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**Author:** Buter, Reindert Klaas (Renald)
**Title:** Scientific structures in context : identification and use of structures, context, and new developments in science
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Identification of Converging Research Areas using Publication and Citation Data*

Abstract

Converging research is the emergence of new interdisciplinary research from fields which showed limited mutual interdisciplinary connections before. This paper describes three search strategies to identify converging research using publication and citation data extracted from the Web of Science database, including the Social Sciences and Humanities. The search strategies differ in how they represent the originating research fields and the interdisciplinary connections. The field-to-field references (ffr) approach uses journal subject categories (jscs), and citations from one category to another; the keyword sets (kws) approach uses sets of keywords associated with jscs in 1995/1996, and the co-occurrence of keywords from different sets after 1996; and the affiliation patterns (afp) approach uses textual patterns which match affiliations associated with fields of research, and the co-occurrence of patterns in papers. The sets of publications which resulted these three search strategies were assessed using additional data, such as journal names, titles and cited publications. After a final validation by experts, a total of nine converging research areas have been detected using the KWS and FFR approaches, and none with the AFP approach.

7.1 Introduction

In one of its February 2008 issues, the Lancet published an article on the outcomes of a trial which studied the effects of a treatment with probiotics on patients suffering from severe acute pancreatitis (Besselink et al., 2008). The most significant outcome of this study was an increased risk for mortality in the group that was supplied the

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probiotics, and the study was stopped prematurely. In the same issue, the Lancet published an editorial bearing the suggestive title “Probiotics or con”, which was devoted to this grave outcome and its larger consequences. The editorial concluded that without further research, it was no longer tenable to regard the use of probiotics in consumer products as completely risk-free. This trial and its editorial response illustrate an interesting interdisciplinary phenomenon. First, probiotics, which are well-known food additives, were included in the treatment of severely ill people. Next, following the suggestion of the Lancet editorial, probiotics as food additives should now be scrutinized due to the outcome of this application. In a sense, this would complete an interdisciplinary circle, where a result (probiotics) from one field (Food Science and Technology) influences research (trial study) in another field (Clinical Medicine) and vice versa. Developments such as this, where distinct research areas start to apply problems and tools from one another, possibly leading to new research directions or even new research areas, are considered examples of converging research in this paper. More formally, we define converging research as the emergence of new interdisciplinary research from fields which showed limited mutual interdisciplinary connections before. In this definition, emergence is understood as the appearance of thematically related research which shows a significant growth in the number of publications. Also, the converging research is the result of research in two areas which had limited interdisciplinary connections before, and is thus both new interdisciplinary research, and a novel combination of disciplines. Our definition explicitly excludes intra-disciplinary emergence (i.e. within fields), and emergence of this type was not considered in our research.

The publication of the report on the NSF/DOC-sponsored workshop “Converging Technologies for Improving Human Performance” (Roco and Bainbridge, 2003), was important for the widespread introduction of the notion of converging research. There, it was presented as a conceptual framework based on a “unification of science in nature” which allows the creation of mutually enabling research areas with “synergistic effects” (ibid, p.1). The workshop focused on the four fields Nanotechnology, Biotechnology, Information Sciences and Cognitive Sciences (the NBIC fields), and the application to the improvement of human performance in general. The European response to this workshop was the assembly of an expert group. This group published a report (Nordmann, 2004) titled “Converging Technologies for a Knowledge Society” (CTEKS). This report stated that converging research was not limited to the NBIC fields, but could originate from anywhere in science, and that the application was generalised to current societal, economical and scientific problems (instead of the improvement of human performance). However, both the NBIC and the CTEKS reports stressed the importance of the research in the Social Sciences and Humanities to investigate aspects such as social and ethical consequences of the application of the research.

