not correspond with the opinion of colleagues. For instance a poor correlation was found between citation indicators and the originality of research proposals in application oriented research (Van den Beemt & Van Raan 1995).

In order to explore in more detail the correlations between scores on bibliometric indicators and the outcomes of peer judgements, we conducted a specific study as part of a larger bibliometric research project on physics in The Netherlands performed by the Centre for Science and Technology Studies (CWTS, Leiden University) and the Foundation for Fundamental Research on Matter (FOM).

In this paper we discuss the results of a comparative analysis between the outcomes of a peer evaluation recently held (October 1996) of research programmes in condensed matter physics and the results of a bibliometric study on research programmes in academic physics in The Netherlands (Van Leeuwen et al 1996). For this comparison we focus on the bibliometric as well as on the peer review side on several specific elements of the assessments, in order to gain more insight into relevant aspects of the evaluation procedures. We stress that there are always bibliometric elements in each peer evaluation, for example publications in important journals. So peer evaluation and bibliometric assessment will inevitably show some correlation, they are never 'orthogonal dimensions' in evaluation space. The important questions for empirical investigation are therefore *which* particular bibliometric indicators do correlate to *what* extent, and under *what* 'circumstances'.

7.2 Method

7.2.1 The FOM Condensed Matter Peer Review Procedure

As a first element of this analysis we use data of an evaluation held in October 1996 of 62 research programmes in condensed matter physics carried out at universities or (para) academic institutes in The Netherlands. This physics subfield accounts for more than one third of the total output in physics, both in the Netherlands and in the world. (Rinia 1991). The programmes involved have been evaluated within the framework of a periodical peer evaluation by the national working community for condensed matter physics of the Foundation for Fundamental Research on Matter (FOM), the Netherlands Physics Research Council. The results of this assessment are the basis for the funding of the programmes by FOM for the next two years.

The judgement of research by this evaluation procedure is in fact an assessment of the ongoing research programme. The scientific work performed in the past years is the primary target of evaluation, but also the research planned for the next period is assessed. These plans may be an extension of current research but also new projects can be proposed. So, a mix of both past performance and potential performance is assessed.

The programmes involved are carried out by research groups ('FOM working groups') all of which but two are part of the FOM working community for condensed matter physics. Although the main goal of FOM is the advancement of basic research, this research council recently focused special attention to the application potential of basic research for other sciences, society or industry. Therefore, the evaluation procedure in this working community was split up in two categories. The one category (*B*) concerns 'curiosity driven' research, the main motivation here is to expand basic knowledge. The other category (*A*) concerns 'application driven' research which means primarily basic research, but with an application-oriented ('strategic') or technological relevance. Groups were allowed to submit their research programme for evaluation (and, by that, as a request for funding) in both categories. For each category a separate jury of experts was installed. In category *A* about half of the jury consists of scientists from industrial laboratories.

Each programme was reviewed by on average four and at least three (mostly foreign) referees. Referees were explicitly asked to comment on scientific merit of the programme (relevance, originality, appropriateness of methods), quality and productivity of the group (including past performance), and on the programme as a whole. Programmes submitted for evaluation in the 'application driven' category have been judged also for their strategic/-technological relevance. All programmes were also submitted for review to the members of the jury and to the group leaders of the working community. The paraphrased comments of the referees and, in some cases, of the other peers, were presented to the principal investigators of each programme in order to have their reactions. The complete set of referee and peer comments as well as the reply of the investigators finally was laid down in

a protocol. On the basis of this protocol, and the programme involved, the juries rated all programmes according to the principal criteria (quality of the team, goal, method). It should be noted that the description of these three criteria in both categories is to a greater extent similar. However, as discussed above, in category *A* more emphasis is put on technological relevance and in category *B* on the advancement of basic knowledge. Besides these three criteria, in category *A* 'strategic' technological relevance was also considered as a separate criterium. For each criterium a rating was given on a scale of 1 (excellent) to 9 (poor). Finally, an overall judgement was given which served as the basis for grant supply. Because of the additional criteria concerning strategical and technological relevance in the assessment of programmes in category *A*, and because of the reviewing by different juries, the overall ratings for the two categories are not standardised. Therefore, a direct comparison of the jury scores between the two categories is not allowed. Thus, correlations between bibliometric indicators and jury ratings are analysed within the context of each category separately.

7.2.2 The Bibliometric Research Performance Assessment

As a second main element of this analysis, we used bibliometric data of the earlier mentioned comprehensive bibliometric study on the research performance of 220 research programmes in physics, which was carried out in the context of an evaluation of academic disciplines at universities in The Netherlands. These programmes relate to the large majority of research groups in academic physics in The Netherlands, among which those in condensed matter physics. This extensive bibliometric study is based on the publication oeuvre in the period 1985-1994 of all senior scientists participating in the selected programmes (Van Leeuwen et al. 1996). The process of data-collection and the methodology applied are to a large extent similar to those adopted in previous studies on academic research performed by CWTS, for example, on chemistry in The Netherlands (Moed & Hesselink 1996). The main data source are the bibliographic data of all papers with a Dutch address published during the period 1985-1994 in journals processed by the Institute for Scientific Information (ISI) for the Science Citation Index (SCI), SSCI and the A&HCI. A detailed description of the data system is given in Moed et al. (1995) and in a recent overview by Van Raan (1996).

In this 'broad scale' bibliometric study also papers of Dutch physicists with *only* a foreign address are included. As a source of bibliometric data for those publications, CD-ROM versions of the Science Citation Index (SCI) were used. Publication data were carefully verified and missing data were completed by scientists and institutes involved. This latter procedure is a very important part of the CWTS bibliometric studies.

It is of special interest, particularly in relation to the peer review process described above, that in the bibliometric study, scientists are 'linked' to programmes on the basis of the situation as of May 1995. Those who participated in a programme in the past but left before May 1995 (for instance, retirement) were excluded. For senior scientists recently

appointed, his or her total publication output and impact generated during the period 1985-1994 has been included in the analysis of the programme concerned. By this choice the bibliometric analysis focuses specifically on the past performance of those who have the task to shape the future of a programme (the 'back to the future' option, instead of analysing 'total' past performance of a group's oeuvre, for instance from the perspective of accountability of research funds). We think that this 'modality' methodologically improves the comparison between peer evaluation and bibliometric assessment.

However, as the peer evaluation procedure took place in 1996 and contains a mix of assessment of both past and potential performance, it might be interesting to further compare in the future the results of this evaluation with bibliometric data of a more overlapping time span, for instance for the period 1994-1998.

The research groups in condensed matter physics and their programmes analysed in the bibliometric study and the programmes submitted to the above discussed peer evaluation procedure are not completely identical. The bibliometric study aimed at an assessment of the total programme involved (based on the publication output of *all* senior researchers), whereas programmes submitted to the peer evaluation procedure in some cases consist of smaller or specific parts of the total programme. A matching of programmes identified in both procedures and of the data concerned was performed on the basis of the *participation of the same senior physicists*. Six programmes in a total of 62 programmes submitted to the peer review procedure could not be matched well with programmes included in the bibliometric analysis. They have been excluded from this study. For the remaining 56 programmes a fairly good match was obtained, though in a few cases a complete overlap between participating senior researchers was not reached. In eight cases the same group submitted their research programme for evaluation in both categories *A* and *B*. In these cases the bibliometric results of these programmes were matched twice with the two different jury ratings. The results concerning the correlations between peer review judgements and bibliometric indicators are based on the data of these 56 programmes.

7.3. Results and Discussion

7.3.1 Bibliometric Indicators Used in This Study

The bibliometric indicators calculated in the study on Dutch academic physics (see Van Leeuwen et al. 1996) are given in Table 7.1 together with the numerical values for the entire set of groups participating in the FOM (national) working community for condensed matter physics.

Output and impact indicators are measured 'cumulatively' during a fixed time period (1985-1994). Indicators are based on all publication and citation data related to this period (so called 'total block indicators', Schubert et al. 1989). For a detailed description of the methodology used, we refer to Moed et al. (1995) and to Van Raan (1996).

The same indicators as given in Table 7.1 are calculated for each programme separately. The number of papers per programme in the period 1985-1994 varies from 574 to 21. It should be noted that some overlap between programmes exists because of co-authorship. There are four programmes with less than 50 publications.

To give an impression of the scattering of the citation scores within the entire set of 56 programmes: 42 programmes obtain a citation rate above the world-wide field citation rate (*CPP/FCSm*). Of these, 27 programmes have a score which is significantly above this world average. 14 programmes obtain a citation score below the world-wide field average, of which 5 programmes have a score significantly below average. Concerning the citation rate compared to the world-wide journal average (*CPP/JCSm*): 34 programmes obtain a

Table 7.1

Indicators of publication output and impact (1985-1994), for the FOM working community for condensed matter physics.

BIBLIOMETRIC INDICATOR ^a		Score 1985-1994
The number of papers (normal articles, letters, notes and reviews) published in journals processed for the CD-ROM version of the Science Citation Index (SCI).	<i>P</i>	5,327
The number of citations recorded in SCI journals to all publications involved. Self-citations are included.	<i>C</i>	46,858
The average number of citations per publication, or citation per publication ratio. Self-citations are included.	<i>CPP</i>	8.80
The average number of citations per publication. Self-citations are not included.	<i>CPPex</i>	6.42
Percentage of papers not cited during the time period considered.	<i>%Pnc</i>	28.21
The world-wide average citation rate of all papers published in journals in which a group has published (the group's journal set).	<i>JCSm</i>	7.05
The world-wide average citation rate of all publications in (sub)fields in which the group is active. Subfields are defined by means of SCI journal categories.	<i>FCSm</i>	5.47
The impact of a group's publications, compared to the world-wide average citation rate of the group's journal set (self-citations included).	<i>CPP/JCSm</i>	1.25
The impact of a group's publications, compared to the world-wide citation average in (sub)fields in which the group is active (self-citations included).	<i>CPP/FCSm</i>	1.61
The impact of journals in which a group has published (the group's journal set), compared to the world-wide citation average in (sub)fields covered by these journals.	<i>JCSm/FCSm</i>	1.29
The percentage of self-citations. A self-citation is defined as a citation in which the citing and the cited paper have at least one author in common (either a first author or a co-author).	<i>%SELF CIT</i>	27.05

^a In this case 'group' is the entire (national) working community.

citation rate at or above world average. Of these, 16 programmes have a rate significantly above average. 22 programmes have a citation score below the world-wide journal average. Of these, 9 programmes have a score which is significantly below average.

7.3.2 Scattering of jury ratings

For the peer evaluation of programmes in the FOM working community of condensed matter physics, 26 programmes have been reviewed in category *A* (application-oriented research), and 30 in category *B* (basic physics).

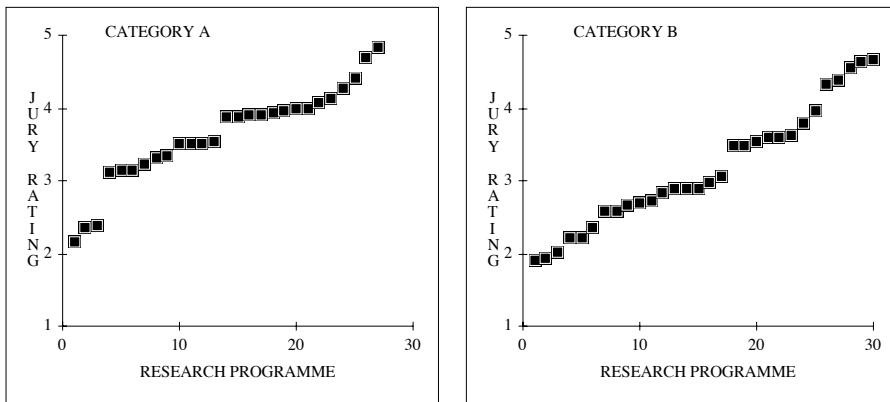


Fig. 7.1. Jury ratings of the 56 condensed matter physics programmes in two categories (*A*: application-oriented; *B*: basic research).

The jury-ratings for each of the 56 programmes are given in Figure 7.1. Whereas individual ratings could be given from 1 (excellent) to 9 (poor), the actual (average) ratings vary between 1.89 and 4.84. Partly this might certainly be explained by the quality of the reviewed programmes, but also by the tendency of the jury to level ratings off at the high and low end of the scale.

The average of the scores amounts to 3.61 in category *A*, and 3.16 in category *B*. In Figure 7.1 is shown that the differences between these averages are caused by the fact that more programmes receive a (high) rating (between 1 and 3) in the basic physics category (*B*) than in the application-oriented category *A*. However, it can not be concluded that programmes with a main emphasis on extending basic physics knowledge are of higher quality than programmes with a strong strategic component. As explained above, criteria for assessment of programmes and the composition of the jury are not completely identical for the two categories .

7.3.3 Correlations Between Bibliometric Indicators and Overall Jury Ratings

Linear regression analysis clearly shows different correlations between jury ratings and the various bibliometric indicators. A graphical display of the jury ratings for both categories

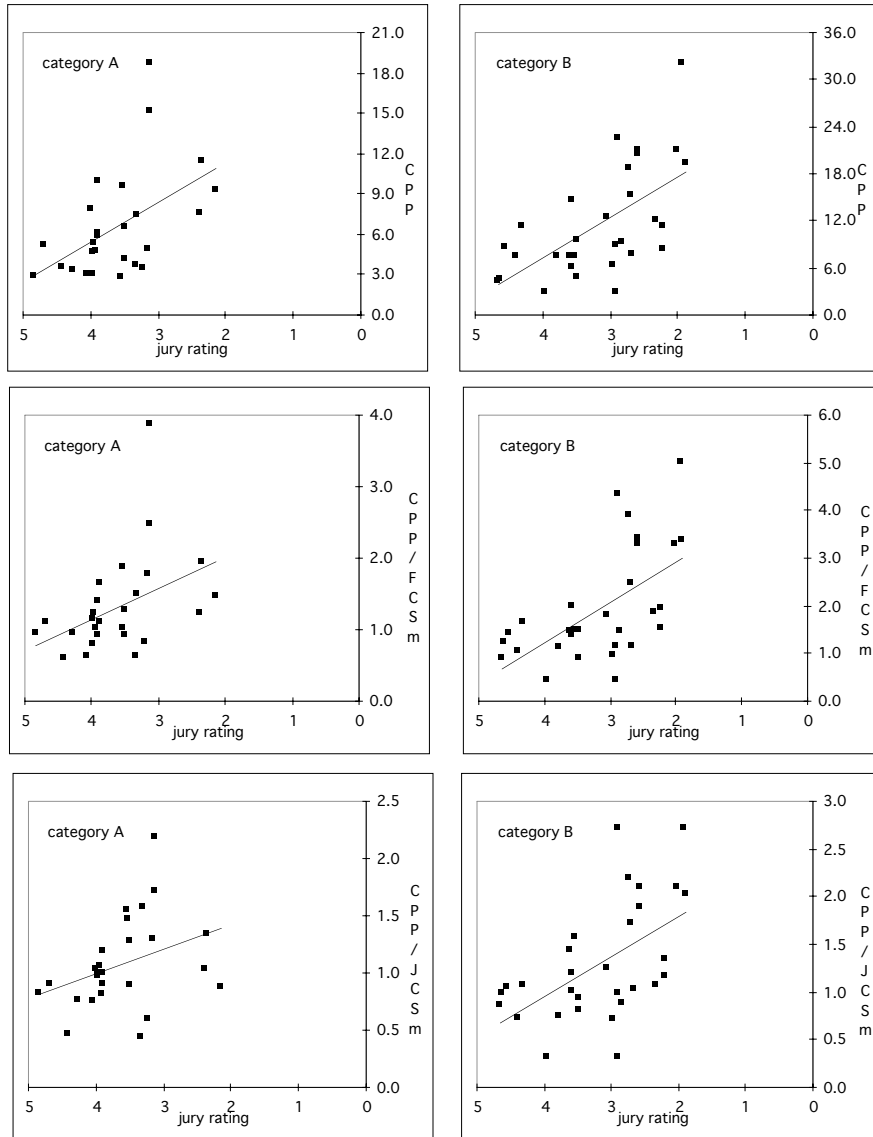


Fig. 7.2. Graphical display of jury ratings and bibliometric indicators for 56 programmes in two sectors of condensed matter physics (A: application-oriented; B: basic research).

and the indicators *CPP*, *CPP/FCSm* and *CPP/JCSm* is given in Figure 7.2. It is shown that these indicators, though differently, in general correlate positively with peer ratings. We observe too that all figures reveal a more or less similar pattern: for programmes with relatively high scores on bibliometric indicators, no further differentiation is visible among the jury rates. This finding would confirm our earlier observation that jury assessments level off at the top end of the scale.

For the 56 programmes we calculated for *each* of the eight bibliometric indicators described in Table 7.1 rank-correlations with the *overall ratings* received in the peer (jury) review procedure. Spearman rank-correlation coefficients were calculated, as only a small number of ties occurred in the rankings of the scores. The results are given in Table 7.2.

A first and very interesting finding is that there appears to be *no significant correlation* between jury ratings and the number of journal publications (*P*) produced by the programmes involved. The other, citation-based bibliometric indicators correlate quite differently with peer review. All bibliometric indicators containing actual citation rates, based on citations obtained by papers of a group analysed, (*C*, *CPP*, *CPPex*, *CPP/FCSm* and *CPP/JCSm*) do correlate significantly at the '99 % confidence' level.

Table 7.2

Spearman rank-correlation coefficients (r_s) of bibliometric indicators (1985-1994) and overall jury ratings in category *A*: application-oriented and category *B*: basic research

Period	1985-	CATEGORY A (r_s)		CATEGORY B (r_s)	
	1994				
Indicator					
<i>P</i>	0.37			0.16	
<i>C</i>	0.54	(+)		0.47	(+)
<i>CPP</i>	0.57	(+)		0.65	(+)
<i>CPPex</i>	0.51	(+)		0.68	(+)
<i>% Pnc</i>	-0.35			-0.13	
<i>FCSm</i>	0.29			0.01	
<i>CPP/FCSm</i>	0.57	(+)		0.63	(+)
<i>JCSm</i>	0.48	(+)		0.28	
<i>CPP/JCSm</i>	0.46	(+)		0.58	(+)
<i>JCSm/FCSm</i>	0.47	(+)		0.51	(+)
<i>% Selfcit</i>	-0.19			-0.63	(+)

^a A '+' sign indicates that correlation is significant at a confidence level of 99%.

From Table 7.2 we observe that the highest correlations are obtained for the average number of citations per publication, in- and excluding self-citations (*CPP*, *CPPex*) and for the (relative) citation indicator using the *field-based world averages as reference standard*,

CPP/FCSm . The relative citation indicator using the *journal-based world average as reference standard*, *CPP/JCSm*, correlates significantly with jury-ratings in both categories. The absolute number of citations (*C*) also correlates significantly with peer judgements, though less than the before mentioned indicators. For these indicators (except for the absolute number of citations) higher and more significant correlations are found for programmes in basic physics research (category *B*) than for programmes with a stronger technological component (category *A*). The lower correlations found for the application-oriented programmes in category *A* between most indicators based on actual citation rates (*CPP*, *CPPex*, *CPP/FCSm* and *CPP/JCSm*) and the jury ratings, are in agreement with earlier results in studies on the relation between bibliometrics and fields of technological research (see for instance Le Pair 1988; Van Els et al. 1989). In this respect, however, also factors related to the peer review process should be taken into account. In the case of category *A*, the jury judged programmes belonging to a large number of subfields (materials science, semiconductor physics, applied physics), whereas programmes in the basic physics category (*B*) were much more coherent. This additional factor in category *A* of judging programmes belonging to a broad spectrum of subdisciplines, is reflected by the jury ratings which show a larger dispersion in category *A* than in category *B*.

As might be expected relatively low correlations coefficients are found for the 'only-journal-based' indicators (*JCSm*, for the journals used by the research group; and *FCSm*, for the journals of the field as a whole), especially in category *B*. It shows that the status of the journals involved, as reflected by the impact of the journals, do not correspond very well with the quality of a research programme as perceived by peers. However, in the application oriented category *A* the impact of the journal set (*JCSm*) correlates slightly with jury ratings.

In category *B* the indicator expressing the relative impact of the journals in which a group publishes, comparing the *journal-based world average citation rate with the field-based world average citation rate* (*JCSm/FCSm*), correlates significantly with jury ratings, as is the case with the indicator expressing the percentage of selfcitations (*%Selfcit*). A negative correlation found between the percentage of self-citations and jury ratings in category *B* means that in the case of basic physics programmes in condensed matter physics lower levels of self citation correspond significantly with higher jury ratings.

When bibliometric indicators are calculated for the shorter and more recent period 1990-1994 (Table 7.3), for programmes in the application oriented category *A* correlations with jury ratings decrease compared with the correlations found for the period 1985-1994 and significant correlations disappear. In the basic physics category *B*, most indicators which correlate significantly in the whole period 1985-1994 also correlate significantly in the period 1990-1994.

Table 7.3

Spearman rank-correlation coefficients (r_s) of bibliometric indicators (1990-1994) and overall jury ratings in category *A*: application-oriented and category *B*: basic research

Period	1990-1994	CATEGORY A (r_s)	CATEGORY B (r_s)	
Indicator				
<i>P</i>		0.27	0.25	
<i>C</i>		0.35	0.51	(+)
<i>CPP</i>		0.30	0.64	(+)
<i>CPPex</i>		0.27	0.72	(+)
<i>% Pnc</i>		-0.22	-0.13	
<i>FCSm</i>		0.23	0.31	
<i>CPP/FCSm</i>		0.29	0.66	(+)
<i>JCSm</i>		0.36	0.50	(+)
<i>CPP/JCSm</i>		0.13	0.50	(+)
<i>JCSm/FCSm</i>		0.38	0.53	(+)
<i>% Selfcit</i>		-0.06	-0.67	(+)

^a A '+' sign indicates that correlation is significant at a confidence level of 99%.

7.3.4 Correlations Between Bibliometric Indicators and Specific Criteria

Next to the *overall* assessment, the juries also gave ratings for four specific criteria in their assessment: *team*, *goal*, *method*, and *strategical & technological relevance*. The criterium *team* consists of an assessment of the researchers and the research team. The criterium *goal* includes the choice of the problem and the relevance for the advancement of basic physics knowledge and 'urgency' of the programme. The criterium *method* concerns originality of methods and contribution to extending basic physics knowledge. Finally *strategical & technological relevance* was judged as separate criterium for programmes in category *A*. Though all criteria contain elements of past performance and future prospects, the criterium *team* is most explicitly concerned with past performance, whereas the criteria *method* and *goal* represent a mix of both elements (past performance and future prospects). The mutual dependence of these three and four specific criteria, respectively, for each programme is shown in Figure 7.3. Linear correlation coefficients between the overall ratings and the criteria *team*, *goal* and *method* range from 0.83 to 0.95 with those for the *team* deviating most. Correlations between the overall ratings and the judgements for the specific criteria are slightly higher in category *B* than in the application oriented category *A*. This finding might also be related to the fact that programmes in the latter category concern more heterogeneous subfields than in the basic condensed matter physics category *B*.

