Jointly published by Akadémiai Kiadó, Budapest
and Kluwer Academic Publishers, Dordrecht

Scientometrics,
Vol. 54, No. 3 (2002) 347–362

Measuring knowledge transfer between fields of science

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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.

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.

0138–9130/2002/US $ 15.00

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?[1]

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.[2,3]

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.[4]

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.[5,6] *Porter* and *Chubin* were among the first to study knowledge transfer across disciplines by use of bibliometric data.[7] In a comparative study using both methods, *Urata* showed that citation analysis and analysis of migration of scholars of social science fields in Japan produced more or less similar results.[8]

In recent years the interest in empirically investigating interdisciplinary knowledge exchange is increasing.[9–13] 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.[14] 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.[5,6,8] In the study of *Porter* and *Chubin* a relatively low share of references crossing the boundaries of broad disciplinary categories was found.[7] 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.

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.[10] 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.[16] It refers in part to a matrix $(R_{i,j})_{i,j}$, 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* ($\gamma_{i,j}$) is presented in Table 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* ; $C = \sum_j C_j$.

$\gamma_{i,j} = R_{i,j} / R_i$ 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*), $\gamma_j = \sum_{i \neq j} \frac{R_{i,j}}{R_i}$.

$\gamma'_j = \frac{\sum_{i \neq j} R_{i,j}}{\sum_{i \neq j} R_i}$ 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).

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 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. This means that in the following we will use, instead 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.

Table 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	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

Table 2. Shares of references per discipline in the world total of publications 1999. Numbers and shares are based on weighted numbers of references

	Percentage references to:																Weighted number of
Cited discipline (j)	Basi	Biol	Chem	Clin	Comp	Engi	Envi	Food	Geo	Mate	Math	Mult	Phar	Phys	Psyc	Total	ref's
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	0.0	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

A field to field distribution of the shares of references is given in Table 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* defined this rate of (disciplinary) self-citation as an index of independence.[8] In Table 2 it 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 self-citations. In more applied and technical fields like Engineering and Food, Agriculture & 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.

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 & 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 self-citing 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 self-citing 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 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 & 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 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 3. It shows subfields in Life Sciences referring most to articles in Physics. Citations reflect a link, of current research in Radiology & 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 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.

Table 3. Subfields in Life Sciences referring most to articles in the discipline of Physics

	Number of references to all disciplines	Number of references to Physics	Weighted number of references to Physics	Share of references to Physics
Basic Life Sciences				%
Biochemical Research Methods	50540	1905	114	3.8
Biophysics	130907	3391	131	2.6
Biochemistry & Molecular	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

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 there 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.[5] 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.[15,16] 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).[16] 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.

$$RO_{i,j} = \gamma_{i,j}\, \alpha_i\, (1- \alpha_j)\ . \tag{1}$$

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 ($\gamma_{i,j}$), 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*.

$$RE_j = \sum_{i \neq j} \gamma_{i,j} \, (\alpha_i) \, (1 - \alpha_j) \, . \tag{2}$$

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,

$$RE_j = \gamma'_j \, (1 - \alpha_j)^2 \, . \tag{3}$$

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

$$RE_j = \sum_{i \neq j} \gamma_{i,j} \, (\alpha_i) \, (1 - \alpha_j) \;\; (2) \;\; = \gamma'_j \, (1 - \alpha_j)^2 \;\; (3).$$

Note that Eq. (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- α_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.

$$RE_j = \sum_{i \neq j} \gamma_{i,j} \, (\alpha_i) \, (1 \, / \, \alpha_j) \text{ , or (when references are not weighted)}$$

$$RE_j = \gamma'_j (1-\alpha_j)(1/\alpha_j) \tag{4}$$

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)/(3) and *RE* (4), due to a different weighting of the size of the cited disciplines, is shown in Table 5.

Separate *RE* (4) outcomes for each discipline are given in Table 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. Furthermore, among others a relatively high impact of articles in Basic Life Sciences and Pharmacology on Clinical Life Sciences is shown.

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

	Cited Discipline (j)														
	Basi	Biol	Chem	Clin	Comp	Engi	Envi	Food	Geo	Mate	Math	Mult	Phar	Phys	Psyc
Citing Discipline (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

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.[17]

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

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:

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

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 $P_{'80\text{-}'99}/P_{'99}$.

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 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 are, on average, the least often cited by other disciplines.

Table 5. Different measures of interdisciplinary impact per discipline compared

Discipline	Basi	Biol	Chem	Clin	Comp	Engi	Envi	Food	Geo	Mate	Math	Mult	Phar	Phys	Psyc
RE (2)	0.09	0.02	0.03	0.04	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.05	0.01	0.04	0.00
Ranking	1	7	5	3	13	6	11	9	12	8	14	2	10	4	15
RE (4) =*Cex/P*	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
Ranking	2	6	12	13	14	7	4	10	8	11	15	1	3	9	5
IER	1.68	0.73	0.73	0.71	0.42	0.63	0.88	0.48	1.07	0.55	0.66	4.26	0.69	1.47	0.66
Ranking	2	7	6	8	15	12	5	14	4	13	11	1	9	3	10

Table 6. *RE* (4) and *IER* per subfield of *Physics*

Subfield	*P*	*RE (4)* = *Cex/P*	Ranking	*IER*	Ranking
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

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 5 it 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.

Results for subfields in the discipline of Physics are given in Table 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.

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 en 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 deserve 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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We thank Mark *Brocken*, Leo *Egghe*, Henk *Moed* and Ronald *Rousseau* for their comments.

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Received October 12, 2001.

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