The possibility to apply research developments on current problems shows the potential use converging research can have for policy makers. However, just what sets converging research apart from other interdisciplinary developments is not always clear. Expanding our knowledge about this issue was one of the objectives of an
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EU project titled “New Emerging/Converging Clusters of Science and Technology”. The project’s most important goal was to identify and describe converging research addressing current societal, economical or scientific problems using publication data. Even more, these data should not only focus on well-covered fields such as the Life Sciences or the Material Sciences, but also include those from Social Sciences and Humanities. In this paper we will review the methodology developed during the EMCOTEC project and reflect upon the results as well as on some of the design choices made.

Converging research is defined as a case of emerging research of a novel, interdisciplinary nature. Many examples exist of descriptions and analyses of emerging research areas with both disciplinary and interdisciplinary roots, like for example Mathematical Logic (Berg and Wagner-Döbler, 1996), Superstring Theory (Budd and Hurt, 1991), elements of Spectroscopy (Ródenas-Torralba et al., 2006), Bioelectronics (Hinze, 1994) or Nanoscience and Nanotechnology (Schummer, 2004). Also, general methodologies to find emerging patterns exists, like those described by Morris (2005), Shibata et al. (2008) and Takeda and Kajikawa (2009). However, like the descriptions of the emerging research areas, these general approaches are applied to a limited set of publications or with a specific topic in mind. Moreover, none of these publications deal with the general and broad search for converging research as defined above.

7.2 Data and Method

This paper presents an approach to find converging research. The development of this approach faced some important challenges:

- The many possibilities to combine research from different parts of science;
- The many ways in which one area can influence another, such as cognitively, socially or methodologically;
- The subjective aspects of core notions such as “research area”, or “interdisciplinary connections”;
- The difficulty in generalising known examples of converging research, so that finding one does not necessarily help finding others;
- The unknown number of examples of converging research, making it very difficult to quantify search performance in terms like recall and precision.

The resulting approach is a combination of both quantitative and qualitative aspects, which we will explain in more detail below.

The quantitative aspects use publication and citation data extracted from the Web of Science (WoS) database, which is available to the CWTS under license from Thomson Reuters. The publication data consisted of elements such as source (journal) names, titles and abstracts, affiliations, and keywords for publication published
between 1990 and 2005. The citation data consisted of all citations from these publications to publications also covered by the WoS.\footnote{The WoS database available to the CWTS contains publication data from 1980 and onwards.}

We identified converging research in a three-step process: search, inspection and validation by experts. Search was performed by using three strategies described below, which differed in the representation of research field and interdisciplinary connections: the field-to-field references approach; the keywords-sets approach; and the affiliation patterns approach. All strategies tested the development of interdisciplinary connections between pairs of fields. The selected pairs were inspected by using additional publication data to understand what the potentially converging research between these pairs was about. Finally, pairs which appeared to represent converging research, were subsequently shown to experts and only accepted if they also recognised it as such. Before we explain the individual approaches in more detail, together with basic notions about growth and size. As will become clear, the strategies show variation in the implementation of these basic notions, because details of the approaches were developed and fine-tuned during the project, and experience gained from the application of one strategy was used in the fine-tuning of the next.

The above definition makes convergence a case of (interdisciplinary) emergence. Therefore, a notion of significant growth is needed. In our project, we focused on fast, non-linear growth, since this type has in many studies been associated with emerging research themes (Tabah, 1999; Goffman, 1971 and O’May, 1966). One of the tools we developed to identify such growth, which we called the Relative Total Growth ($rtg$), is the absolute difference between the number of papers in the first and last year, divided by the total number of papers. Since smaller values of the $rtg$ are either due to a small difference between the first and last years, or to a small change relative to the total number of papers, important examples of fast growth can be found at the top of a list sorted on descending $rtg$. However, this indicator is not perfect, and for example does not take into account the shape of the development between the first and the last year; therefore, the $rtg$ was only used to sort promising results.

A research area should show a basic, noticeable level of activity, which should also be measurable in number of publications. However, it is very difficult to quantify “a basic level” exactly. Looking at examples of emerging research areas described in the literature, a total number of publications published per year at the end of the development, can be for example around 100 for Fuzzy Set theory (Berg and Wagner-Döbler, 1996), or around 250 for Bioelectronics (Hinze, 1994). Moreover, the number of publications involved in earlier years can be small: even less than 10 publications per year (ibid). The search strategies described below used different lower bounds on the number of publications, due to the experience gained in applying earlier strategies.