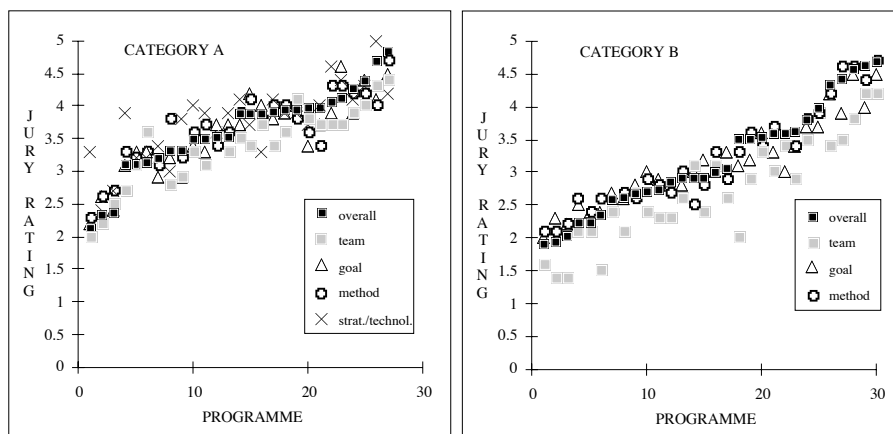


Fig. 7.3. Jury ratings for overall judgements and the four (category *A*: application-oriented) and three (category *B*: basic research)) specific criteria of 56 programmes in condensed matter physics.

A quite remarkable finding is that the correlation between the overall rating for programmes in the application-oriented category *A* and ratings for the *strategical & technological relevance* criterion is less ($r^2=0.65$) than between the other criteria. This might indicate that for category *A*, covering programmes with an emphasis on technological relevance, the jury still attaches a relatively great value to the basic scientific merits of a programme.

All criteria can be seen as representing different aspects of the broad concept of quality of scientific research. It may be expected, however, that aspects related to the first three criteria (competence of the team, relevance of the problem and originality of the methods) are more directly related to impact and visibility as measured in the international scientific literature than the criterium of strategical and technological relevance. To investigate this, in Table 7.4 Spearman's rank-correlation coefficients are calculated for bibliometric indicators and each of the four specific criteria used by the juries. Taking the r_s values for the specific criteria we observe that, in general, the highest correlations are found between bibliometric performance indicators and the criterium *team*. This is the case for both categories, with again higher and more significant correlations in the basic physics category *B*. As explained above, the criterium *team* is indeed the most explicit criterium for the assessment of 'past performance' of a research group by peer review. It confirms the expectation that citation-based indicators relate well with past achievement. In category *A* (application-oriented research) the quality

Table 7.4:

Spearman rank-correlation coefficients (r_s) of bibliometric indicators and jury ratings for the overall judgements and specific criteria. (A: application-oriented; B: basic research)

Indicator	Jury rating ^a				
	Overall (r_s)	Team (r_s)	Goal (r_s)	Method (r_s)	S&T (r_s)
<i>Category A</i>					
P	0.37	0.44	0.34	0.27	0.39
C	0.54 (+)	0.55 (+)	0.42	0.40	0.50 (+)
CPP	0.57 (+)	0.52 (+)	0.40	0.48 (+)	0.44
CPPex	0.51 (+)	0.47 (+)	0.34	0.43	0.37
%Pnc	-0.35	-0.36	-0.22	-0.37	-0.34
FCSm	0.29	0.44	0.30	0.28	0.06
CPP/FCSm	0.57 (+)	0.40	0.34	0.46 (+)	0.52 (+)
JCSm	0.48 (+)	0.51 (+)	0.37	0.47 (+)	0.25
CPP/JCSm	0.46 (+)	0.35	0.28	0.36	0.46 (+)
JCSm/FCSm	0.47 (+)	0.30	0.33	0.48 (+)	0.33
%Selfcit	-0.19	-0.18	-0.11	-0.21	-0.08
<i>Category B</i>					
P	0.16	0.21	0.13	0.13	
C	0.47 (+)	0.50 (+)	0.41	0.39	
CPP	0.65 (+)	0.67 (+)	0.60 (+)	0.54 (+)	
CPPex	0.68 (+)	0.68 (+)	0.63 (+)	0.55 (+)	
%Pnc	-0.13	-0.08	-0.09	-0.10	
FCSm	0.01	0.02	0.07	0.01	
CPP/FCSm	0.63 (+)	0.63 (+)	0.60 (+)	0.52 (+)	
JCSm	0.28	0.29	0.25	0.26	
CPP/JCSm	0.58 (+)	0.58 (+)	0.54 (+)	0.50 (+)	
JCSm/FCSm	0.51 (+)	0.48 (+)	0.53 (+)	0.44 (+)	
%Selfcit	-0.63 (+)	-0.59 (+)	-0.64 (+)	-0.53 (+)	

^a A '+' sign indicates that correlation is significant at a confidence level of 99%.

of the team as perceived by peers, shows a correlation with not only the *C*, *CPP* and *CPPex* indicator but also with the *JCSm* indicator, which is based on only the impact of the journals used by the research group.

For the 'basic physics' programmes (category *B*) lowest correlations are found between bibliometric indicators and the criterium *method*, for the 'applied physics' programmes (category *A*) lowest correlations are found between bibliometric indicators and the criterium *goal*.

It is shown for most indicators that the numerical values of the correlations for the specific criteria are to a certain degree interrelated. This may be explained by the mutual dependence of the separate specific criteria as shown by the jury ratings mentioned before (see also Figure 7.3).

7.4. Conclusions

Undoubtedly, a lot has been published on the comparison between quantitative indicators and peer review. Nevertheless, few studies offer hard empirical with sufficiently broad differentiation in type of indicators and type of research. Part of these latter studies consider the correlation between indicators and peer review in the publishing process (e.g., Daniel 1993, Korevaar and Moed 1996). Other studies compare bibliometric indicators and peer judgements based on questionnaires among scholars or experts (e.g., Anderson et al. 1978, Martin and Irvine 1981).

In this study detailed evidence based on a sample of 56 research programmes in condensed matter physics in the Netherlands has been analysed in which expert assessment was the basis for funding decisions concerning these programmes.

Our conclusions are summarized as follows:

(a) Positive and significant but not perfect correlations are found between a number of bibliometric indicators and peer judgements of research programmes in condensed matter physics in the Netherlands.

(b) At the level of overall peer judgements, we find the highest correlations between peer judgement and the average number of citations per publication (CPP , CPP_{ex}) and the citation averages normalised to world average ($CPP/JCSm$ and particularly $CPP/FCSm$).

The latter two indicators compare the average number of citations per publication with the world standards of the corresponding journals and fields. These indicators containing normalised citation rates are included because citation characteristics may vary considerably among journals and fields, which may be a main cause for differences between citation averages. It is shown that both indicators correlate with peer judgements at almost the same degree as the average number of citations. For both categories of programmes it is shown that the mean citation rate normalised to the world-wide field average gives a slightly higher correlation with peer ratings than the mean citation rate normalised to the world-wide journal average.

(c) The impact of journals in which is published by a programme, as reflected by the mean journal citation rates, alone does not correlate well with the quality of these programmes as perceived by peers. From a bibliometric point of view this might be expected, as the mean citation rate of a journal or a journal category is only partly related to its (relative) impact. For another part it also reflects differences between citation patterns of the subfield(s) concerned. Moreover, the impact of research published within one journal may differ largely. The low correlations found in this study between peer ratings and the average citation rate of the journals used by the research group ($JCSm$) and of the journals of the fields involved ($FCSm$), support conclusions that journal impact factors alone do not provide a sufficient basis for assessing research performance.

(d) Correlations between bibliometric indicators and expert judgements are higher in the case of 'curiosity driven' basic research than in the case of 'application driven' research. On the one hand this might be explained by a diminished bibliometric visibility of fields of

applied science, on the other hand the circumstance of peer reviewing programmes belonging to a large number of subfields, as was the case in the 'applied physics' category (A), may have played a role.

(e) At the level of the four specific criteria used by juries, the highest correlation is found between ratings for bibliometric indicators and the criterium '*team*'. A.M Weinberg mentioned this criterium - the assessment of the competency of researchers and the research team - as one of the two 'internal criteria' for scientific choice which are most often applied when a panel decides on a research grant (Weinberg 1963). The results presented in this study confirm that judgement of the team, as an important element in peer review closely related to the assessment of past performance, correlates significantly to a number of citation-based indicators. From the analysis of the jury ratings on each criterium, however, it appeared too that a high overall rating is not uniquely determined by having a good research team. Programmes are judged on other aspects as well.

(f) When bibliometric indicators are calculated for a shorter period, correlations with peer judgements tend to decrease, especially in the case of application oriented research.

(g) A negative correlation is found between the percentage of self-citations (*%Selfcit*) and jury ratings for basic physics programmes in category B. The level of selfcitation can be interpreted negatively as giving an indication of the relative isolation of a group. However, more positively it can be explained as an indication of the uniqueness of the research carried out by the programme. Lower jury ratings given to programmes with a high level of selfcitation, as is found in this study for programmes in basic condensed matter physics, may indicate that selfcitation here is more related to isolation than to uniqueness.

With respect to the level of agreement between different bibliometric indicators and peer judgements, it should be noted that at the basis of this analysis are data from two different evaluation studies. As explained before programmes and the researchers belonging to them identified in the peer evaluation procedure and in the bibliometric analysis were more or less identical, but did not match perfectly. A more perfect match between programmes analysed might be obtained in future studies, for instance by tuning in more precise on scientists, research outcomes and publications which are evaluated by the different methods. In such cases correlations between bibliometric indicators and peer opinion might even prove to be stronger.

The numerical values of the correlations between bibliometric indicators and expert assessments, although in a number of cases clearly significant, also indicate that the two assessment methods are certainly not completely dependent. The empirical findings clearly indicate that both assessment methods offer supplementary information about the performance of research groups or programmes. Though in our view a final quality judgement on a research group can be given by peers only, on the basis of their expert insight into the content and nature of the work conducted by that group, we also conclude that bibliometric indicators may provide important additional information to peers evaluating research performance. Thus, bibliometric indicators act as a *support* to peer

review, for instance in cases of incorrect or biased views of peers on a group's scientific quality.

The supplementary information offered by bibliometric indicators may also be relevant for other science policy purposes. Incidental, exceptional differences between results obtained by both methods may yield interesting cases which can function as an eye-opener. Often such cases are interesting topics for further research. It may point at limitations of the bibliometric methodology, but also to biases in the peer review procedure, for instance because the research to be evaluated is not identical with the expertise of the members of a peer college (for a more extensive discussion on the relation between peer review and bibliometric indicators, see Van Raan 1996).

A final remark is related to the time span concerned in both evaluation procedures analysed in this study. As described above, in the FOM Condensed Matter peer evaluation procedure not only past performance but also future prospects of the programmes have been assessed. The latter aspect might even be more important in the judgement of programmes in the application-oriented category because of the stronger emphasis put on strategical-technological relevance. Bibliometric indicators used in this study, though they may form a part of predictive models (Kostoff 1995), are by necessity based on an assessment of past performance. Therefore, it might be interesting to include in further studies several time spans in order to test more extensively the (prospective and retrospective) reliability of bibliometric evaluations and peer assessments.

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8 Influence of interdisciplinarity on peer-review and bibliometric evaluations in physics research

E.J. Rinia ^a, Th.N. van Leeuwen ^b, H.G. van Vuren ^a, A.F.J. van Raan ^b

^a *Foundation for Fundamental Research on Matter(FOM), P.O. Box 3021, 3502 GA, Utrecht Netherlands*

^b *Centre for Science and Technology Studies(CWTS), University of Leiden, Wassenaarseweg 52, P.O. Box 9555, 2300 RB, Leiden Netherlands*

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Influence of interdisciplinarity on peer-review and bibliometric evaluations in physics research

Abstract

It is often argued that interdisciplinary research is valued less in both qualitative (peer-review based) as well as in quantitative (bibliometric) assessments. A recent extensive, nation-wide evaluation of all academic physics groups in the Netherlands allowed us to investigate this problem empirically. Therefore, we first developed an operationalization of ‘interdisciplinarity’. On the basis of our findings, we refute the above statement, at least for the field and the country involved. We found that (i) peer judgements do not significantly correlate with the degree of interdisciplinarity; (ii) only elementary bibliometric indicators correlate negatively, but (iii) ‘advanced’ indicators do not correlate with the degree of interdisciplinarity, except a small correlation in the case of large programs. Thus, we found no general evidence for a peer-review bias as well as a bibliometric bias against interdisciplinary research.

8.1 Introduction

Should interdisciplinary research be reviewed the same way as disciplinary research? This topic has become increasingly important as national research policies lay more emphasis on problem-oriented research which often exceeds traditional boundaries between disciplines (Weingart and Stehr, 2000). The question is also a topical subject in a recent evaluation of physics research held in the Netherlands (VSNU 1996). Assessments of research programs by peer-review have been supplemented with an extensive bibliometric analysis. Our methods (van Leeuwen et al. 1996), go far beyond the rather simple notions of bibliometric analysis as described by the Committee on Science, Engineering, and Public Policy (COSEPUP) of the US National Academy of Sciences in its recent report on evaluating federal research programs (COSEPUP 1999).

In general, peer judgements are rather well in agreement with the outcomes of bibliometric indicators (Rinia et al. 1998). However, for *interdisciplinary* programs some specific contrasting results were found (Porter and Rossini 1985). We now analysed the results of this nation-wide physics evaluation particularly from the perspective of interdisciplinarity. The concept of interdisciplinarity is operationalized as the extent to which articles are published in journals in *other* scientific fields than the main field (physics) of a program.

8.2 Methodological Approach

The quality assessment procedure of the universities in the Netherlands consists of a discipline-wise judgement of research performance by international committees of independent experts. In this context an evaluation of Dutch academic physics was carried out by the International Review Committee for Physics (VSNU 1996). In an additional bibliometric analysis, which was made available in a final round to the Committee, we gathered data for about 200 academic physics research programs, covering more than 15,000 publications in the period 1985–1994. For a detailed presentation of the applied bibliometric approach and in particular the construction of the advanced indicators, we refer to van Leeuwen et al. 1996, also available via our website ¹, and to van Raan 1996.

We now used these bibliometric data to construct, for each program, a ‘research profile’ which represents the frequency distribution of publications over research (sub)fields (defined by journal classification according to the ‘journal categories’ of the Institute of Scientific Information, ISI). On the basis of ample empirical experiences with the thus defined research profiles (see van Raan 1996, and our contribution to Weingart and Stehr,

Table 8.1

Distribution of publications of an arbitrary programme over research (sub)fields. Publications may be attributed to more than one (sub)field. In that case they are fractionally counted

<i>Subfield</i>	<i>Main Field</i>	<i>Number of Publications</i>
PHYSICS, PART & FI	PHYS	17.0
PHYSICS, NUCLEAR	PHYS	3.3
PHYSICS, MISCELL	PHYS	1.0
PHYSICS, MATHEMA	PHYS	1.0
PHYSICS, COND MA	PHYS	146.2
PHYSICS, AT,M,C	PHYS	4.3
PHYSICS, APPLIED	PHYS	50.5
PHYSICS (GEN.)	PHYS	47.3
Subtotal physics subfields		270.7
MULTIDISCIPL SC	MULT	5.5
METALLURG & MINING	META	55.8
MATERIALS SC	MATE	66.8
MATER SC, COATING	MATE	0.8
ENGINEERING	ENGI	5.5
ENG, ELECTRICAL	ENGI	6.5
ELECTROCHEMISTRY	ELEC	0.5
CRYSTALLOGRAPHY	CRYS	1.0
COMPU SCI, INT AP	COMP	1.0
CHEM,PHYSICAL	CHEM	61.0
CHEM, INORG & NUC	CHEM	0.5
ASTRON & ASTROPH	ASTR	0.3
Subtotal non-physics subfields		205.3
Total		476.0.

¹ <http://www.cwts.nl>

2000), we claim that this approach provides a sufficiently reliable representation of interdisciplinarity. In Table 8.1 we present as an example one of the research programs with 476 publications, 271 of which can be assigned to physics (i.e., the journals concerned belong to physics fields), and 205 are published in journals which belong to *non-physics* fields. So the percentage of ‘non-physics’ papers is 43%. We define the percentage of *non-physics* papers as the degree of interdisciplinarity. The analysis was restricted to 185 programs with 10 or more publications, with an average number of 96 publications. As can be observed in Table 8.1, interdisciplinarity in this study does not cover a very broad spectrum of fields. It is confined to fields rather closely related to physics, such as engineering and chemistry.

8.3 Empirical findings

The distribution of interdisciplinarity of physics research programs in the Netherlands is given in Fig. 8.1. The average degree of interdisciplinarity per program is 36%. For 93 programs a quality judgement was given by the International Review Committee for Physics, which was compared to the interdisciplinarity of these programs. Calculating a Spearman rank-correlation coefficient between these two variables, we find $r_s = -0.13$.

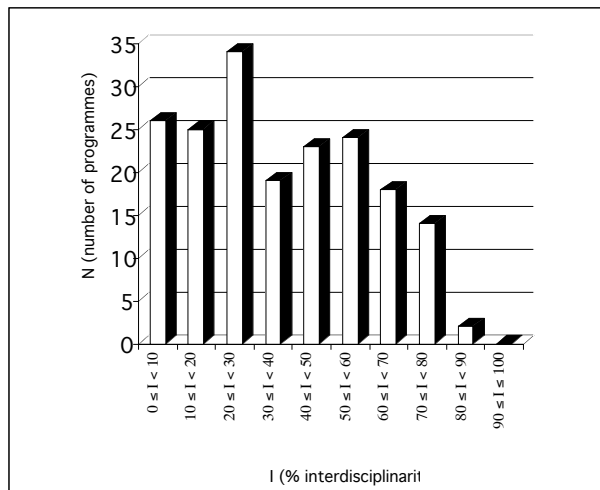


Fig. 8.1 Degree of interdisciplinarity of research programmes in physics in the Netherlands (1985–1994)

We conclude that the peers did not judge interdisciplinary programs differently than ‘monodisciplinary’ programs. It may also be concluded that, according to the peers, the quality of the more interdisciplinary programs is, on average, equal to that of other more ‘monodisciplinary’ ones.

Next we compared results of the whole set of bibliometric indicators (van Leeuwen et al. 1996; van Raan 1996) applied to all 185 physics research programs with the degree of interdisciplinarity of these programs. Linear correlation coefficients (r) of logarithmic values of the indicators (Stewart 1993) and interdisciplinarity are given in Table 8.2, where we also distinguish between classes of program size (in terms of number of publications). It appears that in several cases the correlation coefficient is significantly *negative*. This means that with *increasing interdisciplinarity a lower score of the bibliometric indicators concerned is obtained*.

There are, however, striking differences between the various indicators. First the more elementary indicators. The number of publications (P) per program does *not* significantly correlate with interdisciplinarity. The total number of citations (C) of a program, and the average number of citations per paper (CPP) show, in the case of the larger programs, a small but significant *negative* correlation. Correlation coefficients also show that work in interdisciplinary programs is published in fields characterised by a lower field-specific average number of citations ($FCSm$), and in journals with a lower journal-specific citation mean ($JCSm$). The latter indicator shows the largest (negative) correlation. These correlations may partly be related to the well-known phenomenon that citation characteristics vary by journal and field. In applied fields for instance, they are often lower than in basic science fields.

More *advanced* bibliometric indicators correct for these differences by taking world-average citation rates of journals or fields as a reference level (van Leeuwen et al. 1996). Two of such indicators, used in the bibliometric analysis of Dutch academic physics, compare citation averages of a research program with citation averages of its journals ($CPP/JCSm$), and with citation averages of its field (i.e., *all* journals in a specific field, $CPP/FCSm$). We find that the outcomes of these indicators are considerably *less* correlated

Table 8.2

Linear correlation coefficients (r) between interdisciplinarity and bibliometric indicators (logarithmic values). The number of publications per program (three size classes) is indicated by n . The number of programs in each class is indicated by N . Correlations significant at a confidence level of 99% are indicated with a ‘+’ sign. The bibliometric indicators and their symbols are briefly explained in the text and extensively discussed in van Leeuwen et al. (1996) and van Raan (1996).

Number (n) of publications per program	Number (N) of programs	I (% interdisciplinarity) vs.							
		P	C	CPP	$JCSm$	$FCSm$	$CPP/JCSm$	$CPP/FCSm$	$JCSm/FCSm$
10–50	60	-0.17	-0.17	-0.28	-0.43+	-0.40+	-0.01	-0.10	-0.23+
50–100	62	-0.15	-0.39+	-0.37+	-0.56+	-0.45+	0.00	-0.17	-0.36+
>100	63	-0.17	-0.53+	-0.52+	-0.51+	-0.27	-0.28	-0.47+	-0.49+

with interdisciplinarity. There is *no* significant correlation between interdisciplinarity and the indicator normalizing the measured impact of publications of a program to the world-wide citation averages of the journals involved (see Table 8.2, column *CPP/JCSm*).

This result clearly indicates that interdisciplinary research, at least in Dutch physics, has the same impact as ‘monodisciplinary’ research when citation scores are compared with citation averages of the journals concerned. We conclude that impact normalisation on journal characteristics (and article type as well) indeed takes into account the scope of the research, in this case the more interdisciplinary character. Measured by the other advanced indicator which normalizes on field citation characteristics (i.e., *all* journals in a specific field, *CPP/FCSm*), interdisciplinarity only shows a small significant, negative correlation in the case of the larger programs. Our explanation is that in such cases field averages are dominated by the larger monodisciplinary journals, and we conclude that ‘fields’ (defined as larger sets of journals) are probably too ‘broad’ to have an interdisciplinary focus. Finally, interdisciplinarity and the indicator comparing the journal citation average to the field citation average (*JCSm/FCSm*, in fact a measure of the ‘status’ of the journals used by the researchers in a program), correlate slightly but significantly negative. This again indicates that interdisciplinary research is often published in journals with a citation level below the average of the fields involved. As already noticed in the discussion on the elementary indicators, the results presented in Table 8.2 show that negative correlations between interdisciplinarity and outcomes of a number of indicators, generally tend to *increase* for larger programs (in terms of publication output).

8.4 Conclusions

Our results demonstrate that peer judgements of Dutch academic physics by a panel of international experts show no significant correlation with the degree of interdisciplinarity of the programs concerned. In other words, it shows that there is no general bias concerning interdisciplinary projects in this quality assessment. Porter and Rossini, (1985) found some evidence that interdisciplinary proposals are downgraded in peer review because reviewers tend to rate proposals from their own discipline more favourably. However, these findings are based on a more ‘focused’ peer-review procedure which differs from the above-mentioned evaluation with an expert panel assessing a broad, nation-wide discipline. We showed that interdisciplinary research in the framework of physics programs receives slightly but significantly lower scores on some elementary bibliometric indicators. To our opinion these negative correlations do not reflect differences in scientific impact as assessed by bibliometric indicators between ‘monodisciplinary’ and interdisciplinary research. They are mainly related to differences in citation characteristics between fields and between journals within these fields. This conclusion is supported by the finding that the peers do not judge interdisciplinary programs differently, in combination with the

finding that the more advanced indicators which correct for differences between fields and journals, do not correlate significantly with the degree of interdisciplinarity.

Thus, both types of assessment do not show a significant bias with respect to interdisciplinarity. Evidently, impact normalisation on journal characteristics takes into account the scope of research, in this case the more interdisciplinary character. We conclude that for interdisciplinary research, the indicator *CPP/JCSm* (impact normalization on *journal* characteristics) appears to be the most appropriate bibliometric measure. The indicator *CPP/FCSm* (impact normalization on *field* characteristics) is slightly biased in case of (larger) interdisciplinary programs in Dutch physics. The correlations found between degree of interdisciplinarity and the outcomes of elementary citation-based indicators without journal- or field-specific normalization, may be a warning against poorly informed use of citation data, especially in the case of interdisciplinary research. Also the correlations found between interdisciplinarity and the average citation level of journals in which a group publishes, may be a warning particularly against the uninformed use in research performance evaluations of simple citation-based characteristics of journals, like ISI's journal impact factors (Moed and van Leeuwen 1996).

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9 Impact measures of interdisciplinary research in physics

E.J. Rinia,¹ Th.N. Van Leeuwen,² A.F. J. Van Raan²

¹ Foundation for Fundamental Research on Matter (FOM), Utrecht (The Netherlands)

² Centre for Science and Technology Studies (CWTS), Leiden University, Leiden (The Netherlands)

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Impact measures of interdisciplinary research in physics

Abstract

In an evaluation of physics research programs in the Netherlands, held in 1996, assessments of research by expert panels were supplemented with bibliometric analysis. This latter analysis included the calculation of several bibliometric indicators, among which some taking journal impact measures as a baseline. Final outcomes of this evaluation provided an opportunity to re-examine the results of this assessment from the perspective of the degree of interdisciplinarity of programs involved. In this paper we discuss results of this latter analysis, in particular with respect to the relation between several citation based indicators and interdisciplinary research in Dutch physics.

9.1 Introduction

Should interdisciplinary research be reviewed the same way as disciplinary research? And if the answer is negative, which methods and indicators give reliable assessments of performance in interdisciplinary fields? This topic becomes increasingly important as in research policy more emphasis is put on problem oriented research which often encompasses traditional boundaries between disciplines. The topic has also been discussed in the context of a nation wide evaluation of research programs in academic physics and related subfields, held in the Netherlands in 1996 (VSNU 1996).

This evaluation was part of a regular quality assessment procedure of the universities in the Netherlands which consists of a discipline wise judgement of research performance by international committees of independent experts. As part of the physics evaluation procedure, results of a bibliometric analysis had been supplemented to the expert committee, during the review procedure (Van Leeuwen *et al* 1996).

After the evaluation, the outcomes were examined more closely. Among others the expert judgements for each program were compared with the outcomes of the bibliometric study.

In Figure 9.1 the correlation between the expert judgements for the criterion quality for programs in Dutch physics and the bibliometric indicator CPP/FCSm is shown¹. The latter indicator normalises citation rates of publications of a program by the mean citation rates of the fields involved. Fields are defined by ISI journal categories. Quality scores given by

¹ The bibliometric indicators used in this study are: the number of publications (P), the total number of citations (C), the average number of citations per paper (CPP), the average number of citations of journals in which is published (JCSm), the average number of citations of the fields in which is published (FCSm), the comparison of the citation average of publications with citation averages of journals involved (CPP/JCSm), the comparison of the citation average of publications with citation averages of the fields involved (CPP/FCSm), and the comparison of the citation average of journals involved with those of the fields involved (JCSm/FCSm).

the committee range from 1-5, with 5 being excellent. In this plot the scores of 95 physics programs at universities are given. In general, final expert judgements were found to be rather well in agreement with the outcomes of the selected bibliometric indicator, though not perfect. It should be noted, that the bibliometric data were made available to the committee during the review procedure. So, final judgements of the committee were not obtained independently from bibliometric results.

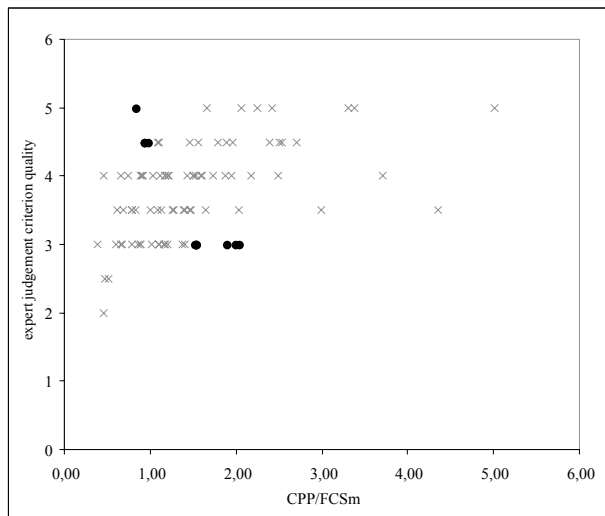


Figure 9.1. Scatterplot of expert judgements and relative citation rates for research programs in physics in the Netherlands.

In spite of a general correlation, in some cases remarkable discrepancies between outcomes of the two methods are shown. Because such discrepancies may give insight in strengths and weaknesses of both methods, a small enquiry was held. Program leaders of eleven programs, showing strongly contrasting results, were asked for their comments. The programs concerned are marked. Seven programs obtained a low jury rating but high bibliometric impact scores. In four cases the opposite was shown.

Part of the comments were related to specific conditions of this evaluation and are not discussed here. Among the more general topics, several program managers mentioned the fact that their programs were situated at the borderline between physics and other disciplines. In some cases this was said to have been playing a role in the expert judgements, in other cases in the outcomes of bibliometric indicators. In the latter case among others, the use of ISI-journal categories as reference standard was mentioned to be less adequate in case of interdisciplinary programs.

In order to see to what degree this explanation was valid, and also on the basis of earlier indications, the results of the evaluation procedure were examined more closely from the

perspective of interdisciplinarity. Main results of this analysis, also with respect to outcomes of the peer review procedure and implications in the context of research policy have been discussed elsewhere (Rinia *et al* 2001). In this paper, we discuss results of this examination especially with regard to the appropriateness of (aggregates of) journal citation impact measures as a standard for comparison of the citation impact of interdisciplinary research programs.

9.2 Method

The bibliometric analysis, which formed part of the evaluation procedure, included data for about 200 research programs, mostly at physics faculties and institutes, covering more than 15,000 publications over the period 1985-1994 (Van Leeuwen *et al* 1996). These bibliometric data, gathered for the original evaluation procedure, were used again in order to determine the degree of interdisciplinarity of each program. Interdisciplinarity was determined on the basis of a 'research activity profile', which shows the distribution of the publication output of a research program among different subfields (Van Raan 2000). Subfields are defined by journal classification according to the journal categories included in the *Science Citation Index* (SCI) of the Institute of Scientific Information (ISI).

Interdisciplinarity is defined as the extent to which articles are published in journals attributed to other disciplines than those belonging to the main discipline of a program. In most cases this main discipline is Physics, being the key discipline in this evaluation procedure. We define the percentage of non-main discipline papers as the degree of interdisciplinarity.

In determining (main) disciplines, two disciplinary classification systems were used. One is a more narrow classification and attribution of subfields to disciplines, based on the first six characters of an ISI-category. In this way, for instance, only the eight ISI-categories starting with the term 'Physics' are assigned to the discipline of Physics. By using this definition, 25% of the programs included in this evaluation, have their main field outside the discipline of Physics.

In the other, more broad classification system, 17 main disciplines are distinguished. For instance, apart from the eight specific Physics ISI-categories, also the categories of Acoustics, Astronomy & Astrophysics, Crystallography, Instruments & Instrumentation, Microscopy, Optics, Spectroscopy and Thermodynamics are assigned to the discipline of Physics. This latter discipline-classification has been used before in science indicators reports in the Netherlands. By using this classification, for 18% of the programs involved, the main discipline is another one than Physics.

In summary, two variants of defining interdisciplinarity are examined here: the percentage of publications outside the main discipline in a restricted sense (A) and outside the main discipline more broadly defined (B). Interdisciplinarity, defined as such, was then

compared with the outcomes of the physics evaluation. The analysis was restricted to 185 programs, the average number of publications per program being 96.

9.3 Results

Interdisciplinarity of the programs concerned, is confined in most cases to fields rather closely related to physics, such as materials sciences or chemistry. However, the assessment procedure also included programs with a much more diverse publication output, distributed among a larger number of disciplines. Numbers of programs are more or less equally spread among classes of degree of interdisciplinarity. Only two programs have a degree of interdisciplinarity of over 80%. The average degree of interdisciplinarity varies, depending on the discipline classification used, from 36% (A) to 33% (B).

It was found that for 93 programs for which a quality judgement was given by the expert committee, there was no significant correlation between these expert judgements and degree of interdisciplinarity. A Spearman rank correlation of $r_s = -0.13$ (A) and $r_s = -0.11$ (B) respectively, was found. It shows that interdisciplinary programs were not judged differently by the experts and that, according to the peers, the quality of interdisciplinary programs in Dutch physics on average is equal to that of monodisciplinary ones (Rinia *et al* 2001).

A comparison was made between the outcomes of bibliometric indicators per program and the degree of interdisciplinarity for 185 research programs included in the bibliometric analysis. A more detailed explanation of the bibliometric indicators concerned can be found elsewhere (Moed *et al* 1995). Linear correlation coefficients of the logarithmic values of a number of indicators and degree of interdisciplinarity were calculated (Stewart 1993). A distinction was made between classes of program size in terms of numbers of publications. A class with 'smaller' programs (10-50 publications), a medium class (50- 100 publications) and a class with 'larger' programs (>100 publications) was distinguished. Each class contains about 60 research programs.

It was found that a number of 'elementary' bibliometric indicators correlate slightly but significantly negative (at a confidence level of 99%) with the degree of interdisciplinarity of a research program. This means that with increasing interdisciplinarity a lower score of the bibliometric indicator concerned is obtained. An exception is the number of publications which shows no relationship with interdisciplinarity. However, the total number of citations (C) and the average number of citations per paper (CPP), show a small but significant negative correlation in almost all cases, ranging from $r = -0.36$ to $r = -0.53$. Only for the class of small programs (10-50 publications) and using the more restricted discipline classification (A), no significant correlation was found for both indicators.

Correlation coefficients show even more strongly that work in interdisciplinary programs in Dutch physics is published in journals with a lower average citation rate (JCSm). In each class of program size and for both discipline classifications a significant negative

correlation is found between this journal impact measure and interdisciplinarity (ranging from $r=-0.43$ to $r=-0.56$).

The average citation rate of subfields (based on journal sets) in which a group publishes (FCSm), on average also appears to be lower for interdisciplinary research programs. In most cases (except for the class of large programs and using the more restricted discipline classification), the field citation mean correlates slightly but significantly with interdisciplinarity, with linear correlation coefficients ranging from -0.30 to -0.45 .

The correlation found between degree of interdisciplinarity and a number of 'elementary' indicators may be partly related to the well known fact that citation characteristics vary by journal and subfield. For instance, in fields of applied physics the average citation rate is generally below the one in more basic fields, for example elementary particle physics. The tendency in interdisciplinary programs to publish in journals and subfields with lower average citation rates, in this analysis was found to be stronger for programs at departments of applied physics than for programs in other physics departments. In the first case correlation coefficients range between -0.46 and -0.59 , in the second case between -0.16 and -0.41 .

9.4 Journal and field impact measures as reference standard

Relative impact indicators, which compare citation rates of papers with a world average of journals (CPP/JCSm) or fields (CPP/FCSm) involved, may be expected to correct for specific differences in publication and citation characteristics. In the analysis of the influence of interdisciplinarity on an evaluation of research programs in Dutch physics, we found that to a large degree this is the case. The indicator which compares (observed) citation rates with (expected) citation rates of the journals involved (CPP/JCSm), shows no relation with the degree of interdisciplinarity. Also when a split up is made between classes of program size and using both discipline classifications, in no case a significant relationship is found between this indicator and the degree to which research is done at the periphery of physics (correlation coefficients range from 0.0 to -0.28). It appears that normalising citation rates on journal impact measures, takes into account the more interdisciplinary character of physics research programs in the Netherlands.

When the citation average per publication is compared with the citation average of the fields involved (CPP/FCSm), only in the case of large programs (>100 papers) we find a slight relation between impact normalised to field average and degree of interdisciplinarity (Figure 9.2). This is found both when a more narrow discipline classification (A) is used ($r=0.47$) as, to a slighter degree, when the more broad classification (B) is taken ($r=0.35$).

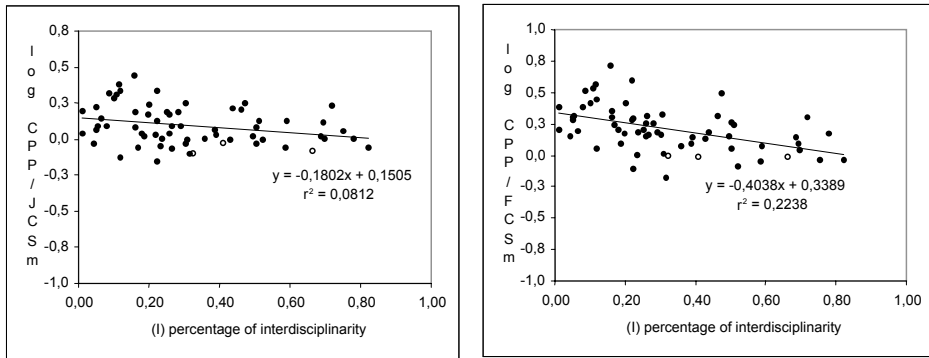


Figure 9.2. Degree of interdisciplinarity and relative citation rates for 63 large research programs in physics in the Netherlands. The selected programs that showed remarkable discrepancies between expert judgement and bibliometric indicators are separately distinguished, Programs with a high jury rating and a low bibliometric score are indicated with open circles, programs with a low jury rating and a high bibliometric score are indicated with open squares.

In the other two program classes no significant relation between the indicator CPP/FCSm and interdisciplinarity was found, except a very slight correlation for small programs (10-50 papers), when using the broad discipline classification ($r=0.35$).

The relative indicator (CPP/FCSm) compares the citation rate of a paper with the average citation rate of the specific ISI-category to which the journal in which it appears belongs. An explanation for the slight bias found for larger programs may be that in such cases world average citation rates of (sub)fields, may not be fully representative for the field(s) in which interdisciplinary groups are active. Possibly, field averages in that case are dominated by larger monodisciplinary journals. Fields (defined as larger journal sets) in such cases probably may be too broad to reflect the interdisciplinary character.

Some support for this presumption is found when for each program the indicator comparing the average citation rates of journals to average citation rates of fields involved (JCSm/FCSm) is analysed from the perspective of interdisciplinarity. The comparison of these two citation means gives a measure of the 'status' of the journals used by researchers in a program. In almost all classes of program size, correlation coefficients show that researchers active in subfields at the periphery of physics, publish in journals with an impact which generally is below the average impact of the fields involved. A more detailed analysis of the journals involved was not carried out. However, correlation coefficients of the degree of interdisciplinarity and the indicator JCSm/FCSm (which vary between -0.36 and -0.49) give an indication that interdisciplinary research in Dutch physics is generally more often published in lower impact journals.

9.5 Conclusion

Re-examination of results of an evaluation of physics research programs in the Netherlands shows that outcomes of relative indicators, applied in a bibliometric analysis, are not biased in case of interdisciplinary research. Programs at the periphery of physics receive slightly but significantly lower outcomes on some elementary bibliometric indicators, like total number of citations or average citation rate. This can be explained to a large degree by the well known fact that citation characteristics vary between journals and fields. Variations in these characteristics also will play a role in the small but significant relation found between degree of interdisciplinarity of a program and the average citation rate of journals and the average citation rates of fields in which researchers in these programs publish.

The correlations found between elementary indicators as the average citation rate of a program and degree of interdisciplinarity are a warning against uninformed use of citation data, especially in the case of interdisciplinary research. Also the correlations found between interdisciplinarity and journal impact measures may be a warning against the uninformed use of citation-based characteristics of journals, like ISI's journal impact factors.

Relative indicators correct for differences between journals and fields by using (aggregates of) journal citation impact measures as a standard for comparison of the citation rates obtained by research programs. It was found that in case of interdisciplinary research programs in Dutch physics, the indicator normalising citation rates to the average of journals involved, is the most appropriate bibliometric measure. Finally, we conclude that further research on journal impact measures in relation to interdisciplinary research, defined by bibliometric and other measures, will be needed.

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10 Citation delay in interdisciplinary knowledge exchange

E.J. Rinia*, Th.N. van Leeuwen**, E.E.W. Bruins*, H.G. van Vuren*, A.F.J. van Raan**

* Foundation for Fundamental Research on Matter (FOM), Utrecht, The Netherlands

** Centre for Science and Technology Studies (CWTS), University of Leiden,
The Netherlands

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Citation delay in interdisciplinary knowledge exchange

Abstract

As part of a larger project to investigate knowledge flows between fields of science, we studied the differences in speed of knowledge transfer within and across disciplines. The age distribution of references in three selections of articles was analysed, including almost 800.000 references in journal publications of the United Kingdom in 1992, 700.000 references in publications of Germany in 1992, and more than 11 million references in the world total of publications in 1998.

The rate of citing documented knowledge from other disciplines appears to differ sharply among disciplines. For most of the disciplines the same ratio's are found in the three data sets. Exceptions show interesting differences in the interdisciplinary nature of a field in a country. We find a general tendency of a citation delay in case of knowledge transfer between different fields of science: citations to work of the own discipline show less of a time lag than citations to work in a foreign discipline. Between disciplines typical differences in the speed of incorporating knowledge from other disciplines are observed, which appear to be relatively independent of time and place: for each discipline the same pattern is found in the three data sets. The discipline specific characteristics found in the speed of interdisciplinary knowledge transfer may be point of departure for further investigations. Results may contribute to explanations of differences in citation rates of interdisciplinary research.

10.1 Introduction

Investigations in the ways knowledge flows between disciplines of science gain interest, because cutting-edge science nowadays increasingly involves collaboration across disciplinary boundaries. In many science policy documents high expectations for benefits from interdisciplinary research are expressed and at many places efforts are undertaken to encourage scientists to engage in interdisciplinary projects. Policies to stimulate interdisciplinary co-operation among others are based on evidence found in the history of science that breakthroughs in one field proved to be important for the progress of other fields. One of the many examples is the work on atomic spin in the field of physics that led to magnetic resonance imaging in medicine which in turn led to many applications and new discoveries in medicine and biology.

Studies on such interdisciplinary impacts often are of a qualitative nature. Given the increasing relevance of interdisciplinary research, however, also questions about the extent at which knowledge exchange across disciplines takes place, about fields where 'it happens'

or about changes in the course of time, become more interesting. (The term interdisciplinary research is used here as equivalent to terms like multidisciplinary, cross-disciplinary or interdependent research).

Studies in which interdisciplinary knowledge transfer is quantitatively measured, are rather scarce. An earlier example is the examination of the mutual influencing of different disciplines by taking field mobility of individual scientists as an indicator (Le Pair 1980, NRC 1975) Not only scientist can be carriers of knowledge from one discipline to another, transfer may also take place by means of instruments or methods. Another, even more obvious carrier of knowledge appears to be the scientific article. One of the first attempts to study interdisciplinary research processes by bibliometric methods was undertaken in an NSF-project exploring potential indicators of interdisciplinary research (Porter and Chubin 1985).

Our present approach is based on the assumption that empirical studies may contribute to the further understanding of processes of interdisciplinary knowledge transfer. A project was started to investigate whether bibliometric methods may yield empirical data about the mutual influencing of different disciplines of science. We further proceed along the methodological line of the study by *Porter et al.*, assuming that citations to scientific articles partly reflect the use made of (documented) knowledge by researchers in successive research. However, compared to this explorative study a much larger set of journals is used and a lower aggregate level of (17) disciplines is chosen.

In this paper one aspect of the mutual influencing of different disciplines of science is analysed, namely differences in the time involved and the speed at which knowledge is transferred within and across disciplines. Which period should be considered before research performed in one discipline eventually has impact in other disciplines? Is the speed at which knowledge is exchanged with other disciplines the same in all fields? Are there obstacles for rapid exchange? By intuition, one might expect that scientific results from more distant disciplines take more time before eventually being incorporated, than results from within a discipline. Indications for such a delay were first reported by *Moed en Van Raan* (1986), based on a small scale study of publications at two faculties.

If citation delay is a general aspect of interdisciplinary knowledge flows, then it will be useful to obtain insight into these processes, in order to offer a basis for further analyses of interdisciplinary knowledge transfer. An additional question is the role interdisciplinary journals play in knowledge transfer between disciplines and in the speed at which it takes place.

The time passing in the process of citing scientific literature, also called 'aging', has been extensively studied. *De Solla Price* already showed that indications of differences among the sciences in their processes of knowledge growth can be found in referencing patterns (De Solla Price 1970). Many studies further elaborated these findings, particularly with respect to aging processes of (articles in) scientific journals (Glänzel and Schoepflin 1995; 1994). Most of these studies however, deal with aging irrespective of disciplinary

boundaries. To our knowledge no study was done on aging processes involved in knowledge exchange between different disciplines.

Referencing or citation speed is related to the subject of the first citation process (Rousseau 1994). It is also related to the so-called publication delay (Egghe and Rousseau 2000; Luwel et al. 1998). However, these processes are not our first objective. Although they may play a role in the speed of knowledge transfer, we are primarily interested in the general process of (delay in) knowledge exchange between disciplines.

10.2 Method

Three data sets were used, based on the CD-ROM version of the *Science Citation Index* (SCI) produced by ISI, including publications with an address in the United Kingdom and Germany in 1992, and for the world total in 1998. The data sets were processed in the context of a larger project in order to investigate various aspects of knowledge flows between fields of science. The study of citation delay, reported in this paper, is part of this larger project. References given in these publications were examined for the period 1960-1992 in case of the two countries and for the period 1966-1998 for the world total, so an equal period of thirty-three years has been considered for all three data sets. Articles in press, which should have to be attributed to the year of publication of the citing article (or the subsequent year), were not included.