We now describe the three strategies in more detail. The most important difference between these strategies is the way they characterise research fields (sets of papers with related research), as well as interdisciplinary connections (use of research from different areas). In the different characterisations, we have tried to span different
dimensions of the science system: references represent (among others) the social and cognitive dimensions, the social and geographical dimensions, and keywords the cognitive and vocabulary dimensions.

Field-to-field references (FFR)

The first strategy we developed is the field-to-field references strategy (FFR). It characterises research fields as Journal Subject Categories (JSCs), which assign each journal in the WoS to at least one and at most six categories. These JSCs are part of the WoS and at the time our research was conducted, there were 243 JSCs. Although this classification is not perfect, it provides a clear, fixed and consistent field definition suitable for automated procedures (Van Raan, 2008). Nevertheless, problems exist, especially with the differences in size and (breadth of) scope, and the multiple assignments of journals to different JSCs. However, such multiple assignments can also be regarded as hubs between categories, which was used by Morillo et al. (2003) to develop an indicator for interdisciplinarity. The FFR strategy characterised interdisciplinary connections by the references from one category to another. To give an interesting example of this, the JSCs Religion and Allergy are connected through a citation in 2000 from the journal Zeitschrift für Evangelische Ethik to the journal International Archives of Allergy and Immunology by Haniel (2000) citing Hammer et al. (1998). Our strategy excludes author self-citations and journal self-citations, since these may be indicative for other processes than use or exchange of knowledge (Price, 1981a). Our analysis covered 15 years of publication data (1991-2005). The lower bound on the total number of references was set to at least 200 references, employing a three-year citation window. Additionally, the growth should be positive for the last five years, i.e., every subsequent year should have more references than the year before. Finally, the last two years should show a growth that is either larger than the average growth in the previous year, or larger than the average growth the in the last two years of the all other remaining pairs.

Affiliation patterns (APP)

The second search strategy characterises research fields by textual patterns for the affiliations (addresses) associated with publications. The list of patterns was created as follows. For each JSC, frequency lists of affiliation names were collected. Based on these lists, patterns like “econ*” for Economics or “fam*” for Family Studies were devised manually. Additionally, related JSCs were combined and used one affiliation pattern, resulting in a 121 patterns for 243 JSCs. Interdisciplinary connections are characterised as the co-occurrence of different patterns in the list of affiliations associated with a single paper, like in Gundersen and Ziliak (2004) where Department of Human Development and Family Studies of the Iowa State University co-authored

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62 A citation window is the maximum number of years between the citing and the cited publication.
with the Department of Economics of the University of Kentucky. Experience with the FFR strategy caused a reconsideration of the lower bound on the number of publications, notion of significant growth and the number of years in the analysis: a single year with at least ten publications was used as the lower bound, the RTG was used to rank the most promising ones at the top, and we now use eleven years of data (1995–2005), because we focus on recent developments. The choice for ten publications was based on the inspection of the distribution of the RTG, which appeared to resemble a normal distribution without too many outliers when at least ten publications were required. The inspection of the sorted list was stopped after inspecting 50 pairs.

**Keyword sets (KWS)**

The third and final search strategy characterises research fields as sets of keywords. The keywords we use are the “keywords plus”, which are associated with many of the publications in the WoS (Garfield and Sher, 1993). For each JSC, keywords are selected based on publications published in the first two years (1995–1996). The objective of this selection is to catch the cognitive core of the fields, i.e. the content which differentiates the fields. To accomplish this, the top 20% most frequently used keywords is selected first. Then, to reduce overlap between sets, only keywords were kept which had at least 50% of their covered publications in one JSC. Finally, to reduce the processing requirements, we selected at most 500 of the keywords sorted on ascending coverage percentage and descending frequency. Based on our experience, 500 can be considered large enough. Additionally, we did not create sets for multi-disciplinary JSCs as well as general, interdisciplinary JSCs, because early inspection revealed that such categories had too many words in common with too many other categories, and negatively influenced the set creation.