References to journals not included in the SCI, but in the SSCI or A&HCI, were excluded from this analysis. References to non ISI journal literature (conference proceedings, books or private communications) were also excluded. We suppose that for most basic fields, the scientific journal is the primary means of communication and will offer a first insight into interdisciplinary knowledge exchange. It is realised, however, that conferences may play an important role with respect to the speed of knowledge transfer, and may deserve a separate analysis.

Publications of the United Kingdom in 1992 contained almost 800.000 references to ISI journals, publications of Germany in 1992 included 700.000 references. The world total 1998 contained more than 11 million references. Source publications as well as cited references were classified according to the ISI- category to which the journal belongs. If a journal belongs to more than one category, articles are fractionally counted for each of the categories. We realise that a journals-based field classification of articles is not a perfect means of attributing publications to a discipline. However, it is one of the few classification system available, spanning all disciplines.

ISI-journal categories apparently are too small for our present goal: a number of the 163 categories sometimes are too closely related to interpret cross referencing between them as interdisciplinary. In this analysis the primary aim is namely, not to examine knowledge exchange between smaller subfields, for instance between nuclear physics and elementary particle physics, but exchange between larger disciplines, like for instance between physics

and biology. Therefore, we classified all 163 ISI-categories to 17 broader disciplines and the latter were taken as primary object of this study. Two disciplines, Economics and Social Sciences, appeared to contain a very low number of articles included in the *SCI* and were left outside this analysis.

In total 26% of the journals which belong to more than one category are in turn classified in more than one discipline. It is realised that this type of journals may play an essential role in interdisciplinary knowledge transfer. This will be discussed afterwards.

In this analysis cross referencing between one of the remaining fifteen broader disciplines is perceived as interdisciplinary knowledge transfer. Therefore, a basic distinction among the references was made between references to articles in the same discipline, *internal references*, (R_i) and references to other disciplines, *external references*, (R_e). These two categories are comparable with the distinction made by *Chubin and Porter* (1985) into citations inside and citations outside category.

It provides a way to discover whether knowledge which is referred to by present research, is stemming from the same or from other disciplines and it may give an indication of the degree of knowledge transfer between disciplines.

The ISI category of Multidisciplinary Sciences is a special category, which consists for a large part of mono disciplinary articles in multidisciplinary journals as *Nature*, *Science* and others. Recently, a method was described to distinguish the subject of the papers published in these journals (*Glänzel et al.* 1999). We did not apply this method in this study, and Multidisciplinary Sciences was considered as a separate category, both from the citing as from the cited perspective. From the citing perspective it was considered as a separate 'discipline', though it should be realised that it is the journals, not the articles, that are multidisciplinary. Nevertheless we think it is informative to see what the characteristics of articles in these journals are, for instance concerning the average age of references.

From the cited perspective Multidisciplinary Sciences was not included. Citations to this 'discipline' can as well be to articles in the same field as to some other field. Therefore, references from another discipline to articles in the Multidisciplinary Sciences were singled out and excluded from the category of external references of the discipline concerned.

We concentrate in this article on 'references to' older publications by current research, assuming that it gives indications of the (cross-)disciplinary usage of research findings (*Porter and Chubin* 1995). An analysis of the same data from the viewpoint of the 'citations by' measure, which takes the citing of older literature as a starting point, is not given here.

10.3 Results

First a general characteristic of the age distribution of all references (both internal and external) is given in Table 10.1. On average 42% of the references in the world total of publications are given to publications of the last five years (Price-index). For the United Kingdom and Germany this fraction is somewhat higher. Typical differences between

disciplines can be observed. The extent at which recent literature is cited more often (immediacy effect), was found to correlate with intuitive divisions between the ‘hard’ and ‘soft’ sciences (De Solla Price 1970). As has been shown before by others (Moed 1989), also within the 'hard sciences' some disciplines build more rapidly on recent research than others. Here we find that Multidisciplinary Sciences and Basic Life Sciences are on top with around 50 %, Environmental Sciences and Geo Sciences at the bottom, with around 35% of the references of age 0-4. Percentages in United Kingdom and Germany are more or less identical and in the world total

Table 10.1. Proportions of references of age 0-4 and of age 0-9.

	References age 0-4			References age 0-9		
	World	UK	Germany	World	UK	Germany
	1998	1992	1992	1998	1992	1992
	% rank	% rank	% rank	% rank	% rank	% rank
Multidisciplinary Sciences	49 1	57 1	55 1	79 1	84 1	83 1
Basic Life Sciences	45 2	52 2	49 3	77 2	81 2	80 3
Physics	44 3	49 3	49 5	76 3	79 3	79 5
Clinical Life Sciences	44 4	49 4	47 6	73 4	79 4	77 6
Engineering	42 5	48 5	50 2	72 5	79 5	79 2
Computer Sciences	41 6	47 7	49 4	72 6	75 7	76 4
Materials Sciences	41 7	44 8	45 7	71 7	75 8	75 7
Pharmacology	40 8	48 6	45 8	70 8	71 6	73 8
Chemistry	39 9	42 9	41 9	68 9	71 9	67 9
Mathematics	36 10	41 10	39 13	67 10	71 10	68 13
Psychology & Psychiatry	35 11	39 13	36 14	66 11	71 13	69 14
Biology	35 12	39 12	41 10	65 12	69 12	70 10
Food, Agriculture & Biotechnology	35 13	41 11	40 12	64 13	67 11	70 12
Environmental Sciences	34 14	36 15	41 11	63 14	68 15	65 11
Geo Sciences	33 15	37 14	36 15	62 15	68 14	66 15
Total	42	48	46	73	77	75

they are slightly lower. When disciplines are ranked, considerable agreement in the order of disciplines is shown between the United Kingdom, Germany and the world.

This order remains largely the same when the proportion of references to articles of the last ten years is considered. Generally about 73% of all references concerns literature published in the last 10 years.

Between disciplines this percentage differs considerably. Again there is a striking similarity of the ranking of disciplines between the United Kingdom, Germany and the world.

When we focus our attention on external references (R_e) only, rather large differences between disciplines become apparent (Table 10.2). On top is Multidisciplinary Sciences where 81% of the references in journals included in this 'discipline' are given to other disciplines. At the other end is *Physics* with about 21% external references.

Disciplines which generally refer for more than two third to publications from other disciplines are Computer Sciences, Engineering & Technology, Multidisciplinary Sciences, Pharmacology and Psychology & Psychiatry. At the other end are disciplines like Clinical - and Basic Life Sciences, Geo Sciences, Mathematics, Chemistry and Physics which refer for less than one third to publications in other disciplines. For most disciplines a rather

large correlation between the values and the rankings for the two countries and the world is found, showing that the rate of knowledge import is to a large degree specific a discipline.

Table 10.2. Proportions of external references (R_e) in publications of the United Kingdom and Germany in 1992 and of the world total in 1998.

	World 1998 %	UK 1992 %	Germany 1992 %	WORLD 1998 rank	UK 1992 rank	Germany 1992 rank
Multidisciplinary Sciences	81	77	78	1	1	1
Psychology & Psychiatry	78	76	76	2	2	2
Pharmacology	74	69	70	3	3	3
Computer Sciences	73	68	66	4	4	5
Engineering	69	64	67	5	5	4
Food, Agriculture & Biotechnology	61	61	55	6	6	9
Materials Sciences	59	60	66	7	7	6
Environmental Sciences	58	57	62	8	8	7
Biology	55	56	55	9	9	8
Mathematics	34	36	19	10	10	14
Chemistry	34	32	33	11	11	10
Clinical Life Sciences	33	25	25	12	13	12
Geo Sciences	32	22	22	13	14	13
Basic Life Sciences	32	32	28	14	12	11
Physics	21	21	17	15	15	15
Total	39	35	32			

However, in some disciplines slight differences between the two countries are visible. This is most clearly the case for Mathematics in Germany. This discipline appears to be less interdisciplinary oriented when compared with United Kingdom and the world, with only 19 % of external references. Taking a closer look at the ISI-categories which make up this discipline, we find that in Germany, for instance in the subfield of Applied Mathematics much less (external) references are made to the discipline of Physics, as compared with the United Kingdom. Mathematics in the United Kingdom appears also to be more related with Social Sciences than in Germany. Here, we cannot go into more detail. It shows, however, that a separate analysis of internal and external references and citations may reveal interesting patterns, for instance in national characteristics in subfields.

It should be noted that the size of a discipline and also the attribution of (peripheral) ISI-categories to disciplines plays a role in the rate of referring to other disciplines. However, it might also be stated that inclusion of such categories is often typical for a discipline, and the (partial) reflection of it in figures in Table 10.2 is revealing aspects of the nature of this discipline.

A special case is Multidisciplinary Sciences, where a relatively large number of articles published in journals like *Science* and *Nature* actually are in the discipline of Basic Life Sciences. This is also reflected by a large fraction of around 40% of references from Multidisciplinary Sciences to Basic Life Sciences and is a main cause for the large share of external references (81%) found for this 'discipline'.

A first impression of the age distributions of external and internal references is given in Figure 10.1. It shows the distributions of numbers of internal and external references in the word total of publications. In order to make comparisons possible, in this figure also the number of external references per year, scaled with the total number of internal references ($R_e(y) \cdot \Sigma R_i / \Sigma R_e$), is shown.

It gives a first indication of the differences between the two categories. Internal references (straight line) appear to be given relatively more often to literature of the most recent years, external references (dotted lines), relatively more often concern older literature.

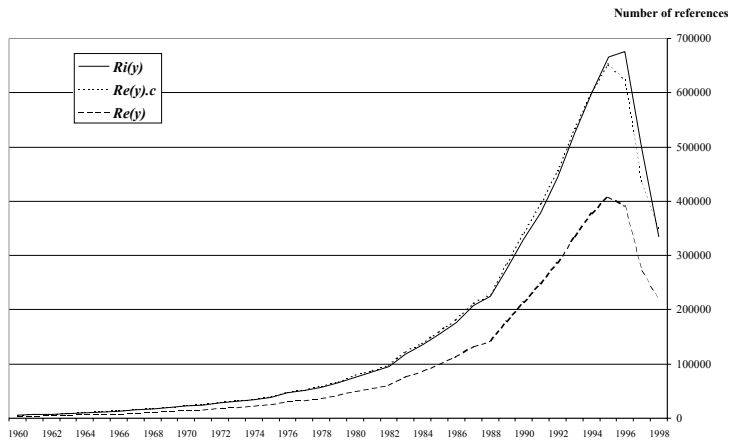


Figure 10.1. Age distribution of external and internal references in the world total of publications 1998. The age distribution of the number of external references is drawn for both the real values (line with large dots) as for the values scaled with the total number of internal references ($c = \Sigma R_i / \Sigma R_e$) (line with small dots).

In order to make the differences between the age distributions of the two categories better visible, in Figure 10.2 the ratio between internal references (R_i) and external references (R_e scaled with R_i), for each year is given for all disciplines combined and for the disciplines of Basic Life Sciences and Clinical Life Sciences. The first discipline is shown as an example of the typical pattern found in most the disciplines, the second as example of a discipline showing a more rare and contrasting pattern.

The figure (Figure 10.2^a), representing the distribution of the R_i/R_e -ratio for all disciplines combined, shows a ratio above one for references of age 1-4 years and a ratio below one for references 'older' than five years. So, internal references take a relatively larger share among references of the first years, whereas in later years external references are represented relatively more. More pronounced this is shown by the R_i/R_e -ratios of the two countries. The first data point, which represents references to articles of the same year

as the citing publication, shows hardly any differences between R_i and R_e . Just as in the distribution of Figure 10.1, it is shown that internal knowledge flow is relatively more represented in the short term than external knowledge flow, and it may be concluded that knowledge transfer within the same discipline proceeds faster than between different disciplines. The more so because the share of references of age 1-4 makes up almost 40% of the total number of references. Furthermore, for the world and both countries, a very a similar pattern of the distribution of the ratio of internal and external references can be observed.

Examining the R_i/R_e -ratios for each discipline separately, we find in a majority of disciplines the same trend as the general pattern of all disciplines combined, though often more pronounced. Most disciplines show ratios of $R_i/R_e > 1$ for references of younger age and $R_i/R_e < 1$ for references of older age. A clear example is given in the case of Basic Life Sciences (Figure 10.2^b). Largely the same pattern is shown in Computer Sciences, Engineering & Technology, Environmental Sciences Materials Sciences, Multidisciplinary Sciences, Pharmacology and Physics.

Some disciplines show a less clear difference between R_i and R_e (Biology, Food, Agriculture & Biotechnology, Geo Sciences, Psychology & Psychiatry). In three disciplines a more exceptional reverse pattern is shown. This is the case in Clinical Life Sciences (Figure 10.2^c) and in Mathematics and Chemistry. Here a reverse process appears to take place by which documented knowledge of other disciplines (in case of Clinical Life Sciences mainly of the Basic Life Sciences) is incorporated slightly faster than results from within the discipline itself.

Interestingly, in almost all of the disciplines the patterns of the distribution of the R_i/R_e -ratio for the United Kingdom, Germany and for the world are very similar (deviations in the longer term between the United Kingdom and Germany, for references of older age, may be related to the fact that after many years smaller and smaller numbers are concerned). These similarities of the trends give a further indication that patterns in the speed of interdisciplinary knowledge exchange are for a large part particular for a discipline.

Remarkably, references to articles of the same year (age zero) show in most disciplines a deviation of the general trend per discipline. As is shown in Figure 10.2^b, for instance in Basic Life Sciences, articles of other disciplines published in the same year as the citing publication, are referred to relatively fast, whereas documented knowledge from other disciplines in general is referred to relatively slow.

Citation delay in interdisciplinary knowledge exchange

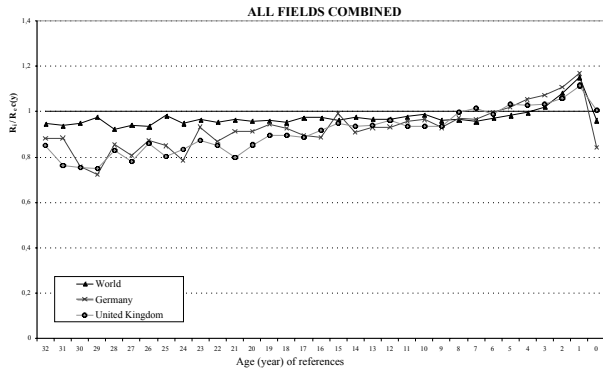


Figure 10.2^a. Ratio of the number of internal and external references, All fields combined

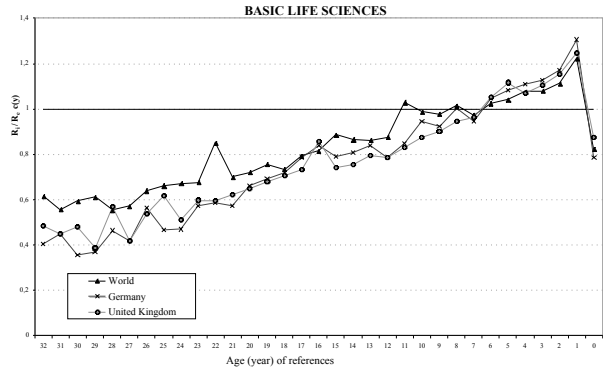


Figure 10.2^b. Ratio of the number of internal and external references, Basic Life Sciences

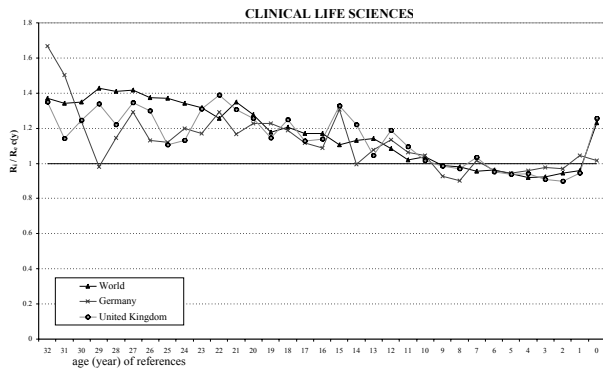


Figure 10.2^c. Ratio of the number of internal and external references, Clinical Life Sciences

The same tendencies as found above, are also reflected when the average age of external and internal references is compared. In the world total of publications, in eight disciplines internal references are clearly younger than external references (for instance in Basic Life Sciences 7.1 years versus 7.8 years respectively). In four disciplines they are of about the same age. In three disciplines, exceptionally, documented knowledge from outside the discipline is clearly referred to more quickly: internal references are on average older than external references (Mathematics (10.1 versus 8.8 years) and Clinical Life Sciences (7.6 vs. 7.1 years) and to a lesser degree Chemistry (9.4 versus 9.2 years).

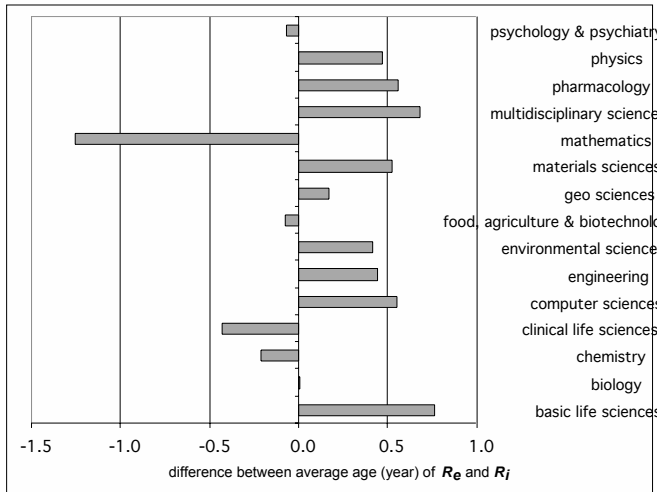


Figure 10.3. Differences between the average age of external and internal references ($R_e - R_i$) in the world total of publications 1998

Because the average age is only partially reflecting the differences in the age distributions of internal and external references, a more refined measure to compare the distributions of R_i and R_e per discipline is proposed. It is based on the well known observation that numbers of references increase exponentially as a function of age. When R_i and R_e -numbers of all disciplines are plotted on a logarithmic scale (Figure 10.4), we see that this holds for all cases, except for references to publications of age zero to one, a fact which will be discussed afterwards.

Citation delay in interdisciplinary knowledge exchange

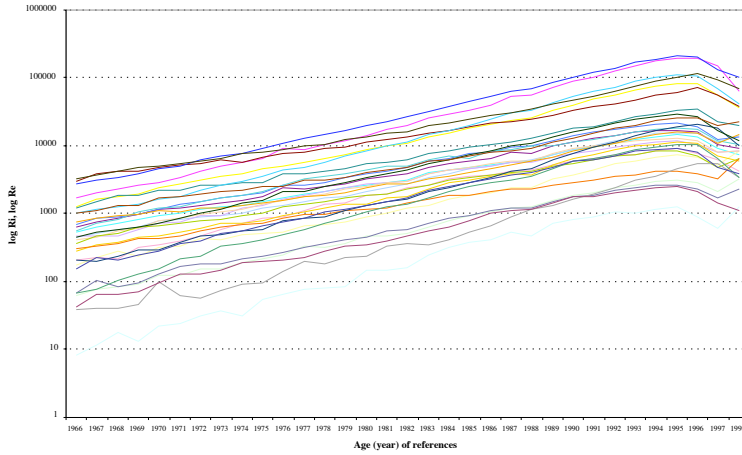


Figure 10.4. Age distributions of R_e and R_i in the world total of publications 1998 plotted on a logarithmic scale.

This exponential trend was used as a starting point for a new indicator. It expresses the differences between distributions of internal and external references by calculating the ratio of the slopes (regression coefficients) of the linear best fit of the logarithmic values of the number of references, R_i and R_e . This ratio of regression coefficients is called RRC . If $RRC > 1$, this indicates that literature from the same discipline is referred to relatively rapid, whereas literature from other disciplines is cited at a slower rate. For $RRC < 1$, literature from the own discipline is referred to relatively slow and literature from other disciplines is cited at a relatively faster rate. The resulting RRC -values are given in Figure 10.5 for all disciplines.

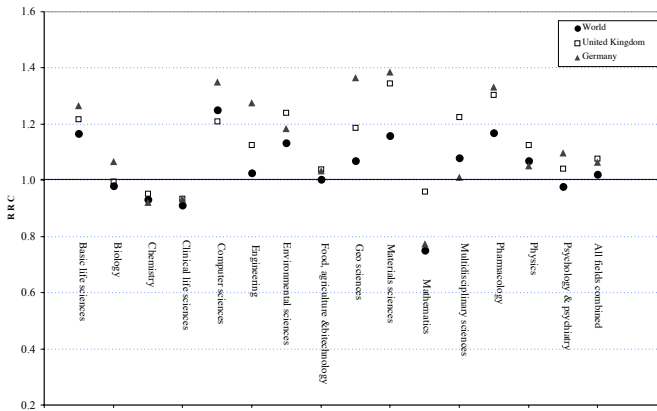


Figure 10.5. RRC -values for the world total, United Kingdom and Germany.

The general impressions discussed before, are confirmed by the results of the *RRC*-indicator.

Most of the disciplines show a *RRC*-value > 1 , reflecting that research findings from other disciplines are picked up slower in the journal literature than those from the own discipline. A value above one is also obtained for all disciplines combined, though here values seem to be levelled off. Highest *RRC*-values are found for Basic Life Sciences, Pharmacology and Computer Sciences .

Values below one are found for Mathematics, Clinical Life Sciences and Chemistry. As also became apparent in a previous section, the latter disciplines, especially Mathematics, appear to demonstrate a more interdisciplinary character and to cite relatively quickly results published outside the own discipline. Compared to the world and the United Kingdom, German publications in Mathematics in the short term show less interdisciplinary orientation. This was also concluded based upon findings given in Table 10.2.

The differences found in the speed at which publications of other fields are cited, compared to those of the same field, may play a role, especially when short term impact is concerned. This may be illustrated by, for example, citations to Physics publications. We find that of all citations to Physics, given by articles of the same discipline in 1998, 29% is to publications of the last three years (age 0-2), whereas of all citations given to physics publications by other fields, 25% is to publications of the most recent three years. In the reverse and more exceptional case of Mathematics, these shares are 25% versus 31%, respectively. Especially for groups or specialties with a relatively more or less interdisciplinary orientation, short term impact rates may deviate from the average in a given discipline.

In nine out of fifteen disciplines, the *RRC*-values of the world, the United Kingdom and Germany are more or less the same. In the other disciplines, the results vary somewhat between the three datasets, especially in Engineering, Multidisciplinary Sciences and Geo Sciences. Most deviations between the United Kingdom, Germany and the world appear to be in Geo Sciences where German publications are in the short term, much more building on results in their own discipline than in the United Kingdom and in the World.

However, *RRC*-values of the world and the two countries never show quite opposite trends. We may conclude that rates and speed at which knowledge from within a discipline or from other disciplines is incorporated, is to a large degree typical for each discipline.