**Inspection**

We inspected selected pairs as follows. First, we dismissed pairs judged to be related a priori, usually pairs of JSCs with similar scope. Such judgements used objective criteria, like the number of journals in common, but also background knowledge. Background knowledge also was also used to dismiss “old convergence”, i.e. pairs we knew to represent the result of convergence, but which took place some time ago. Next, the content of remaining pairs was inspected, with the objective to find a limited number of subjects that would indicate the research focus of the convergence. Candidates would be dismissed if too many subjects were found or if the subjects were too unrelated. Finally, the candidates were given tentative names that reflected their research focus and passed on to experts.

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63 This was based on visual inspection and not verified statistically.
### 7.3 Results

#### 7.3.1 Application of the search strategies

In this section we present the application our search strategies and the inspection and validation of the results. The combined result of all strategies is given in Table 5.

<table>
<thead>
<tr>
<th>Research Area</th>
<th>Strategy</th>
<th>Category 1</th>
<th>Category 2</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomaterials</td>
<td>FFR</td>
<td>1 Chemistry, Multidisciplinary</td>
<td>Engineering, Biomedical</td>
<td>8,806</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Chemistry, Multidisciplinary</td>
<td>Materials Science, Biomaterials</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 Chemistry, Physical</td>
<td>Materials Science, Biomaterials</td>
<td></td>
</tr>
<tr>
<td>Biosensors and Biodevices</td>
<td>FFR</td>
<td>1 Biochemical Research Methods</td>
<td>Electrochemistry</td>
<td>2,982</td>
</tr>
<tr>
<td>ICT Networks</td>
<td>FFR</td>
<td>1 Computer Science, Theory &amp; Methods</td>
<td>Telecommunications</td>
<td>8,474</td>
</tr>
<tr>
<td>Health Aspects of Nutritional Components</td>
<td>KWS</td>
<td>1 Food science &amp; Technology</td>
<td>Endocrinology &amp; Metabolism</td>
<td>224</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Nutrition &amp; Dietetics</td>
<td>Gerontology</td>
<td></td>
</tr>
<tr>
<td>Mild Cognitive Impairment and Cerebrovascular Disease</td>
<td>KWS</td>
<td>1 Peripheral Vascular Disease</td>
<td>Neuroscience</td>
<td>60</td>
</tr>
<tr>
<td>Neuro Imaging and Brain Imaging</td>
<td>KWS</td>
<td>1 Radiology, Nuclear Medicine &amp; Medical Imaging</td>
<td>Psychology, Experimental</td>
<td>215</td>
</tr>
<tr>
<td>Polymers and the Central Nervous System</td>
<td>KWS</td>
<td>1 Polymer Science</td>
<td>Neuroscience</td>
<td>75</td>
</tr>
<tr>
<td>Quantum Information Science</td>
<td>KWS</td>
<td>1 Polymer Science</td>
<td>Engineering, Electric &amp; Electronic</td>
<td>145</td>
</tr>
<tr>
<td>Surface Physics and Chemistry for Biological and Medical Applications</td>
<td>KWS</td>
<td>1 Physics, Applied</td>
<td>Dentistry, Oral Surgery &amp; Medicine</td>
<td>107</td>
</tr>
</tbody>
</table>

*Too old*

Table 5.a The research areas identified using the different strategies, together with their expert assessment and the candidate pairs grouped together into one area. The overlap was calculated as the total number of (citing) publications published between 1995 and 2005.
### Table 5.b

<table>
<thead>
<tr>
<th>Research Area</th>
<th>Strategy</th>
<th>Category 1</th>
<th>Category 2</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioinformatics</td>
<td>FPR</td>
<td>1 Biochemistry &amp; Molecular Biology</td>
<td>Statistics &amp; Probability</td>
<td>22,999</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Biotechnology &amp; Applied Microbiology</td>
<td>Statistics &amp; Probability</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 Computer Science, Interdisciplinary Applications</td>
<td>Genetics &amp; Heredity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 Computer Science, Theory &amp; Methods</td>
<td>Biotechnology &amp; Applied Microbiology</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 Genetics &amp; Heredity</td>
<td>Mathematics, Interdisciplinary Applications</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 Statistics &amp; Probability</td>
<td>Biotechnology &amp; Applied Microbiology</td>
<td></td>
</tr>
<tr>
<td>Cancer Supportive Care</td>
<td>KWS</td>
<td>1 Clinical Psychology</td>
<td>Oncology</td>
<td>67</td>
</tr>
<tr>
<td>Psychological Distress in People with Diseases of the Respiratory System</td>
<td>KWS</td>
<td>1 Respiratory Systems</td>
<td>Psychiatry</td>
<td>54</td>
</tr>
<tr>
<td>Genetic Deficiencies and Dermatological Diseases in Relation with Neurological Phenomena</td>
<td>KWS</td>
<td>1 Dermatology</td>
<td>Clinical Neurology</td>
<td>54</td>
</tr>
<tr>
<td>Glasses for Fibre Lasers and Amplifiers</td>
<td>KWS</td>
<td>1 Materials Science, Ceramics</td>
<td>Engineering, Electrical &amp; Electronic</td>
<td>25</td>
</tr>
<tr>
<td>Simulation and Modelling of Nanotubes and Hollow Fibre Membranes</td>
<td>KWS</td>
<td>1 Microbiology</td>
<td>Agriculture, Soil Science</td>
<td>55</td>
</tr>
<tr>
<td>Socio-Psychological Aspects of Socio-Economic Changes and Circumstances</td>
<td>KWS</td>
<td>1 Developmental Psychology</td>
<td>Economics</td>
<td>91</td>
</tr>
<tr>
<td>Soil Microbiology and Soil Analytical Chemistry</td>
<td>KWS</td>
<td>1 Mathematics</td>
<td>Engineering, Chemical</td>
<td>86</td>
</tr>
</tbody>
</table>

**Dismissed**

About 37,000 pairs contained at least one reference from the citing to the cited category, and about 5,900 pairs had at least 200 references in 15 years. Applying our growth requirements reduced this to 38 candidate pairs. Of these 38 pairs, those that had too many journals in common were dismissed, because we considered such pairs as representing well-known converged areas (for instance Nanotechnology). The
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final selection consisted of 11 pairs. Some of these pairs showed enough overlap to combine them in a single research area. Consequently, the 11 pairs were grouped into four converging research areas. In Table 5 these four areas are indicated with the FFR label in the strategy column.

Affiliation Patterns
About 5,200 pairs of patterns had at least one publication in common and almost 3,000 pairs had at least one year with ten or more publications. Unfortunately, no research focus could be found in the top 50 pairs sorted on descending RTG. Instead, publications referred only research in one of the fields, or to research in fields that appeared not related to the affiliation, or contained a range of subjects instead of only limited number. For example, the pair Opthalmology (opth*) and Neuroimaging (neuroimag*) was a selected candidate, but the associated publications dealt with variety of (in our opinion) unrelated topics, such as “fatal insomnia” and “kinase inhibitors”.

Keyword Sets
Over 7,500 pairs of sets had at least one publication in common and almost 3,000 pairs had at least one year with ten or more publications. These pairs were sorted on descending RTG and the top 50 was inspected. After inspection, we selected 15 pairs. Again, some of these pairs again showed overlap and were grouped together. The final result consisted of 13 research areas. In Table 5 these areas are indicated with a KWS in the strategy column.