In order to check *RRC*-results, we have compared these with the *GINI* index, which compares two distributions x_i and y_i using:

$$GINI = 2 \sum_{i=1}^N (x_i - y_i) \Delta x_i$$

where $_x_i = 1/N$. For our analysis $x = R_i$ or R_e , and y represents a distribution equally spread over the years (Stuart and Ord 1994).

For the world total of publications, both *RRC*- and *GINI*-index values show a large correlation, as is visible in Figure 10.6. The data support our view that the *RRC*- indicator is a reliable measure of citation speed and delay.

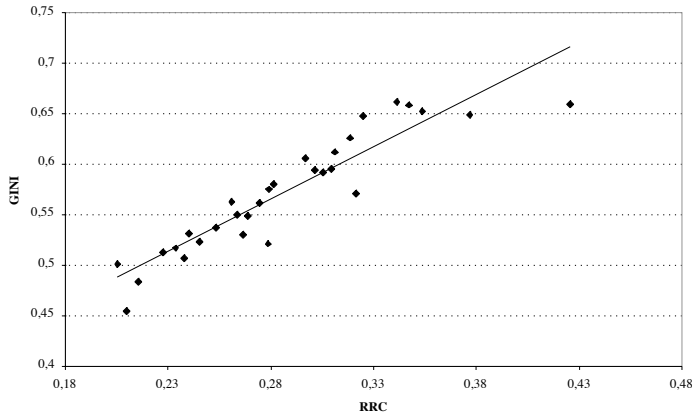


Figure 10.6. Scatter plot of *RRC*-values and *GINI*-index for the world total 1998

We have checked whether the deviation from the linear trend in the age distribution of references, for references of age zero to one (see Figure 10.4), is of influence on the results of the *RRC*-indicator.

It was found that when referencing year 0 and 1 were disordered from the analysis, results did not significantly change.

As a check, for some disciplines we have also calculated a revised ratio of the regression coefficients of R_i and R_e , in which standard errors of the separate data points were taken into account. (Standard errors were chosen to be \sqrt{N} , where N is the number of references). However no significant differences were found.

10.4 Conclusion

Scientific methods, techniques and results published in scientific journals in other disciplines, in general appear to take more time to be incorporated in a discipline than results from within this discipline. This may be concluded on the basis of an analysis of publications and references of the United Kingdom and Germany in 1992 and the world total in 1998. The degree to which a citation delay occurs, differs per discipline. Most visible it is in Basic Life Sciences, Computer Sciences, Materials Sciences and

Pharmacology. The findings confirm intuitive assumptions that scientists first of all focus on results in their own field and secondly pick up results from more distant disciplines.

Exceptionally, in Mathematics and to a lesser degree in Clinical Life Sciences, results of other disciplines are incorporated faster than those of the same discipline. An explanation for this different pattern could not be found yet.

If the general tendency of a citation delay is an indication for a real delay in interdisciplinary knowledge transfer, then the findings are important for e.g. evaluation studies. Especially when looking at short term effects, interdisciplinary impact may be relatively underrepresented and as such undervalued. Delayed transfer of knowledge across different disciplines should be taken into account also in bibliometric analyses. Citation indicators, especially when restricted to a short, recent period, may be effected by these differences in delay.

Secondly, for each discipline we see striking similarities in the age distributions of internal and external references when the three data sets are compared. The patterns found for the two selected countries and the world appear to correspond to a large degree. This seems to indicate that processes of incorporation of knowledge from within or outside a discipline, as reflected by references, are very typical for a discipline. Future studies on these specific patterns may give further insights in the dynamics of knowledge exchange between disciplines. It may also reveal interesting characteristics of national research profiles.

As mentioned before, in this analysis both journals attributed to one discipline, as journals which belong to more than one discipline, are included. A future analysis which separately examines journals which are classified only once, versus those which are multiply classified, will give more insight in the role mono - and multiply classified journals play in knowledge exchange among disciplines.

Furthermore, this analysis of citation speed and delay was carried out for rather large disciplines. Future analyses at lower aggregate levels and for more specialised journal sets may yield further interesting outcomes.

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11 Measuring knowledge transfer between fields of science

E. J. Rinia¹, Th. N. van Leeuwen², E.E.W Bruins¹, H.G. van Vuren¹, A.F.J. van Raan²

¹ Foundation for Fundamental Research on Matter (FOM), Utrecht, The Netherlands

² Centre for Science and Technology Studies (CWTS), Leiden University, Leiden, The Netherlands

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Measuring knowledge transfer between fields of science

Abstract

In this paper we report on the results of an exploratory study of knowledge exchange between disciplines and subfields of science, based on bibliometric methods. The goal of this analysis is twofold. Firstly, we consider knowledge exchange between disciplines at a global level, by analysing cross-disciplinary citations in journal articles, based on the world publication output in 1999. Among others a central position of the Basic Life Sciences within the Life Sciences and of Physics within the Exact Sciences is shown. Limitations of analyses of interdisciplinary impact at the journal level are discussed. A second topic is a discussion of measures which may be used to quantify the rate of knowledge transfer between fields and the importance of work in a given field or for other disciplines. Two measures are applied, which appear to be proper indicators of impact of research on other fields. These indicators of interdisciplinary impact may be applied at other institutional levels as well.

11.1 Introduction

Breakthroughs in one field of science can have large impact on other fields. As an example, the research on nuclear spin in physics in the 1940 's can be mentioned. These discoveries were at the basis of MR scanning techniques nowadays widely applied in medical research. They in turn led to new developments in fields of medicine and biology. Insight in the ways scientific developments in one field influence progress in other disciplines, is interesting from several points of view. Among others, it can contribute to a better understanding of the effects of interdisciplinary collaboration in science. It is also of particular relevance when talking about strategic relevance of research, a topic which has become more important in science policy since the last decade. In that context much attention has been given to more direct and short term contributions of science to societal goals. Less attention, at least from a science policy point of view, has been given to the influence of discoveries in basic or fundamental science in the longer term.

Therefore, and inspired by examples like the one mentioned above, we started a project to explore ways in which an often neglected aspect of the significance of basic research, being the strategic relevance for other disciplines, might be made visible.

At the background questions about the way scientific development proceeds is playing a role. Can we think of a model by which knowledge flows from basic science to applied and technical fields? Or is the model of a science_technology spiral more valid, by which

technology uses science and science in turn is driven by new developments in technology (Casimir 1983)?

In science studies, external relevance of research has been addressed in various ways. Part of these studies have dealt with this question from an economic perspective. For instance, rates of return of investment in R&D were analysed (Mansfield 1998; Salter and Martin 2001).

Contributions of science more specifically to technological development and innovation are studied, for instance, by analyses of references to non-patent literature in patents, based on the presumption that such references reflect part of a science-technology linkage (Narin *et al* 1997).

Studies of the effects of research on surrounding disciplines are more scarce. Such studies of interdisciplinary impacts often are of a descriptive or historical nature. In the 80's some pioneering studies were done, based on more large scale empirical data. Among others the contribution of one discipline to others by field migration of scientists was analysed (Le Pair 1980; Hargens 1986). *Porter & Chubin* (1985) were among the first to study knowledge transfer across disciplines by use of bibliometric data. In a comparative study using both methods *Urata* (1990) showed that citation analysis and analysis of migration of scholars of social science fields in Japan produced more or less similar results.

In recent years the interest in empirically investigating interdisciplinary knowledge exchange is increasing (Steele and Stier 2000; Morillo *et al* 2001; Pierce 1999; NSB 2000; Kostoff and Del Rio 2001). We proceed along this line in a project in which we further explore possibilities to study knowledge transfer between disciplines by analysing cross-disciplinary citations in research literature. Part of this project was a comparison of age distributions of mono- and cross disciplinary citations, in which field specific differences were found between the speed of knowledge transfer within a discipline and that with other disciplines (Rinia 2001). A question, which is addressed in the present study, is whether the analysis of referencing behaviour in current research can give indications of the degree to which results of one field of science are of use in other disciplines. A more specific goal is to investigate relations between physics research and other disciplines. A further question is which measures might be applied in order to quantify interdisciplinary impact of fields, specialties but also research institutions. This latter topic is an important subject of this paper.

A presumption of this study is that references made to documented knowledge account for the relevance of this previous work to present research. Cross-disciplinary citations in scientific and technical publications therefore, may give a partial indication of knowledge transfer between fields and subfields of science. A partial indication, among others, because interdisciplinary impact often will be effective in the longer term and may not be visible by 'first generation' citations. For instance, although many medical instruments are in fact physics based, references made in recent medical research articles to underlying discoveries in physics more than 50 years ago will be scarce. Or in other words, the effect of 'obliteration by incorporation' will play a role. Citations will give a partial indication also

because they reflect only some aspects of knowledge transfer and other carriers of knowledge across disciplines should be considered as well, for instance instruments, methods or scientists who migrate to other fields (Le Pair 1980; Hargens 1986; Urata 1990). In the study of *Porter & Chubin* (1985) a relatively low share of references crossing the boundaries of broad disciplinary categories was found. In contrast to this study, we here use a less broad classification of disciplines and a large dataset. By this approach we hope to obtain more evidence on interdisciplinary relations in current research and at the same time obtain further indications of the appropriateness of bibliometric methods to study knowledge transfer.

11.2 Methods

We selected the bibliographic data of all papers (articles, notes, reviews, letters), published in journals included in the Science Citation Index (SCI) on CD-ROM in 1999. A total number of 643000 articles were found, containing more than 11 million references given to articles published in the period 1980-1999. In a previous analysis, based on 1998 data, we found that references to articles of age 1- 20-year made up 90% of the total number of references in the period 1960-1998. So it was decided that a restriction to a twenty year period could be made. References to non-journal literature and to journals not included in the SCI are excluded. We suppose that for most 'basic' disciplines journals are the primary means of communication. Review articles and books may play an important role in knowledge transfer between disciplines, a role which may also differ between fields. These two categories were not separately distinguished in this study. Review articles are included in this selection of journal articles, but not separately analysed. Books are not included. In future studies on this subject, however, these two categories may deserve special attention. In a next step, citing and cited articles were fractionally attributed to subfields on the basis of the ISI- classification of journals to categories. We further classified all 167 ISI journal-categories to 17 broader disciplines. Among these the category of Multidisciplinary Sciences (consisting of mostly monodisciplinary articles in multidisciplinary journals as *Nature* and *Science*) is separately distinguished. Methods to classify each single article in the latter journals were not applied here. Two disciplines, Economics and Social Sciences, which appeared to contain a low number of publications in the Science Citation Index, were omitted from the analysis.

It was found that around 25% of the journals are classified to more than one ISI-category, which in turn belong to more than one discipline. We used the journal classification method to attribute papers to fields. Therefore, articles in multi-assigned journals were fractionally attributed to categories and disciplines associated with these journals. As a consequence the role of articles in multi-assigned journals in interdisciplinary knowledge exchange is underexposed. Indications were found that multiply-classified journals have a more interdisciplinary nature than those assigned to just one category *Morillo et al*). We realise

that supplementary and more fine-tuned analyses of this group of journals will be necessary in further studies of interdisciplinary impact. Restrictions, related to the journal classification method, therefore, have to be kept in mind when interpreting the data presented below.

Secondly, it is evident that the inclusion or exclusion of a specific journal in a category, and of a specific category in a discipline, plays an important role when studying interdisciplinary knowledge transfer. However, an analysis of the effects of different classifications, was not a first aim of the present analysis. In this study we have chosen to take existing classifications (ISI journal-categories and a discipline-classification used in science indicators reports in the Netherlands) as starting point.

As mentioned before, an important goal of this study is to investigate ways in which the extent of interdisciplinary impact might be measured. Such measurements involve several elements. Apart from the number of citations, also the size of the citing and the cited (sub)field and the citation characteristics of the fields concerned, appear to play a role.

In order to take into account these latter characteristics, numbers of references of (sub)fields are normalised by the average number of references per publication in these (sub)fields. Because of this normalisation, the unit of measurement is in fact a citing publication.

In the following, we assume the share of publications in the world total in 1999 to be an indicator of the size of a (sub)field. This share is also assumed to approximate the size of a (sub)field in the citing period 1980-1999. It should be noted that this share is not necessarily constant over time.

We present the following notation, partly in accordance with notations given previously (Egghe and Rousseau 2000). It refers in part to a matrix $(R_{ij})_{i,j}$, where $R_{i,j}$ denotes the number of references given by discipline i to publications in discipline j . Such a matrix, showing the share of references given by publications in discipline i to publications in discipline j (γ_{ij}) is presented in Table 11.2.

P_i Number of publications of discipline i in 1999 ; $P = \sum_i P_i$.

$\alpha_i = P_i/P$ Share of publications of discipline i in 1999.

$R_{i,j}$ Total number of references given by publications in discipline i to publications in discipline j ; $R_i = \sum_j R_{i,j}$; $R = \sum_i R_i$.

$C_j = \sum_i R_{i,j}$ Total number of citations given to publications in discipline j ; $C = \sum_j C_j$.

$\gamma_{ij} = R_{i,j}/R_i$ Share of references given by publications in discipline i to publications in discipline j (as percentage of the total number of references given by

publications in discipline i), $\gamma_j = \frac{\sum_{i \neq j} R_{i,j}}{\sum_{i \neq j} R_i}$

Share of references given to publications in discipline j by all other disciplines (as percentage of the total number of references given by these other disciplines).

11.3 Results

Almost 644000 publications included in the SCI contain on average 17.6 references to literature in the period 1980-1999. Per discipline the average number of references differs considerably. An overview is presented in Table 11.1. For instance, in Basic Life Sciences publications on average contain 29.4 references, in Computer Sciences and Mathematics an average of 5.8 and 5.9, respectively is found. In order to take into account these different citation characteristics of disciplines, the average number of references per publication in 1999 per (sub)field is incorporated in tables and calculations of interdisciplinary impact in the next sections.

Table 11.1 Numbers of publications and references in the world total of publications 1999

Citing Discipline	number of publications 1999	number of references	average number of references per publication
Basic Life Sciences	110.844	3.263.306	29,4
Biology	21.534	409.162	19,0
Chemistry	71.082	1.063.397	15,0
Clinical Life Sciences	149.403	2.855.573	19,1
Computer Sciences	15.102	87.095	5,8
Engineering & Technology	31.808	243.012	7,6
Environmental Sciences	15.058	249.494	16,6
Food, Agriculture & Biotechnology	28.291	437.200	15,5
Geo Sciences	19.417	325.410	16,8
Materials Sciences	34.528	332.207	9,6
Mathematics	19.479	113.958	5,9
Multidisciplinary Sciences	9.622	186.738	19,4
Pharmacology	16.218	380.605	23,5
Physics	95.435	1.283.952	13,5
Psychology & Psychiatry	6.095	108.684	17,8
Total	643.916	11.339.792	17,6

This means that in the following we will use, in stead of the absolute number of references, the weighted (normalised) number of references, obtained by dividing the number of references given by a (sub)field by the average number of references per publication in this (sub)field.

A field to field distribution of the shares of references is given in Table 11.2. It becomes clear that in most disciplines the largest share of references is given to publications of the own discipline. However, the degree to which differs considerably. *Urata* (1990) defined this rate of (disciplinary) selfcitation as an index of independence. In table 11.2 is shown that high levels of self citation in most cases correlate with the basic or applied character of a field. In Physics the highest self citing rate is found. Of all disciplines, it appears to develop most independently, on the basis of results published in literature from the own discipline, and least of all on (documented) knowledge of other disciplines. Also publications in Mathematics, Geo Sciences, Chemistry and both Life Sciences disciplines show a high share of *selfcitations*. In more applied and technical fields like Engineering and ‘Food, Agriculture and Biotechnology’ these shares are considerably lower. Exceptions are Multidisciplinary Sciences, Pharmacology and ‘Psychology & Psychiatry’ where is referred more to articles in the Basic Life Sciences than to articles of the own discipline.

Table 11.2 Shares of references per discipline in the world total of publications 1999. Numbers and shares are based on weighted numbers of references

Cited discipline (j)	Percentage references to:															Total	weighted number of ref's	
	Bas	Biol	Chem	Clin	Comp	Engi	Envi	Food	Geo	Mate	Math	Mult	Phar	Phys	Psyc			
Citing discipline (i)																		
Basic Life Sciences	62,9	2,6	1,6	15,0	0,1	0,1	0,3	1,9	0,1	0,1	0,0	11,5	2,3	0,5	1,0	100	110844	
Biology	31,4	35,8	1,0	5,1	0,1	0,2	8,3	5,4	1,4	0,1	0,4	7,9	1,0	0,5	1,3	100	21534	
Chemistry	7,4	0,5	63,2	2,7	0,2	1,3	0,9	1,7	0,7	4,9	0,1	2,8	1,3	12,3	0,0	100	71082	
Clinical Life Sciences	22,2	0,6	0,6	66,9	0,1	0,4	0,1	1,2	0,0	0,1	0,1	4,9	2,1	0,3	0,5	100	149403	
Computer Sciences	5,8	0,8	2,4	3,0	45,3	19,2	0,5	0,3	1,1	0,5	10,0	2,5	0,2	7,9	0,6	100	15102	
Engineering & Technology	2,8	0,5	5,1	6,7	5,2	39,1	3,4	1,2	3,7	6,2	2,6	1,4	0,3	21,5	0,1	100	31808	
Environmental Sciences	7,1	12,9	4,0	2,8	0,1	3,8	44,5	6,9	9,6	0,3	0,3	4,1	2,4	0,7	0,5	100	15058	
Food, Agricult. & Biotechn.	26,0	7,1	3,8	14,7	0,1	0,6	4,1	35,0	1,4	0,5	0,1	4,4	1,5	0,3	0,4	100	28291	
Geo Sciences	1,0	1,8	1,8	0,2	0,3	2,8	6,6	1,5	69,8	0,5	0,2	7,2	0,1	6,1	0,0	100	19417	
Materials Sciences	1,3	0,1	14,8	1,4	0,2	5,2	0,2	0,7	0,7	49,4	0,1	2,3	0,2	23,6	0,0	100	34528	
Mathematics	1,3	1,7	0,5	1,5	4,9	5,6	0,4	0,2	0,5	0,3	72,9	1,2	0,1	8,8	0,1	100	19479	
Multidisciplinary Sciences	45,5	4,0	2,2	10,0	0,2	1,0	1,3	1,7	3,9	0,8	0,6	20,1	1,4	6,7	0,6	100	9622	
Pharmacology	31,7	1,2	3,3	29,0	0,1	0,3	1,6	1,6	0,1	0,2	0,1	5,4	23,2	0,2	2,1	100	16218	
Physics	1,5	0,1	6,4	0,7	0,4	3,5	0,1	0,1	1,5	3,5	0,5	2,8	0,1	78,8	0,0	100	95435	
Psychology & Psychiatry	33,8	4,7	0,1	16,4	0,2	0,2	1,4	1,0	0,0	0,1	5,1	8,1	0,3	28,5	100	6095		
Total	21,6	2,8	9,9	21,0	1,6	3,8	2,2	2,9	3,1	4,1	2,7	5,4	1,9	16,3	0,7	100	643916	

In the first case this can be explained by the large share of biomedical articles in multidisciplinary journals as *Nature* and *Science*, making up this ‘discipline’; the latter case shows that journals attributed to ‘Psychology & Psychiatry’, included in the *SCI*, are closely related to the biomedical disciplines.

The same pattern as mentioned above is also observed in subfields. High 'self-citing' rates (to publications in the same subfield), which for instance in the subfield of ‘Astronomy and Astrophysics’ amount to 84%, show that research in some subfields proceeds mainly on the

basis of advances within the own subfield. On the other hand there are subfields like, Manufacturing Engineering, Petroleum Engineering and General Biology in which low selfciting rates are found of around 6%. It should be noted that those shares reflect typical characteristics of subfields, but also to some extent characteristics of the journal set, selected for a specific ISI-category. Especially in more general ISI categories, like General Biology, which include more often general and miscellaneous journals within a discipline, the specific selection of journals will play a role in low selfciting rates.

At the level of larger disciplines, we find that in current research, 53% of all references are given to literature in the two life science disciplines. Taking into account the average number of references per discipline, as shown in table 11.2, this share is 43%. These two disciplines make up 40% of the world total of publications in 1999. 16% of all references are given to literature in the discipline of Physics, compared to a world share of publications in Physics of almost 15%. Smaller disciplines, in both respects, are Computer Sciences, Environmental Sciences and Pharmacology which have a world share of both citations and publications of around 2%.

In an absolute sense, journals in the Basic Life Sciences are the most important source of external (documented) knowledge for other fields. In six disciplines (Multidisciplinary Sciences, Biology, Clinical Life Sciences, 'Food, Agriculture and Biotechnology', Pharmacology and in 'Psychology & Psychiatry') references given to articles in journals in Basic Life Sciences are most important after, or even more important than, those given to articles of the own discipline. Within the exact sciences the discipline of Physics appears to have a comparable position. In four disciplines (Chemistry, Engineering & Technology, Materials Sciences and in Mathematics), references given to articles in Physics are most important after those given to publications in the own discipline. Disciplines within these two larger clusters show close mutual relationships. The disciplines of Computer Sciences and Geo Sciences occupy a position between these two clusters. The first discipline shows strongest ties with 'Engineering & Technology' and Mathematics but also, though less, with Basic Life Sciences and Physics. Geo Sciences and Environmental Sciences show relatively strong mutual relations.

An example of small, but interesting citation relations between more distant fields and subfields is given in Table 11.3. It shows subfields in Life Sciences referring most to articles in Physics. Citations reflect a link, of current research in Radiology and Medical Imaging to physics research of the past two decades. In the subfield of Otorhinolaryngology (research of ear, nose- and throat), references to Physics literature

Table 11.3 Subfields in Life Sciences referring most to articles in the discipline of Physics

	Number of references to		Weighted number of	Share of
	all disciplines	<i>Physics</i>	references to <i>Physics</i>	references to <i>Physics</i>
Basic Life Sciences				
Biochemical Research Methods	50540	1905	114	3,8
Biophysics	130907	3391	131	2,6
Biochemistry & Molecular Biology	952023	7095	224	0,7
Cell biology	339990	1400	38	0,4
Neurosciences	516620	1768	55	0,3
Clinical Life Sciences				
Otorhinolaryngology	28435	804	67	2,8
Radiology, Nuclear Med. & Medical Imaging	112616	2337	161	2,1
Medical Informatics	4444	64	7	1,4
Anatomy & morphology	19342	250	11	1,3
Ophthalmology	67335	685	42	1,0

make up almost 3% of all references. For a large part this concerns cross referencing between articles in this medical subfield and articles in the Physics subfield Acoustics.

11.4 Measures

Shares of references given by publications of other disciplines to publications in a particular field offer a first indication of the impact which this specific research has on other fields. However, a question is how the various factors, for instance the size of the fields involved, should be taken into account. In this section we concentrate on measures which incorporate these factors and may offer a basis for indicators of interdisciplinary impact.

In a study of field migration of scientists in the Netherlands, an indicator has been proposed in which a relative contribution of a field to other fields is normalised by the number of scientists in the contributing field (Le Pair 1980). A clue to further calculations is given in some recent studies on measuring preferences of articles in a specific journal to articles of other languages (Egghe and Rousseau 2000; Davidse and Van Raan 1997). Factors involved in measuring such 'language preferences' appear to be quite similar to those involved in measuring 'discipline preferences'.

In the measure of Relative Openness (RO) of a journal in language i for articles of a specific other language j , three parameters are included: the share of references given to articles in language j by articles in a journal in language i ($\gamma_{i,j}$), the size (worldshare) of the citing language (α_i) and the size of the cited language (α_j) (Egghe and Rousseau 2000). The proposed measure RO increases in γ and α_i and decreases in α_j and meets the requirement to respect the corresponding partial orders. In other words, the resulting value of $RO_{i,j}$ is

higher when the share of citations given by i to j is larger, is higher when the size of the citing language (i) is larger, and is higher when the size of the cited language (j) is smaller.

$$RO_{ij} = \gamma_{ij} \alpha_i (1 - \alpha_j) \quad (1)$$

The results obtained by two variations of this function, proposed by *Egghe and Rousseau*, show different outcomes but the same rankings. We therefore confine ourselves to the application of the first function to the analysis of cross disciplinary citations.

Instead of openness to articles written in other languages, we here consider openness to articles stemming from other disciplines. In the function of openness for other disciplines we now use the share of references given by articles in a specific discipline to articles in another discipline (γ_{ij}), and furthermore we take into account the publication worldshare of the citing discipline (α_i) and the publication worldshare of the cited discipline (α_j).

Observed from the perspective of a cited discipline, this function can be perceived as an indicator of the use made of its results by other fields. We then obtain a general indicator of the enabling character of a discipline j with respect to all other disciplines (or in other words, the openness of all other disciplines to the specific discipline j) by taking the sum over the individual RO values. To emphasise that this measure expresses the enabling character, or relative external use made of results, from the perspective of a (cited) discipline, we define this function as RE .

$$RE_j = \sum_{i \neq j} \gamma_{ij} (\alpha_i) (1 - \alpha_j) \quad (2)$$

One might argue that in this way shares of references given by each field are included in the sum, irrespective of the total number of references given by those fields (although a correction is made for the size of these fields as indicated by their number of publications (α_i)).

Therefore, one might instead calculate an indicator of the enabling character of a discipline j by looking at the openness for j by the total group of all other disciplines (perceived as a metadiscipline). The function then includes the sum of references given by all other disciplines to discipline j , as share of the total number of references given by these disciplines (γ'_j). It further takes account of the publication share of the total of all other disciplines, and the publication share of the cited discipline j . As the publication share of all other disciplines is the same as one minus the publication share of the cited discipline j , we obtain,

$$RE_j = \gamma'_j (1 - \alpha_j)^2 \quad (3)$$

However, as indicated before, in this study we use the weighted number of references. In that case both measures are identical and therefore.

$$RE_j = \sum_{i \neq j} \gamma_{ij} (\alpha_i) (1 - \alpha_j) \quad (2) = \gamma_j (1 - \alpha_j)^2 \quad (3)$$

Note that formula 3 is preferred if numbers of references are not weighted.

In case of smaller subfields with world shares of around 1%-2%, the resulting values for $(1 - \alpha_j)$ all lie close to unity. In these cases the share of references given by other fields may vary, but the resulting RE -values will hardly do. Therefore a variation of the above given function is proposed in which, instead of one minus the publications share of the cited discipline, we take the reciprocal value of the publication share of a cited discipline.

$$RE_j = \sum_{i \neq j} \gamma_{ij} (\alpha_i) (1 / \alpha_j) \quad (4)$$

This function also increases in γ and α_i and decreases in α_j , however now the latter is given the same weight as α_i . The difference between RE (2) and RE (4), due to a different weighting of the size of the cited disciplines, is shown in Table 11.5.

Separate RE (4) outcomes for each discipline are given in Table 11.4. As might be expected, articles in the discipline, or better, category of Multidisciplinary Sciences have a relatively large impact on many disciplines, most of all on Basic Life Sciences. Here the large share of biomedical articles in *Nature* and *Science*, making up this category, will play a role.

Table 11.4 RE (4) / Cex/P per discipline based on the world total of publications 1999.

Citing Discipline (<i>i</i>)	Cited Discipline (<i>j</i>)														
	<i>Basic</i>	<i>Biol</i>	<i>Chem</i>	<i>Clin</i>	<i>Comp</i>	<i>Engi</i>	<i>Envi</i>	<i>Food</i>	<i>Geo</i>	<i>Mate</i>	<i>Math</i>	<i>Mult</i>	<i>Phar</i>	<i>Phys</i>	<i>Psyc</i>
Basic Life Sciences		0,13	0,03	0,11	0,01	0,00	0,03	0,07	0,00	0,00	0,00	1,32	0,16	0,01	0,17
Biology	0,06		0,00	0,01	0,00	0,00	0,12	0,04	0,01	0,00	0,00	0,18	0,01	0,00	0,05
Chemistry	0,05	0,02		0,01	0,01	0,03	0,04	0,04	0,03	0,10	0,00	0,21	0,06	0,09	0,00
Clinical Life Sciences	0,30	0,04	0,01		0,01	0,02	0,01	0,06	0,00	0,00	0,01	0,76	0,20	0,00	0,13
Computer Sciences	0,01	0,01	0,00	0,00		0,09	0,00	0,00	0,01	0,00	0,08	0,04	0,00	0,01	0,01
Engineering & Technology	0,01	0,01	0,02	0,01	0,11		0,07	0,01	0,06	0,06	0,04	0,05	0,01	0,07	0,01
Environmental Sciences	0,01	0,09	0,01	0,00	0,00	0,02		0,04	0,07	0,00	0,00	0,06	0,02	0,00	0,01
Food, Agricult. & Biotechn.	0,07	0,09	0,02	0,03	0,00	0,01	0,08		0,02	0,00	0,00	0,13	0,03	0,00	0,02
Geo Sciences	0,00	0,02	0,01	0,00	0,00	0,02	0,08	0,01		0,00	0,00	0,15	0,00	0,01	0,00
Materials Sciences	0,00	0,00	0,07	0,00	0,00	0,06	0,00	0,01	0,01		0,00	0,08	0,00	0,09	0,00
Mathematics	0,00	0,01	0,00	0,00	0,06	0,03	0,01	0,00	0,00	0,00		0,02	0,00	0,02	0,00
Multidisciplinary Sciences	0,04	0,02	0,00	0,01	0,00	0,00	0,01	0,01	0,02	0,00	0,00		0,01	0,01	0,01
Pharmacology	0,05	0,01	0,01	0,03	0,00	0,00	0,02	0,01	0,00	0,00	0,00	0,09		0,00	0,06
Physics	0,01	0,01	0,09	0,00	0,02	0,10	0,01	0,00	0,07	0,10	0,03	0,28	0,00		0,00
Psychology & Psychiatry	0,02	0,01	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,03	0,03	0,00	
Total (RE_j)	0,62	0,47	0,27	0,23	0,23	0,38	0,49	0,31	0,32	0,28	0,18	3,40	0,53	0,31	0,47

Furthermore, among others a relatively high impact of articles in Basic Life Sciences and Pharmacology on Clinical Life Sciences is shown.

Another measure which also takes into account the size of a (sub)field, is the external citation average. It gives the number of external citations (i.e. citations excluding (self)citations to articles in the same discipline) given to publications of a discipline, divided by the number of publications of this discipline. It has been applied in a study in which interdisciplinary impact of institutes in High-Energy Physics was compared (Davidse and Van Raan 1997)

$$Cex_j / P_j = \frac{C_j - R_{j,j}}{P_j}$$

As said before, in our analysis we take the size of fields in the cited period (1980-1999) to be equal to the size of fields in the citing year (1999). In that case, Cex/P is identical to RE (4), when using *weighted* references, as can easily be shown by some calculus. In mathematical form:

$$RE_j(4) = Cex_j/P_j \text{ if } R_{i,j} \rightarrow R_{i,j} / (R_i/P_i)$$

In reality, of course, the number of publications in the cited period (1980-1999) is much larger than the number of publications in the citing year (1999). If the *relative* size of fields does not change significantly in the cited period, then the values for Cex/P all decrease by an (almost constant) factor P_{80-99}/P_{99} .

To our opinion, the measures RE (4) and Cex/P are good indicators of the impact of a discipline on other disciplines, and may be applied as well at other levels like subfields or research institutes.

A drawback of this measure is that the degree to which a field builds on own results, as indicated by the share of references given to the own discipline, does not influence the measures mentioned. To take this into account, the impact of research on other fields can also be compared with the reciprocal: the degree to which results in other fields are of influence on the research concerned. For that purpose, we compare the number of external citations (given to a field by other fields) with the number of external references (given by this field to other fields). It might be called an Import/Export Ratio comparable with the one in economics:

$$IER_j = \frac{C_j - R_{j,j}}{R_i - R_{i,i}}$$

The IER -indicator appears to give complementary information to RE and Cex/P , because it takes into account the extent at which research proceeds on the basis of own results.

An overview of the outcomes of the measures *RE* (4) and *IER* for each of the 15 disciplines is given in Table 11.5.

According to *RE* (4) and *Cex/P*, the discipline of Multidisciplinary Sciences shows the highest ranking (explainable by the nature of the journals making up this 'discipline'). Basic Life Sciences, Pharmacology and Environmental Sciences also rank high. Most disciplines in the cluster of the physical sciences show less high outcomes. Engineering, Geo Sciences and Physics rank in the middle. Publications in Clinical Life Sciences, Computer Sciences and Mathematics on average are the least often cited by other disciplines.

Table 11.5 Different measures of interdisciplinary impact per discipline compared

<i>Discipline</i>	<i>Basi</i>	<i>Biol</i>	<i>Chem</i>	<i>Clin</i>	<i>Comp</i>	<i>Engi</i>	<i>Envi</i>	<i>Food</i>	<i>Geo</i>	<i>Mate</i>	<i>Math</i>	<i>Mult</i>	<i>Phar</i>	<i>Phys</i>	<i>Psysc</i>
<i>RE</i> (2) ranking	0,09 1	0,02 7	0,03 5	0,04 3	0,01 13	0,02 6	0,01 11	0,01 9	0,01 12	0,01 8	0,01 14	0,05 2	0,01 10	0,04 4	0,00 15
<i>RE</i> (4) = <i>Cex/P</i> ranking	0,62 2	0,47 6	0,27 12	0,23 13	0,23 14	0,38 7	0,49 4	0,31 10	0,32 8	0,28 11	0,18 15	3,40 1	0,53 3	0,31 9	0,47 5
<i>IER</i> ranking	1,68 2	0,73 7	0,73 6	0,71 8	0,42 15	0,63 12	0,88 5	0,48 14	1,07 4	0,55 13	0,66 11	4,26 1	0,69 9	1,47 3	0,66 10

There are four disciplines with a *IER*-ratio above one: Multidisciplinary Sciences, Basic Life Sciences, Physics and Geo Sciences. These are basically oriented disciplines which (apart from the special case Multidisciplinary Sciences) all show a high share of references to the own discipline. These fields all have the characteristic that they are cited more by other fields than vice versa. Disciplines with the lowest *IER*-ratio's are Computer Sciences, 'Food, Agriculture & Biotechnology', and Materials Sciences.

In table 11.5 is shown that disciplines like Multidisciplinary Sciences and Basic Life Sciences rank high on both indicators *Cex/P* and *IER*-indicators. Other disciplines like Computer Sciences and Mathematics rank consistently low on both indicators. For other disciplines the results vary.

Table 11.6 *RE* (4) and *IER* per subfield of Physics

SUBFIELD	<i>RE</i> (4)		ranking	<i>IER</i>	ranking
	<i>P</i>	$\frac{Cex/P}{=}$			
Physics, atomic, m.,c.	7787	0,60	1	2,05	2
Thermodynamics	980	0,53	2	0,84	12
Acoustics	1435	0,49	3	0,94	11
Physics, applied	15795	0,43	4	1,71	6
Microscopy	705	0,42	5	0,63	15
Physics, mathematical	3491	0,38	6	1,72	5
Physics, fluids	2654	0,36	7	1,46	7
Instruments & instr.	2457	0,34	8	0,71	13
Physics, cond. matter	14165	0,33	9	1,76	4
Crystallography	4818	0,33	10	0,69	14
Spectroscopy	3445	0,31	11	0,59	16
Optics	6530	0,26	12	1,37	9
Physics, general	14985	0,25	13	1,92	3
Astron & astrophysics	8817	0,13	14	1,12	10
Physics, nuclear	2784	0,11	15	2,28	1
Physics, particles & fields	4534	0,04	16	1,39	8

Results for subfields in the discipline of Physics are given in Table 11.6. The subfield of 'Atomic & Molecular & Chemical Physics' shows the highest average number of citations by other disciplines and also a high *IER*-ratio. Nuclear Physics is an example of a subfield with a low *RE* (*Cex/P*) value. The *IER*-ratio, however, shows that the number of citations by other disciplines exceeds the degree to which Nuclear Physics refers to other fields.

11.5 Conclusions

The analysis of interdisciplinary impact by means of bibliometric methods shows that cross disciplinary citations, together with other indicators, may provide useful insight into relations between fields and subfields of science. Apart from more well known connections, they reveal less commonly expected relations between disciplines and subfields and give insight into knowledge exchange taking place. Measures of interdisciplinary impact, constructed on the basis of references given by other fields, have to take into account the size, as well as the citation characteristics, of the fields involved. As such they demonstrate part of the relevance of results in a given field to progress in other fields. They may be useful for analyses at other institutional levels like institutes or universities as well.

Some comments on the present method can be made. Firstly, when studying interdisciplinarity by bibliometric methods, methods which classify articles to subfields on the basis of journal classification, are not perfect. This is especially the case for articles in multi- and interdisciplinary journals, both those classified in the category Multidisciplinary

Sciences, as those journals which belong to more than one subfield or discipline. These two categories of journals may play an important role in knowledge transfer between disciplines. But especially these categories cannot be analysed well enough on the basis of the journal classification method and fractional attribution of articles alone. Attribution of single articles to (sub)fields, for instance on the basis of subject classification, would be preferable in these cases, especially at lower aggregate levels. However, at a higher aggregate level the ISI classification system is one of few systems spanning all disciplines. In a follow up we intend to further study the role of multiply classified journals in interdisciplinary knowledge transfer.

Secondly, in interdisciplinary knowledge transfer, longer time periods than twenty years may be involved. Bibliometric studies of interdisciplinary knowledge transfer therefore may also be devoted to citation relations at longer terms. Furthermore, we assume that in knowledge transfer over longer periods, also review articles and books will play an important role, a role which deserves more attention in studies of interdisciplinary impact.

Finally, it is evident that ways to classify subfields and disciplines on the basis of ISI journal categories plays an important role when studying interdisciplinary knowledge transfer. Analysis of different classifications were not a topic of this study, but will be important for further studies of interdisciplinarity on the basis of bibliometric methods.

*

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Can bibliometrics contribute to the study of interdisciplinary influence

12 Can bibliometrics contribute to the study of interdisciplinary influence: a case study of physics

E.J. Rinia¹, Th. N. van Leeuwen², L.R. Kouw¹, A.F.J. van Raan²

¹ Foundation for Fundamental Research on Matter (FOM), P.O. Box 3021,
3502 GA Utrecht, The Netherlands

² Centre for Science and Technology Studies (CWTS), University of Leiden,
Wassenaarseweg 52, P.O. Box 9555, 2300 RB Leiden, The Netherlands

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Can bibliometrics contribute to the study of interdisciplinary influence: a case study of physics

Abstract

In this study, the mutual influencing of different fields of science is analysed by looking at the so called 'knowledge balance' between disciplines, based on the difference between numbers of reciprocal references by publications in two disciplines. A conclusion is that *Physics* and *Basic Life Sciences* appear to be important sources of inspiration for developments in other disciplines. Furthermore a method is applied, which compares the age distributions of non-disciplinary citations given to a subfield with exponential regression values. Extreme deviations from the regression lines are indicators for key papers which appear to be responsible for large interdisciplinary effects in current research. Cases in physics lead to the conjecture that large interdisciplinary impact appears to be caused more by diffusion of methods or even software and less by sudden breakthroughs.

12.1 Introduction

The application of citation analysis in science studies investigating the impact of a particular piece of research on subsequent research, is widespread. In analyses of the influence of research outside its own domain, bibliometrics is also widely applied in studying impact of research on innovation, among others by use of patent citation data. However, bibliometric methods have been applied more scarcely in studies of the influence of research on surrounding disciplines. Since 1980's a small number of studies on interdisciplinarity have been performed, starting with *Porter and Chubin* (1985). Recently new applications of bibliometric indicators of interdisciplinary impact in research evaluation have appeared (National Science Board 2000, Davidse 1997, Kostoff 2001, Van Raan 2002). In most of these studies, the Science Citation Index (*SCI*), as one of few databases which spans all disciplines, is used, and the journal classification method (*JCM*) is applied for delineation of fields and subfields.

In this paper we further investigate to what degree useful information on disciplinary interactions can be obtained by citation analysis using *SCI* and *JCM*. Objections against the use of *JCM* (National Science Board 2000, Rinia 2002) are partly circumvented by our present approach.

We especially focus on the citation relations between physics and other disciplines. A leading motivation is that, although many examples of physics discoveries which were influential on other fields have been described, quantitative research on this topic is scarce. In this study, firstly, relations between different fields of science and between subfields of Physics and other fields are analysed by looking at the net import/export balance of

citations exchanged at the level of fields and subfields. Secondly, in order to see what is behind these data, specific cases of cross disciplinary citing (i.e. citing publications belonging to other disciplines) are further examined. We specifically investigate examples of boosts in the number of (recent) non-physics citations to physical research results published in previous years, to see whether these are a sign of real knowledge transfer between disciplines.

12.2 Method

Our study is based on the papers (articles, notes, reviews, letters) included in the *SCI* on CD-ROM in 1999. We follow the method introduced by *Porter and Chubin* (1985), which means that relations between (sub)fields are investigated by looking at the disciplinary origin of the articles cited in these papers. In particular cross-disciplinary citations, also denoted as external citations, are considered. In this study we take into account references to articles in the period 1980-1999, which are included in the *SCI*. Articles are classified by year of inclusion in the *SCI*.

The method to look backwards to older articles which are cited in 1999, also called the synchronous approach, was chosen, because it was preferred to consider the actual impact of previously published results, i.e. from the viewpoint of current research.

It should be noted that between disciplines there may be differences in the share of references to sources not included in the *SCI*.

Articles and references were classified, on the basis of *ISI*- journal-categories, into 15 broader disciplines. Disciplines which are distinguished are: Basic Life Sciences; Biology; Chemistry; Clinical Life Sciences; Computer Sciences; Engineering & Technology; Environmental Sciences; Food; Agriculture & Biotechnology; Geosciences; Mathematics; Pharmacology; Physics; Psychology & Psychiatry. Publications in multidisciplinary journals (e.g. *Nature*, *Science* or *PNAS*) are classified in this study to the 'discipline' Multidisciplinary Sciences.

In case of interdisciplinary journals (covering intersections of several subfields and assigned to more than one *ISI*-category), articles are fractionally attributed to subfields and eventually disciplines. This arithmetic attribution to (sub)fields (instead of classification by content) of articles in multiply assigned journals, is a drawback in studies of interdisciplinarity based on *JCM*. Therefore, to analyse interdisciplinary influence, in this study we introduce the concept of a '*knowledge balance*', in analogy with the concept of '*trade balance*' applied in economics.

If science is conceived as an economic system, then 'referring to' publications of other disciplines can be considered as a sign of 'import of knowledge' developed elsewhere. Conversely, being cited by publications in other disciplines can be considered as an indication of 'export' of knowledge to these disciplines. The difference between these numbers of reciprocal references by publications in two disciplines - or between import and export of knowledge - then yields an indication of the net '*knowledge balance*' between

these disciplines. Such a balance partly circumvents the objections against *JCM*, as effects of multiply assignment of journals and fractionated assignment of numbers of articles in these journals, are cancelled out and play no role in outcomes.

As with all metaphors, the parallel between the economic and scientific system is limited. For instance, the export of goods implies a more active agent than the export of knowledge - being cited. However, keeping in mind these restrictions, we think the analogy may be helpful in better understanding knowledge transfer between disciplines.

We analyse the outcomes of knowledge balances at the level of disciplines in the first part of the next section (Table 12.1). Furthermore, knowledge balances between subfields within the discipline Physics and other disciplines are examined (Table 12.2). Subfields in Physics are: Acoustics; Astronomy & Astrophysics; Crystallography; Instruments & Instrumentation; Microscopy; Optics; General Physics; Applied Physics; Atomic, Molecular & Chemical Physics; Condensed Matter Physics; Physics of Fluids; Mathematical Physics; Nuclear Physics, Physics of Particles & Fields; Spectroscopy; Thermodynamics.

In a second part, we analyse the age distributions of citations given in 1999 by other disciplines to (articles in) subfields in physics in the period 1980-1999. A comparison is made between exponential regression values and the values actually obtained. Extreme deviations are considered to be indicators of particularly relevant external impact. These deviations are separately analysed, based upon the distribution of citations to papers in the years involved. In this study we do not correct for differences in average number of references per field. Explanations for these differences, given in science studies, appear to offer no sufficient theoretical basis for such corrections. Apart from that we observed that global outcomes presented in this paper do not change significantly when weighting by the average number of references per field.

12.3 Knowledge balance between disciplines

Outcomes show that in scientific publications to a considerable amount is referred to research outside the own discipline. By using the classification into fifteen fields and the methods described, we find that more than one third of all references is cross disciplinary. This is a much higher share than found by *Porter and Chubin*. (1985), probably due to the use in our study of a much larger data set and a more refined classification of disciplines.

A conclusion about the extent of interdisciplinary knowledge transfer cannot be directly inferred from this. As mentioned before, partly due to methodological restrictions, a robust classification of disciplines and a rigid definition of cross disciplinary reference is hard to achieve. For a quantitative analysis of relations between disciplines, a calculation of 'knowledge balance' between disciplines is preferred, which is based on the comparison of reciprocal number of references exchanged between disciplines. A surplus on this balance

shows a net export; the reverse shows that net import of references - knowledge - is taking place.