Expert verification
The combined result from the FFR and KWS strategies consisted of seventeen research areas, together with a description of their content. This result was presented to field experts, who were asked if they recognised the research area and if so, whether the area was the result of a convergence of other areas. Additionally, they were asked to verify or improve the (tentative) names given to the areas. The verification resulted in nine confirmed research areas, three areas judged too old, and five dismissed research areas, either because they were not recognised or were not the result of convergence. This result is reflected by the different parts “Accepted”, “Too old”, and “Rejected” in Table 5.

7.3.2 Additional Analyses
The differences in the overlap column of Table 5, which is representative for the size of the interdisciplinary area, are immediately apparent. In the case of the FFR
Figure 19  The combined number of publications involved in the overlap between research areas (Table 7) indexed to 1995.

strategy this was measured by the number of citing publications, while in case of the KWS strategy it was measured by the number of publications associated with both keyword sets. One can also note this difference in size by the names given to the research areas, which are shorter and more general for the larger areas, identified using the FFR strategy, while they are longer and more specific for the smaller KWS areas. To further investigate this difference, Table 6 contains a summary of the distribution of the number of publications in the overlap, measured between 1995 and 2005. This table also includes the numbers for the AFP strategy, because these numbers could hint at reasons for the failure of the AFP approach. The table shows that the coarseness of the categories and the affiliation patterns are comparable, but that the spread of the size is wider in case of the affiliation patterns. Additionally, it shows that the size of a publication set covered by a keyword set is on average about 20% of that of a category, and about 18% of that of an affiliation pattern. However, the difference measured by the median is even larger, and then the size of the keyword sets is only respectively 9% and 13%. Furthermore, for the FFR and KWS approach, Table 7 shows the size from year to year. These numbers are also shown in Figure 19, but normalised by setting the value in 1995 to 1.0. The figure shows that, although the difference in absolute numbers of papers in Table 7 is large, the development of the growth has a comparable shape for both strategies.
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<table>
<thead>
<tr>
<th>Characterisation</th>
<th>Min</th>
<th>Median</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFR</td>
<td>3,243</td>
<td>48,370</td>
<td>78,180</td>
<td>654,700</td>
</tr>
<tr>
<td>AFP</td>
<td>20</td>
<td>31,450</td>
<td>88,160</td>
<td>1,115,00</td>
</tr>
<tr>
<td>KWS</td>
<td>13</td>
<td>4,368</td>
<td>16,080</td>
<td>154,700</td>
</tr>
</tbody>
</table>

Table 6 A summary of the size of the different research area characterisations, measured by the number of (citing) publications published between 1995 and 2005.

<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FFR 965 1,196 1,302 1,568 1,999 2,474 3,082 4,010 6,161 8,664</td>
</tr>
<tr>
<td>KWS 22 37 59 55 79 92 115 133 154 182 330</td>
</tr>
</tbody>
</table>

Table 7 The combined number of publications involved in the overlap between research areas.

A final additional analysis is given in Table 8, which shows the major science fields involved in the validated converging research areas. This table was created by taking the JSCs involved in the research area characterisations, and aggregating those to their major science fields. From Table 8 it is clear that the Life Sciences and the Natural Sciences dominate the results, while only one out of nine areas involved work from the Social Sciences and two out of nine involved work from Engineering. Even more, the two latter fields are never without JSCs that are also associated with the Life Sciences or the Natural Sciences.

<table>
<thead>
<tr>
<th>Research area</th>
<th>Strategy</th>
<th>Main fields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Life</td>
</tr>
<tr>
<td>Biomaterials</td>
<td>FFR</td>
<td>Yes</td>
</tr>
<tr>
<td>Biosensors and Biodevices</td>
<td>FFR</td>
<td>Yes</td>
</tr>
<tr>
<td>ICT Networks</td>
<td>FFR</td>
<td>No</td>
</tr>
<tr>
<td>Health Aspects of Nutritional Components</td>
<td>KWS</td>
<td>Yes</td>
</tr>
<tr>
<td>Mild Cognitive Impairments and Cardiovascular Diseases</td>
<td>KWS</td>
<td>Yes</td>
</tr>
<tr>
<td>Neuroimaging and Brain Imaging</td>
<td>KWS</td>
<td>Yes</td>
</tr>
<tr>
<td>Polymers and the Central Nervous System</td>
<td>KWS</td>
<td>Yes</td>
</tr>
<tr>
<td>Quantum Information Science</td>
<td>KWS</td>
<td>No</td>
</tr>
<tr>
<td>Surface Physics and Chemistry for Biological and Medical Applications</td>
<td>KWS</td>
<td>Yes</td>
</tr>
<tr>
<td>Total involvement</td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>

Table 8 Main fields of science involved in the detection of the selected research areas.