Table 12.1 Knowledge balance between disciplines: the difference between the number of reciprocal references by publications in two disciplines (number of references / 1000). The Net *relative* import or export expresses the net import/export as proportion of the total number of reciprocal references in publications of two disciplines

		Right (upper)half: Net import: $NI(i,j) = ((R(i,j) - R(j,i)) / 1000$																	
		Left (lower)half: Net relative export: $Nri(i,j) = ((R(i,j) - R(j,i)) / (R(i,j) + R(j,i)))$																	
Exporting discipline (j)																		Import excl.	
Importing discipline (i)		Basi	Biol	Chem	Clin	Comp	Engi	Envi	Food	Geo	Mate	Math	Mult	Phar	Phys	Psyc	Import Rank	Multi. Sci. Rank	
Basic Life Sciences		-45	-18	-169	-3	-3	-6	-52	-1	-2	0	289	-46	-2	-6	-65	3	-353	1
Biology	21%		-1	3	0	0	2	-9	0	0	0	25	0	0	0	64	11	40	10
Chemistry	13%	6%		-7	0	1	0	1	2	3	0	26	-5	48	0	86	12	60	11
Clinical Life Sciences	15%	-9%	17%		-1	-6	-3	-30	0	-2	1	122	-43	-1	-2	209	15	87	12
Computer Sciences	39%	40%	2%	14%		4	0	0	0	0	3	2	0	2	0	15	8	13	8
Engineering & Technology	24%	10%	-4%	22%	-14%		-1	0	-1	-2	0	2	0	8	0	9	5	7	5
Environmental Sciences	22%	-3%	2%	24%	-24%	6%		-1	2	0	0	8	0	0	0	18	9	11	7
Food, Agric. & Biotechn.	29%	17%	-2%	31%	2%	-5%	2%		1	0	0	16	0	0	1	109	13	93	13
Geosciences	14%	1%	-12%	32%	1%	7%	-5%	-12%		0	0	16	0	0	0	14	7	-3	3
Materials Sciences	23%	12%	-3%	31%	11%	7%	-3%	1%	12%		0	6	0	34	0	43	10	37	9
Mathematics	15%	13%	-19%	-28%	-22%	0%	-21%	-39%	-17%	-11%		0	0	3	0	-2	4	-2	4
Multidisciplinary Sciences	-63%	-62%	-75%	-77%	-69%	-30%	-62%	-71%	-53%	-67%	-8%		-18	-23	-5	-557	1		
Pharmacology	24%	4%	15%	26%	2%	13%	2%	-3%	18%	10%	37%	77%		0	-1	112	14	94	14
Physics	5%	-4%	-22%	6%	-16%	-8%	-5%	-5%	-1%	-28%	-17%	49%	9%		0	-68	2	-92	2
Psychology & Psychiatry	9%	-2%	1%	7%	-29%	-24%	7%	-24%	-20%	-11%	13%	68%	5%	18%		13	6	8	6
Export (%)		3%	-14%	-13%	-12%	-19%	-3%	-7%	-24%	-7%	-15%	3%	65%	-24%	11%	-9%			
Rank		4	11	10	9	13	5	6	15	7	12	3	1	14	2	8			
Export (%) excl. Multi. Sci.		18%	-9%	-9%	-6%	-17%	-2%	-4%	-21%	2%	-13%	3%		-21%	16%	-6%			
Rank		1	9	10	7	12	5	6	14	4	11	3		13	2	8			

As mentioned, in such a balance effects of multiply assigned journals and fractional attribution of numbers of articles cancel out. In the lower left part of Table 12.1, the net import or export is expressed as percentage of the total number of reciprocal references of two disciplines. The rows give the net *relative* import of a discipline *i*, and the columns give the net *relative* export of discipline *j*.

The results show a stratification at the level of disciplines distinguished. On the one side there are some larger net exporting disciplines like, Basic Life Sciences and Physics. Multidisciplinary Sciences (which in fact is no 'discipline') shows the largest net export. To a lesser degree also Mathematics is a net exporter. Publications in these four disciplines appear to be a relative important source of inspiration for researchers in other disciplines.

The other disciplines show a deficit in their knowledge balance, mostly Clinical Life Sciences, followed by 'Food, Agriculture and Biotechnology' and Pharmacology.

In the case of Physics, we find that in 1999 the total number of references from Chemistry to Physics amounts to 48000 more than the reverse: the total number of references from Physics to Chemistry. This is the result of the difference between around 130000 references from Physics (to Chemistry) and around 82000 references to Chemistry (by Physics). So, Physics is a net exporter to Chemistry. Physics is also a net exporter to Materials Sciences, Engineering & Technology, Mathematics and Computer Sciences. The total number of

external citations to Physics exceeds the total number of external references by Physics by 68000.

Basic Life Sciences appears to be a large net exporting discipline too, especially because of net export to Clinical Life Sciences, 'Food, Agriculture & Biotechnology', Biology and Pharmacology.

In the case of Multidisciplinary Sciences, by far the largest exporting discipline, a surplus of the knowledge balance might be expected. Most likely, specific articles in Multidisciplinary Sciences will often be cited by, or refer to, publications which are in fact in the same discipline, but which are attributed to another discipline than Multidisciplinary Sciences. Consequently, a large part of these citations may not be really cross-disciplinary. Therefore, in the last two columns of Table 12.1, net import outcomes are given in which Multidisciplinary Sciences is not taken into account. It appears that rankings of disciplines, according to the size of net import, hardly change when we leave references to and by Multidisciplinary Sciences aside: Basic Life Sciences, Physics, and Mathematics stay net-exporting disciplines. Geosciences now also shows a small net export. The other disciplines stay net importers.

The absolute size of the net import and export of especially Basic Life Sciences and Clinical Life Sciences, however, changes considerably when leaving citation relations with articles in Multidisciplinary Sciences aside (probably due to the large share of life science articles in *Nature*, *Science* or *PNAS*).

Furthermore, it appears that ranking hardly change when in stead of the absolute (right columns), the relative (bottom rows) net import is taken into consideration.

12.4 Knowledge balance of subfields in Physics

In the same way as at the disciplinary level, a knowledge balance can be constructed on the basis of citation relations between each subfield within a specific discipline and other disciplines. A knowledge balance between Physics subfields and non-Physics disciplines is shown in Table 12.2.

This table displays the difference (by hundreds) between the number of references to (articles in) a Physics subfield, given by a non-Physics discipline and the opposite, the number of references given to this discipline, by a Physics subfield. If the outcome is positive, then there is a net export by the Physics subfield concerned, else there is net import.

Table 12.2 Knowledge balance between Physics subfields and other disciplines: the difference between the number references to a (non-Physics) discipline and the number of citations by this discipline (number of references / 100)

		Net import: $Ni(i,j) = ((Ri,j) - R(j,i)) / 100$															
Exporting subfield (j)																	
Importing discipline (i)	Acous.	Astro.	Cryst.	Instr.	Micro.	Optics	Phys. gen.	Phys. appl.	Phys. at,m,c.	Phys. cond.	Phys. fi & pl	Phys. math.	Phys. nucl.	Phys. part.	Spect.	Therm.	Total Physics
Basic Life Sciences	1	0	15	-2	-17	2	1	-2	9	-2	-2	-3	0	0	-19	0	-17
Biology	0	0	2	0	-1	0	1	1	0	0	0	0	0	0	-1	0	1
Chemistry	2	2	14	5	2	16	78	59	264	75	4	5	2	0	-48	0	478
Clinical Life Sciences	-2	0	-1	-2	-3	2	0	0	-1	0	0	0	0	0	-6	0	-14
Computer Sciences	1	-1	-1	-1	0	2	10	3	2	1	0	5	0	-1	0	0	19
Engineering & Technology	3	2	0	-3	-1	-1	16	39	6	18	5	2	2	-3	-2	-4	78
Environmental Sciences	0	1	0	0	0	0	0	0	0	0	1	0	0	0	-1	0	2
Food, Agricult. & Biotechn.	1	0	0	-1	0	1	0	0	1	0	0	0	0	0	-1	0	1
Geosciences	0	6	2	0	0	3	-1	1	-1	0	0	1	0	0	-6	0	4
Materials Sciences	3	0	16	3	1	12	53	157	15	81	0	-1	1	0	-5	1	338
Mathematics	1	3	0	0	0	2	12	1	0	1	1	9	1	1	0	0	30
Multidisciplinary Sciences	0	-59	-7	-3	-7	-7	-24	-34	-32	-39	-4	-7	-1	-3	-9	0	-235
Pharmacology	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	-1
Psychology & Psychiatry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Total	9	-48	40	-2	-24	30	147	225	263	136	4	11	5	-7	-100	-4	
Rank	8	15	5	11	14	6	3	2	1	4	10	7	9	13	16	12	
Total excl. Multidisc. Sci	9	12	47	0	-18	37	171	259	295	174	8	18	5	-4	-91	-4	
Rank	9	8	5	12	15	6	4	2	1	3	10	7	11	13	16	14	

The import/export outcomes show which disciplines are mostly inspiring or inspired by results in subfields of physics. For instance, we find that Chemistry articles refer 26400 times more often to ‘Atomic, Molecular & Chemical Physics’ than vice versa. So, ‘Atomic, Molecular & Chemical Physics’ is a net exporting subfield to Chemistry, or in other words, Chemistry for a larger part is inspired by ‘Atomic, Molecular & Chemical Physics’ than vice versa.

The second largest net export is by Applied Physics to the discipline Materials Sciences. About half the total net export from the discipline Physics to the discipline Materials Sciences, of about 33800 references, can be attributed to this net export by Applied Physics.

Applied Physics appears to be an intermediary between physics and other disciplines, referring extensively to physics papers but cited more extensively by non-Physics papers. A result which is in agreement with other findings, for instance about the role of publications in the journal *Applied Physics Letters*, which was found to be the most cited journal in *USPTO* patents (Verbeek *et al* 2002)..

According to the size of total net-export (bottom row) to non-Physics disciplines, the subfields ‘Atomic, Molecular & Chemical Physics’ and Applied Physics appear to be the largest net exporting subfields, with a knowledge balance surplus of more than 20,000 references. A third largest net exporting subfield is Condensed Matter Physics.

12.5 Case studies in physics

The calculation of a knowledge balance to investigate cross disciplinary citation flows appears to be an improvement to weaknesses of JCM for studying multidisciplinary research activity. The method yields a global view of the influence of research in one field of science on other fields. However, which research in particular plays a role in impact on other disciplines stays hidden. From case to case, though, citation analysis can be carried through in order to gain further insight in underlying developments.

As an example we take the citations given in 1999 by publications in Chemistry to articles in Condensed Matter Physics. The import/export balance in Table 12.2 shows that in 1999 Chemistry articles refer about 7500 times more often to Condensed Matter Physics articles than vice versa. This appears to demonstrate that Condensed Matter Physics is an 'enabling science' for Chemistry. Further citation analysis was carried out to see what is at the bottom of these data.

We find that of all (19.236) references found in Chemistry papers to Condensed Matter Physics, 90% is by articles in three subfields: 12,670 by articles in Physical Chemistry, 1,535 by Inorganic & Nuclear Chemistry and 2,653 references by articles in General Chemistry. The age distributions of citations to Condensed Matter Physics by these three subfields show striking similar peaks in the number of citations to papers in 1986, 1988 and 1992 (Figure 12.1, left). We find the same peaks in citations to Condensed Matter Physics by other subfields, for instance Chemical Engineering. In these years numbers of citations deviate significantly from values which might be expected based upon the assumption that age distributions normally show an exponential trend.

Closer examination of all cited Condensed Matter Physics publications published in 1986, 1988 and 1992 reveals very skewed distributions. It appears that citations to only five publications explain the peaks observed.

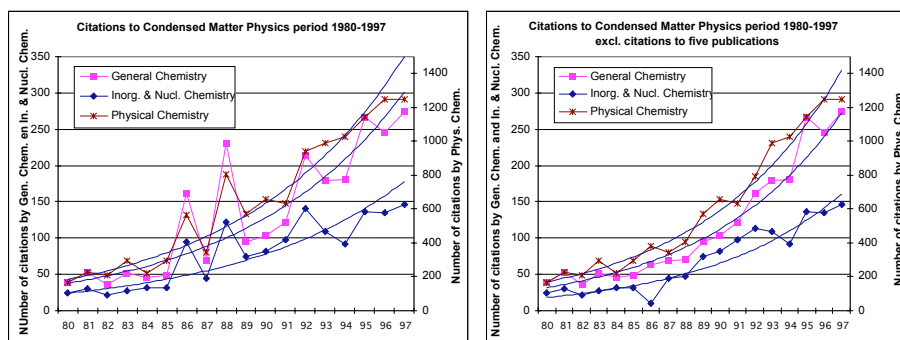


Figure 12.1 Number of citations by publications in three subfields in Chemistry to publications in Condensed Matter Physics over the period 1980-1997. Exponential trends are also shown.

If these 5 papers are left aside, the age distributions show a much closer approximation to an exponential trend (Figure 12.1, right). In all five publications (Table 12.4) methods are described to calculate the electron structure and - density in an electron gas. All papers were published in *Physical Review B*. Computational methods, like the *density function theory (DFT)*, which were developed in physics and are based upon quantum

Table 12.3 Numbers of references to highly cited Condensed Matter Physics publications in 1986,1988 and 1992 by three subfields in Chemistry

References in 1999 by publications in subfield:	to Condensed Matter Physics publications in:					
	1986		1988		1992	
	total	of which to 2 publ.	total	of which to 1 publ.	total	of which to 2 publ.
Inorganic & Nucl. Chemistry	95	(85)	122	(75)	141	(28)
Physical Chemistry	566	(186)	806	(398)	939	(148)
General Chemistry	162	(99)	231	(161)	214	(52)

mechanical principles, give important information on the structure and -dynamics of molecules. In chemistry, however, these methods were not directly accepted and during some time a controversy existed between different approaches. Finally, however, it became clear that these new computational methods yield large progress in the analysis of molecules and their interactions. Nowadays, these methods are widely applied in (quantum)chemistry, biochemistry and materials sciences. A proof of the recognition of the origin in physics is the awarding of the Nobel price in chemistry in 1999 to Walter Kohn, a theoretical physicist, together with Pople.

"Walter Kohn showed in 1964-65 that the energy of a quantum-mechanical system is uniquely determined by its electron density. This quantity is more easily handled than the complicated wave function in the Schrödinger equation. Kohn also provided a method which made it possible to set up equations whose solutions give the system's electron density and energy. This method, called density functional theory, has become widely used in chemistry since, because of its simplicity, it can be applied to fairly large molecules". (The Royal Swedish Academy of Sciences, 1998).

Citation data of the five highly cited papers by Lee and Perdew show too that this work was not immediately broadly recognised. Only after the mid 90's the numbers of citations increase enormously each year. Up till the year 2000 these five papers together were cited over 14000 times.

Table 12.4 Highly cited papers in Condensed Matter Physics in 1986,1988 and 1992

Condensed Matter Physics publications published in 1986, 1988 and 1992, which are cited most by <i>Chemistry</i> articles in 1999.	
1.	PERDEW JP, Density-functional approximation for the correlation-energy of the inhomogeneous electron-gas, <i>Physical Review B-Condensed Matter</i> , Vol. 33, Pg. 8822-8824, 1986. Total number of citations: 3188. Per year: 1 (1986); 7 (1987); 11 (1988); 17 (1989); 16 (1990); 36 (1991); 66 (1992); 107 (1993); 190 (1994); 221 (1995); 340 (1996); 423 (1997); 402 (1998); 468 (1999); 447 (2000); 436 (2001).
2.	PERDEW JP; Correction, <i>Physical Review B-Condensed Matter</i> , Vol. 34, Pg. 7406-7406, 1986. Total number of citations: 958. Per year: 0 (1986); 0 (1987); 2 (1988); 1 (1989); 5 (1990); 15 (1991); 24 (1992); 37 (1993); 80 (1994); 78 (1995); 127 (1996); 156 (1997); 109 (1998); 98 (1999); 117 (2000); 109 (2001).
3.	LEE C.T.; YANG WT.; PARR RG., Development of the Colle-Salvetti correlation-energy formula into a functional of the electron-density, <i>Physical Review B-Condensed Matter</i> , Vol. 37, Pg. 785-789, 1988. Total number of citations: 6455. Per year: 1 (1988); 4 (1989); 9 (1990); 10 (1991); 17 (1992); 37 (1993); 98 (1994); 232 (1995); 439 (1996); 705 (1997); 946 (1998); 1068 (1999); 1345 (2000); 1544 (2001).
4.	PERDEW JP; WANG Y, accurate and simple analytic representation of the electron-gas correlation-energy, <i>Physical Review B-Condensed Matter</i> , Vol. 45, Pg. 13244-13249, 1992. Total number of citations: 1676. Per year: 3 (1992); 16 (1993); 40 (1994); 42 (1995); 123 (1996); 205 (1997); 275 (1998); 260 (1999); 347 (2000); 365 (2001).
5.	PERDEW JP; CHEVARY JA; VOSKO SH; JACKSON KA; PEDERSON MR; SINGH DJ; FIOLOHAIS C, Atoms, molecules, solids, and surfaces - applications of the generalized gradient approximation for exchange and correlation, <i>Physical Review B-Condensed Matter</i> , Vol. 46, Pg. 6671-6687, 1992. Total number of citations: 6455. Per year: 3 (1992); 38 (1993); 73 (1994); 87 (1995); 139 (1996); 205 (1997); 219 (1998); 264 (1999); 292 (2000); 400 (2001).

A comparison of the disciplinary origins of publications citing the two papers by Perdew (1986) (1) and Lee (1988) (3) in the period until 1995 and in the year 2001, also demonstrates the delayed recognition of this work in the field of Chemistry. In the first period, 33% of all citations to the *Perdew* paper (1) and 28 % of all citations to the *Lee* paper (3) are from publications in the discipline of Chemistry. In the year 2001 respectively 74% and 66% of all citations are from Chemistry publications.

In a second case we analysed distributions of citations to the subfield 'Atomic, Molecular and Chemical Physics'. As mentioned before, this subfield is the largest net exporting subfield in Physics, mainly by a large net-export to Chemistry, more specifically to the subfields Physical Chemistry and General Chemistry. Distributions of citations by articles in several subfields in Chemistry to publications in 'Atomic, Molecular and Chemical Physics', in the years 1985 and 1993 all show remarkable deviations from an exponential

trend. Further examination learns that also in this case only a few highly cited articles play a role in citation peaks found. The share of citations to these nine papers in all citations to 'Atomic, Molecular and Chemical Physics' in 1985, amounts to 21% in the subfield Physical Chemistry, 38% in General Chemistry, 73% in 'Inorganic and Nuclear Chemistry' and 60% in Organic Chemistry. If (citations to) these nine publications in 1985 and 1993 are left aside, distributions close to a smooth curve are found.

All nine articles have been published in the *Journal of Chemical Physics*. The most cited paper among these nine is an article by *A.D. Becke* (*Journal of Chemical Physics*, Vol. 98, pg. 5648-5652, 1993) and also deals with applications of the *density functional theory* (DFT). Up till the year 2001, this paper is cited in total more than 6000 times. The other eight highly cited papers all deal with atomic and molecular electronic structure calculations and computational methods which enable chemists to predict structure, binding forces and properties of molecules much more precise than is possible by experimental approach.

The 'deviating' numbers of citations to the papers analysed, appear to be indicators of important interdisciplinary effects. Many citation histories of the top papers, found in both cases, reveal a citation life cycle classified by *Cano* as 'type B' (*Cano* 1991), with a moderate increase of citations in an initial period but a steady take-off thereafter, up till present.

It appears that the method to compare age distributions of non-disciplinary citations with expected values, appears to finally lead us to key papers (some of which for instance have been selected as an *ISI citation classic*), which are responsible for large interdisciplinary effects in current research.

12.6 Conclusions

The cases analysed in the present study show that cross disciplinary citation flows reflect real effects and are indicative of research in a particular (sub)field influencing other fields of science. In studies of knowledge exchange at the level of fields and subfields in science, therefore, the analysis of cross disciplinary citations may provide useful insights. Given the limitations of the journal classification method, an appropriate focus on knowledge flows at a general level is obtained by analysing net import/export rates. More refined classification of articles in inter- and multidisciplinary journals, however, will strengthen the method.

Further citation analysis proves to be useful to analyse from case to case which research exactly is at the bottom of impact on other disciplines, as shown by global data. Cases lead to the conjecture that, at least in the fields of physics and chemistry in the period concerned, large direct interdisciplinary impact appears to be caused more by diffusion of methods or even software and less by key discoveries. Papers found, mainly describe advancements in the area of calculations and computational methods. Effects of

breakthroughs of these methods, for instance in chemistry, appear to be large, judging by numbers of citations.

We conclude that analysis of distributions of cross disciplinary citations appear to be a useful tool for tracing contributions which have a large interdisciplinary effect. The outcomes support the conclusion that bibliometric methods to analyse interdisciplinary influence appear to be interesting, not only for retrospective analyses, but also for studying effects in contemporary research.

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Can bibliometrics contribute to the study of interdisciplinary influence

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Part 3. Conclusions and future prospects

Enhancing interdisciplinarity of research is becoming an increasingly important topic in science policy. However, both theoretically and in practice, processes in science that combine knowledge and approaches from different disciplines appear to be a phenomenon hard to access and assess. Problems concern not only ‘practical’ difficulties, like stimulating its occurrence or finding proper evaluation methods. Also theoretical problems have to be faced. These concern difficulties involved in determining boundaries between subject areas, a requirement for any attempt to study research that crosses those boundaries. Also, seemingly contradictory processes in science, whereby simultaneously trends operate towards integration, but also towards specialisation, even in cases where integration is a goal, complicate its approach. It was found though, that both trends can be perceived as two complementary sides of the scientific process, each contributing to innovation. Furthermore, the ambivalence of scientists aiming at the discovery of new territory and moving to new subjects, but at the same time relying on disciplinary structure and control, plays a role. Also, the interwovenness of interdisciplinarity and innovation, emphasised by science policy measures, hinders a clear view. With respect to this latter topic, we conclude that goals to enhance innovation in a scientific sense and goals to enhance the contribution of science to societal and economic innovation are often mixed up, whereas a clear distinction might be preferred. Therefore, it appears to be fruitful to identify as a distinct form of interdisciplinarity, research that links formerly separated knowledge areas by expanding curiosity driven basic research across frontiers of disciplines. It is characterised by bottom-up processes originating from within disciplines. This form also may explain the inherent interdisciplinary character of large parts of ‘disciplinary’ research, shown up in the field-specific breakdown of bibliometric output profiles of basic research groups, or in high rates of scientists mentioning to perform interdisciplinary research as measured in surveys. As a second form of interdisciplinarity can be distinguished the co-ordinated and integrated approaches, directed at a common subject or theme (for instance climate research), with the primary aim to enhance societal problem solving and utilisation. In this case, the emphasis is on top-down processes in bringing together different fields of expertise. With respect to evaluation, in the first case an important topic is the presence of expertises required in assessment procedures: in the second case the role of external stakeholders in defining research goals and in evaluation of outcomes is relatively more important. We conclude that in research policy aiming to enhance interdisciplinarity and thematic programming, a more clear distinction between these two types might be helpful in further specifying means and goals of these efforts.

It is often stated that interdisciplinarity of research is increasing at such a rate that it will resolve traditional disciplinary classifications in science. In reports, proclaiming this opinion, not seldom rhetoric is playing a role, whereas there is a lack of empirical data

supporting these conclusions. Up till yet, it has been found very difficult to capture and measure the supposed trend that interdisciplinary research is expanding in an unprecedented way. It was concluded that in the alleged transformations, partly also responses of the scientific system and scientists to meet external demands are at stake. However, the effects on research practices cannot be taken at face value. In practice cases also show efforts to enhance interdisciplinarity, that appear to turn out in specialisation. More extended, empirical evidence on the occurrence of interdisciplinary research, and the effects of science policy measures, therefore, appears necessary.

Nonetheless, the emergence of new fields as a result of breakthroughs that connect formerly separated research domains cannot be denied. Biochemistry is an example of previously distinct fields turning into a new discipline. In science theories, the inevitability of the resulting creation of new disciplinary structures has been explained. It has been found how these structures (old or new), as offered by disciplines, are essential because vital elements like problem definition and validation processes in science operate at the disciplinary level. This disciplinary foundation of evaluation mechanisms has important consequences for evaluation of interdisciplinary research.

Experiences in the practice of research evaluation show that in peer review, treating interdisciplinary research as a separate specialty is less fruitful. It appears that often disciplinary and specialist expertise offer a valid starting point also for assessments also of interdisciplinary research. This ability, however, seems to diminish when topics involved are more distant. It then becomes important to organise evaluation procedures in such a way that not only additional expertise is included in the assessment, but also that different approaches enter into discussion. In order to see the possible novelty of an approach, it seems essential that specialties involved are brought into contact on the subject concerned. For ways in which this is introduced in peer evaluation procedures, several adaptations to these procedures have been found. Such adaptations, however, should be seen apart from measures in funding policy, where, based on specific considerations, other criteria may be involved in final priority setting and favouring interdisciplinary research. The thesis that disciplinary and specialist expertise may offer a valid starting point for the evaluation of interdisciplinary research has been supported by our investigation of expert review of research programs in physics. The results, that show no indication of a biased judgement in expert reviews on (inter)disciplinary physics research, are supported by evidence found elsewhere. Though only small scale analyses have been carried out, we conclude that the widespread held view that interdisciplinary research generally is hindered in peer review processes, might be considered more balanced. We conclude that an informed view on this topic should be obtained by more systematic analyses that distinguish between the various existing forms of peer review and also between forms of interdisciplinarity.

Given the widespread attention to promoting interdisciplinarity in science, the relative lack of empirical research on this subject is remarkable. This especially concerns the assessment

of interdisciplinary research. Bibliometric results discussed in this study, support science theories that stress the important role of basic ‘disciplinary’ research in interdisciplinary developments and breakthroughs. At a macro level, this was shown by so-called ‘citation balances’ between disciplines. These revealed an agreement with intuitive assumptions on the ranking of disciplines with respect to their ‘basic’ function for other disciplines. In terms of import (references) and export (citations) of knowledge, disciplines like *basic life sciences*, *physics* or *mathematics* appear to be relatively large suppliers (net exporting areas) of knowledge for other areas, whereas disciplines like *biotechnology* or *pharmacology* were found to be relatively large users or net importing areas. Micro-level analysis of cross-disciplinary citations also provided examples that show the important role of basic disciplinary work for progress in other fields. An interesting case is the initial development by physicists of methods to calculate the structure and density of electrons in an electron gas. This appeared to be of great importance for the analysis of molecular properties. In this thesis, it is quantitatively confirmed that these discoveries are important for, and presently are broadly applied in, other areas like *quantum chemistry*, *biochemistry* and *materials science*. Though several methodological restrictions in the study of cross-disciplinary citations should be kept in mind, they show the potential of bibliometric methods in this respect. Furthermore, the results support the view that basic research within disciplines is an important source of inspiration for developments in other fields. Focusing on enforced stimulation of interdisciplinarity collaboration and thematic programming (let alone utilisation) should not lead to underestimation of this ‘interdisciplinary’ value of basic research within a disciplinary context.

In terms of research evaluation, at a macro/meso level, bibliometric indicators are found to be valuable tools with respect to e.g. monitoring national and institutional research performance, mapping of fields or studying the clustering or relatedness of cognitive developments. At a micro level, its value in research evaluation is made by for instance supplying empirical evidence of output and performance, that may serve as addition or benchmark to existing evaluation forms like peer review. For an extended and excellent overview of the use of citation analysis in research evaluation we refer to a recent study by Moed (2005). Based on the material presented in this thesis and studies performed elsewhere, we conclude that bibliometric analyses are a valuable and promising tool also for research on and evaluation of interdisciplinarity in science (cf. also van Raan and van Leeuwen 2002). At a micro level, bibliometric data were found to offer insight in the interdisciplinary character of research, of fields and actors involved and to provide benchmarking studies for analyses of the functioning of the peer review system in interdisciplinary areas, like has been shown in Chapter 8. At a macro level, bibliometric methods appear to be useful in analysing interdisciplinary developments in fields or to detect interdisciplinary knowledge transfer. More generally, bibliometric methods, as discussed in Section 3.3, are found to support basic analyses of interdisciplinarity in science by providing quantitative information on its occurrence, forms and processes (of

information transfer). A more systematic use of these methods at different levels of analysis may extend insight in processes, scale and outcomes of interdisciplinary research. Depending on the method, different aspects of interdisciplinary processes are addressed: some appear to be more specifically directed at collaboration or border crossing of scientists, others are more directed at the cognitive content of interdisciplinary research, at interdisciplinary influence and at knowledge flows. Depending on level of analysis and the scale of the research to be studied, some methods have to be preferred above others, whereas often a combination of several methods may often be required.

Bibliometric indicators should be considered balanced, when applied in assessments of interdisciplinary research. The results in this study support existing insights that interdisciplinary research on average is published in journals with a lower citation mean and also in fields with a lower field specific average number of citations. This finding may not only be informative for peers assessing interdisciplinary research by disciplinary standards. It also shows that elementary bibliometric indicators, like the average citation rate, or the journal impact factor, should be considered with care, especially in case of interdisciplinarity research. One factor, playing a role in differences in citation impact of interdisciplinary research, is a general delay of knowledge transfer across disciplinary boundaries. We found that this especially concerns the slower speed of knowledge flows between disciplines in the short term and consequently indicators that consider short-term impact. Advanced bibliometric indicators, that correct for field or journal specific characteristics and allow larger impact ‘windows’, appear to be well adapted to reflect interdisciplinary impact. Thereby, minor indications are obtained that in case of interdisciplinary research, methods comparing the citation mean of a specific unit of analysis with average citation rates of journals in which is published, are slightly more appropriate than those comparing with citation averages of fields concerned. This especially is the case when it concerns journals with a multidisciplinary scope in a predominantly disciplinary oriented field. Possibly, the way in which fields bibliometrically are defined, plays a role. This points to the necessity of field definitions and bibliometric reference standards that are able to reflect in the best possible way the characteristics of specialties involved. Therefore, field definitions (and corresponding weighting factors) based on co-word structures or more specific subject classification of articles, instead of journal-categories, might be applied in the future to better cope with assessment of interdisciplinary research. Methods that allow a more accurate classification of research articles would also be advantageous for higher aggregate citation analyses of interdisciplinarity (cf. chapter 11), based on The *Science Citation Index (SCI)* of Thomson-Scientific/ISI. The *SCI*-database is especially suited for research on interdisciplinarity, because it spans all disciplines of science. However, a well known problem is its classification of articles to (sub)fields by journal-category. General *ISI*-categories like *Multidisciplinary Sciences* (not really a multidisciplinary field, but a separate category for *Nature*, *Science* or *PNAS*) and other more general *ISI*-categories appear to contain a too

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heterogeneous set of articles that restricts analysis of interdisciplinarity. Also the classification of part of the journals to more than one category, hinders analysis of interdisciplinary research based on journal categories. Therefore, it can be expected that combining more specific methods to classify research (articles) with citation analysis based on the ISI-database will improve the contribution of bibliometric analysis to the study of interdisciplinarity in the future.

Summary

In this thesis the central theme is the application of bibliometric analysis as a tool in studying science and in research evaluation procedures, especially with respect to science at the frontier of disciplines. Interdisciplinarity of research nowadays raises much interest in worldwide science policy, because it is expected that research that crosses disciplinary boundaries or combines different approaches will offer an essential contribution to scientific and technological innovation. It appears, however, that empirical investigations on processes that play a role in interdisciplinary developments and on (problems concerning) evaluation of interdisciplinary research, are relatively scarce.

A central item in this thesis is the contribution bibliometric methods may offer to further insight into interdisciplinarity in science. The chapters of this thesis present research that has been performed in the last few years on research evaluation by means of bibliometric methods and on the role interdisciplinarity plays, particularly in physics. As an introduction to this issue, in Part 1 of this thesis a number of relevant aspects of interdisciplinarity are discussed, particularly the relation between interdisciplinarity and innovation and the 'contradiction' between specialisation and interdisciplinarity.

We subscribe to science theories by which the important function of disciplinary structure in science with respect to problem definition and knowledge validation is emphasised. Furthermore, in Part 1 we consider the contribution of (basic) disciplinary research and specialisation to interdisciplinary developments. We also discuss the most important elements of the concepts *discipline* and *interdisciplinarity* as well as the problems involved in peer review of interdisciplinary research. In the final chapter of Part 1 we address the state of the art in scientometric research on (evaluation of) interdisciplinarity.

Part 2 of this thesis consists of articles that have been previously published. Together they offer a picture of research results and, especially, methods developed in the practice of research policy in the areas of physics and technical sciences. For the research in these articles the cooperation with CWTS allowed us to use the relevant databases as well as the algorithms to calculate advanced performance indicators.

In the first chapter of Part 2, a historical overview is presented of earlier applications of quantitative research on science and studies aimed at the evaluation of research in the fields mentioned. An important further goal of these studies was to investigate strengths and weaknesses of citation analysis as a tool in research evaluation and differences in this respect between *basic* physical sciences and *applied*, and often *interdisciplinary* research. In Chapter 7 a central question is to what degree bibliometric indicators can supplement research evaluation based on peer review. In this chapter, results of a peer review assessment of research programs in condensed matter physics are compared with the results of a bibliometric analysis of the same programs. A number of slight but significant correlations were found between specific criteria used in the peer review procedure and specific bibliometric indicators. Most clearly, a correlation was found between peer review

judgement of past performance and the results of indicators by which average citation rates are normalised by world average citation rates in the subfields concerned. At the same time, this study shows that bibliometric outcomes and their comparisons with peer review results, should be interpreted with care, especially in individual cases. A combination of both methods, however, may strengthen the reliability of outcomes of research evaluations. The application of bibliometric indicators in the investigation presented in Chapter 8 is partly of a different nature. In this case results of a bibliometric investigation have been included in a research assessment by an expert panel before this panel reached its final judgement on the research programs involved. In a follow-up study, bibliometric methods were used to determine the degree of interdisciplinarity of the programs included in the panel evaluation. Results showed no systematic bias in case of panel judgements of interdisciplinary programs. The idea, though, that peer review is negatively biased in case of interdisciplinary research, is widespread. Thus, in Chapter 9 we investigate more in depth whether biases exist in bibliometric indicators concerning interdisciplinary research. Results show a systematically lower score on a number of elementary bibliometric indicators for interdisciplinary programs. In interdisciplinary programs, there appears to be a tendency to publish in subfields with a lower average citation rate and also in journals with a lower citation impact. On the other hand, it appeared that more advanced indicators, that correct for journal and field specific differences do not correlate with the rate of interdisciplinarity.

It is supposed that citations (i.e., references given) in research publications in one discipline to publications in another discipline, reflect (part of the) knowledge exchange between disciplines. The next chapters of Part 2 more specifically address these processes of knowledge exchange. In Chapter 10, the aging of cross-disciplinary citations is investigated and is compared with the age distribution of citations to publications within the same discipline. In this chapter it is shown that, as might be expected, in general a time delay is present in case of interdisciplinary knowledge exchange, as reflected by citations, when compared with knowledge exchange within a discipline. Patterns that become visible in these age distributions appear to differ between (groups of) disciplines. A comparison, made on the basis of three different data-sets, shows that the speed at which documented knowledge from other disciplines is cited, seems to be characteristic for a discipline. The results are important because they point to a general tendency whereby interdisciplinary research obtains slightly lower short-term citation rates compared to (mono)disciplinary research.

Chapters 11 and 12 address the relations between disciplines with respect to knowledge exchange in an analysis of the influence of disciplines on research in other fields. It was investigated to what degree cross disciplinary citations occur and what kind of relations between disciplines and subfields can be found, by analysing around 11 million references and 644,000 publications worldwide. In that context, we discuss in Chapter 11 an index with which the degree of interdisciplinarity of a specific discipline can be calculated. Apart from the size of this interdisciplinary citation flow, also the size of a discipline as well as

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reference behaviour is taken into account. In order to cope with restrictions caused by multiple classification of research articles, we develop in Chapter 12 a citation balance that reflects ‘knowledge import’ and ‘knowledge export’ of a discipline. Furthermore, a number of cases in subfields of physics are investigated.

A clear and important finding is that only a few key publications are responsible for large interdisciplinary effects in current scientific research.

Samenvatting

Dit proefschrift gaat over het nut van bibliometrische methoden in onderzoek naar de ontwikkeling van wetenschap en procedures bij het beoordelen van wetenschappelijk onderzoek, in het bijzonder met betrekking tot onderzoek op het grensvlak van disciplines. Interdisciplinair onderzoek staat tegenwoordig in het wetenschapbeleid overal ter wereld sterk in de belangstelling vanwege de verwachting dat dergelijk onderzoek een essentiële bijdrage kan leveren aan wetenschappelijke en technologische innovatie. Het blijkt echter dat de processen die in interdisciplinaire ontwikkelingen een rol spelen en (problemen bij) evaluatie van interdisciplinair onderzoek nog relatief weinig empirisch onderzocht zijn. Centraal in deze studie staat de bijdrage van bibliometrische methoden aan verder inzicht in interdisciplinariteit in wetenschap. De hoofdstukken in dit proefschrift behandelen onderzoek dat in de afgelopen jaren is verricht naar evaluatie van wetenschap m.b.v. bibliometrie en de rol van interdisciplinariteit daarbij, met name op het gebied van de natuurkunde. Ter inleiding in de problematiek worden in het eerste deel ('Part 1') van het proefschrift enkele actuele thema's in de discussies rond interdisciplinariteit besproken. Er wordt ingegaan op de relatie tussen interdisciplinair onderzoek en innovatie en op de 'tegenstelling' tussen specialisatie en interdisciplinariteit. Er wordt aangesloten bij wetenschapstheorieën die de belangrijke functies van disciplinaire structuren in wetenschap, zoals probleemdefinitie en kennisvalidatie, benadrukken. Ook wordt in dit eerste deel ingegaan op het belang van (fundamenteel) disciplinair onderzoek en specialisatie voor interdisciplinaire ontwikkelingen. Daarnaast worden de belangrijkste elementen van de begrippen *discipline* en *interdisciplinariteit* besproken en er wordt ingegaan op problemen in peer review bij interdisciplinair onderzoek. Het laatste hoofdstuk van het eerste deel behandelt de huidige stand van zaken in het scientometrisch onderzoek naar (evaluatie van) interdisciplinariteit en de methoden die daarbij ontwikkeld zijn.

Het tweede deel ('Part 2') van dit proefschrift wordt gevormd door artikelen die eerder werden gepubliceerd. Tezamen geven deze artikelen een beeld van onderzoeksresultaten en, in het bijzonder, van methoden die ontwikkeld zijn in de praktijk van het onderzoekbeleid bij onderzoeksorganisaties op het gebied van technische wetenschappen en natuurkunde. Bij dit onderzoek bood de samenwerking met het *CWTS* de mogelijkheid gebruik te maken van de relevante databestanden en van de ontwikkeling van geavanceerde performance indicatoren.

Het eerste hoofdstuk van deel 2 geeft een historisch overzicht van eerdere toepassingen van het (kwantitatief) wetenschapsonderzoek en studies gericht op evaluatie van onderzoek op genoemde gebieden in Nederland. Een belangrijk verder doel van deze eerdere studies was het onderzoeken van sterktes en zwaktes van citatieanalyse als methode in onderzoeksevaluatie en verschillen daarin tussen *fundamentele* natuurwetenschappen en *toegepast*, veelal *interdisciplinair* onderzoek. In hoofdstuk 7 staat de vraag centraal in

hoeverre bibliometrische indicatoren een aanvulling kunnen bieden voor onderzoeksevaluatie op basis van peer review. In dit onderzoek worden beoordelingsresultaten van onderzoekprogramma's op het gebied van vaste stof fysica, op basis van centrale peer review criteria, vergeleken met uitkomsten van bibliometrische indicatoren. Er worden een aantal lichte maar significante correlaties tussen uitkomsten van specifieke peer review criteria en specifieke bibliometrische indicatoren vastgesteld. De meest duidelijke correlatie is te vinden tussen peer review beoordeling van recente wetenschappelijke prestaties en uitkomsten van indicatoren die citatiescores vergelijken met wereldgemiddelden in een subgebied. Tegelijkertijd laat de studie zien dat bij de interpretatie van bibliometrische gegevens en bij vergelijking van uitkomsten van deze twee methoden, met name in afzonderlijke gevallen, voorzichtigheid geboden is. Aanvullend gebruik kan echter de betrouwbaarheid van uitkomsten van evaluaties vergroten. De toepassing van bibliometrische indicatoren in het onderzoek in hoofdstuk 8 heeft deels een andere functie. In dit geval worden uitkomsten van bibliometrisch onderzoek opgenomen in een onderzoeksevaluatie op nationaal niveau, voordat een eindoordeel door een expert panel over de betrokken onderzoekprogramma's werd vastgesteld. In het vervolgonderzoek werden bibliometrische methoden daarnaast gebruikt om het interdisciplinair gehalte van de geëvalueerde programma's vast te stellen. De resultaten laten geen systematisch afwijkend panel-oordeel zien in het geval van interdisciplinaire programma's. De stelling dat dit wel het geval zou zijn, is echter vrij algemeen verbreid. Dit geeft de noodzaak van verder onderzoek naar deze veronderstelling aan, en in hoofdstuk 9 wordt de eventuele bias in een aantal bibliometrische indicatoren bij interdisciplinair onderzoek onderzocht. De resultaten laten voor interdisciplinaire programma's een systematisch lagere uitkomst zien bij een aantal elementaire indicatoren. Daaruit blijkt een tendens in interdisciplinaire programma's om te publiceren in gebieden met een lager citatiegemiddelde en ook in tijdschriften met een lagere citatie-impact. Citatie-indicatoren genormeerd op vakgebied- en met name op tijdschriftgemiddelden blijken in deze studie niet te correleren met mate van interdisciplinariteit.

Verondersteld wordt dat citaties (dus: referenties gegeven) in onderzoekspublicaties in het ene gebied, naar onderzoek in een ander gebied (een deel van de) kennisuitwisseling tussen disciplines reflecteren. De volgende hoofdstukken van deel twee richten zich op deze processen van kennisuitwisseling. In hoofdstuk 10 wordt de 'leeftijd' van deze 'disciplineoverschrijdende' citaties onderzocht en vergeleken met leeftijdsverdelingen van citatieverkeer binnen een discipline. Dit onderzoek laat zien dat bij interdisciplinaire kennisuitwisseling, zoals dat blijkt uit het citatieverkeer, in het algemeen een zekere vertraging optreedt vergeleken met intra-disciplinaire kennisuitwisseling. De patronen die in deze leeftijdsverdelingen naar voren komen, blijken echter per (groep van) disciplines te verschillen. Een vergelijking op basis van drie verschillende dataverzamelingen laat zien dat verschillen in snelheid waarmee naar werk uit andere disciplines wordt gerefereerd, karakteristiek lijken te zijn voor een discipline. De uitkomsten zijn van belang, omdat deze laten zien dat korte termijn citatie impact van interdisciplinair onderzoek in het algemeen

licht achterblijft bij dat van meer (mono)disciplinair gericht onderzoek.. Specifieke relaties tussen disciplines bij kennisuitwisseling staan centraal in onderzoek, op basis van citatieanalyse, naar de invloed van wetenschapsgebieden op onderzoek buiten het eigen vakgebied. Dit wordt in de hoofdstukken 11 en 12 beschreven. Daarbij werd in een analyse van 11 miljoen referenties in 644.000 publicaties wereldwijd nagegaan in welke mate 'discipline-overschrijdend' citatieverkeer optreedt, en welke relaties tussen disciplines en deelgebieden daarbij zichtbaar worden. In hoofdstuk 11 wordt voor de analyse van deze gegevens een index ontwikkeld voor de mate van interdisciplinariteit van onderzoek in een bepaald vakgebied. Daarin worden, naast de omvang van het citatieverkeer, ook variabelen zoals de omvang van en refereergewoonten in een discipline verrekend. Om beperkingen veroorzaakt door meervoudige classificatie van onderzoeksartikelen het hoofd te kunnen bieden, wordt in hoofdstuk 12 een citatiebalans ontwikkeld die de 'kennisimport' en 'kennisexport' per discipline weergeeft. Meer in detail worden enkele cases op een aantal deelgebieden in de natuurkunde onderzocht.

Een duidelijke en belangrijke bevinding is dat slechts een beperkt aantal cruciale artikelen verantwoordelijk is voor grote interdisciplinaire effecten in het huidige wetenschappelijke onderzoek.

Curriculum vitae

Eduard Jan Rinia is geboren in Apeldoorn op 25 mei 1949. Hij behaalde in 1967 het HBS-A-examen op het Christelijk Lyceum in Apeldoorn. Na militaire dienstplicht studeerde hij sociale wetenschappen aan de Universiteit in Utrecht. Na een onderbreking waarin part-time werk, journalistiek en politiek werden gecombineerd, is hij in 1987 afgestudeerd in de sociologie aan de Universiteit Utrecht met als specialisatie methoden en technieken van sociaal wetenschappelijk onderzoek. Sinds 1987 is hij fulltime in dienst van de Stichting voor Fundamenteel Onderzoek der Materie (FOM) in Utrecht. Daar is hij zich in toenemende mate gaan richten op wetenschapsonderzoek en wetenschapstatistiek en de toepassingen daarvan in onderzoekbeleid. In deze functie heeft hij diverse projecten uitgevoerd in samenwerking met het CWTS, Universiteit Leiden. Eind jaren negentig is hij onder begeleiding van prof.dr. A.F.J. van Raan een promotietraject gestart. Hij is auteur van diverse rapporten en artikelen in nationale en internationale tijdschriften. Hij was in 2000 samen met Ronald Rousseau guest editor van een speciaal nummer van het tijdschrift *Scientometrics* met als thema het scientometrisch onderzoek in the Benelux. Hij is associate editor van dit tijdschrift. Momenteel is hij werkzaam als beleidsmedewerker bij het gebied Natuurkunde van de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).