64 A CWTS taxonomy is being maintained which assigns JSCs to science fields and major fields
7.4 Discussion

We presented three strategies for locating converging research using publication and citation data from the WoS database. Converging research was defined as the emergence of an interdisciplinary area from areas between which limited interdisciplinary connections existed before. This type of emerging research has not been studied extensively using publication data before, and it was not known beforehand what the different strategies could yield. It is therefore encouraging to see that our work yielded 26 converging pairs, which were grouped into seventeen research areas. Nine of these passed the judgement of experts, while three others were confirmed but dismissed as “too old”. It was found that a large size difference exists between the converged pairs resulting from the FFR strategy and the KWS strategy. However, the shape of the developments in the resulting areas was found to be comparable for both strategies. Finally, the results were mainly from the Life Sciences and the Natural Sciences.

It is difficult to judge which strategy was more fruitful: although more areas were identified using the KWS strategy (thirteen in total), more than half (eight) of these areas were considered too old or were otherwise dismissed. On the other hand, only four areas were identified using the FFR strategy, yet only one was dismissed as too old. At the same time it is not clear why the AFP strategy could not help to identify converging research: although patterns of fast growing co-occurrences of different affiliation patterns were found, none appeared to focus on the converging pairs, or on a limited number of subjects. Together with the distribution of the size of the overlap between affiliation patterns in Table 6, this may suggest that the current patterns are too multidisciplinary and may fail to provide enough a priori focus. To give an example, the JSC Crystallography has a maximum overlap of 8% with other JSCs, but the affiliation pattern for Crystallography fails to reflect this: only about 25% of the papers are associated with only the JSC Crystallography and the rest with other JSCs. One could argue that this may indicate a multidisciplinary nature of the research in Crystallography, but it also appears not to provide a useful starting point to search for converging research. Perhaps this is for the same reasons for which we excluded the multidisciplinary JSCs in the KWS strategy, but it nevertheless deserves more attention in future research.

7.4.1 Review of the methodology and future research

An important advantage of our approach is that it has a quantitative basis. Therefore, it becomes possible to repeat and update the search with new data or fine-tuned parameters. Additionally, the application of a search strategy on the whole of science avoids a thematic bias and therefore improves the objectiveness of results. Other approaches, such as interviewing experts, may run the risk of a possibly biased view. On the other hand, experts may be able to signal developments sooner, since they may be part of specific developments, and are therefore not limited by the publication delays that are inherent to approaches based on peer-reviewed publication data.
However, it is not an empirical fact that peers are always more up to date than our approach.

Some aspects in the strategies can be improved. Already during the project, the short-term focus provided by the three-year citation window used in the FFR approach was considered too short, given that interdisciplinary knowledge transfer takes time (Rinia et al., 2001a, 2002). Also, a lower limit of 200 citations was high and possibly resulted in a bias toward large (biotechnological) fields. Improved versions of the strategies should select pairs on the basis of growth characteristics instead of (only) size characteristics. Also, the three strategies are (directly or indirectly) based upon the JSCs. Although the JSCs have certainly been extremely convenient in the development of the strategies, alternative groupings could also be employed. For example, the use of smaller groups of journals based on journal citation patterns could improve both the FFR and the KWS strategies. The KWS strategy “freezes” the keywords in the years 1995 and 1996. This was a conscious design choice, since this limited the use of the JSC on which it was based to only those years. However, this implies that knowledge developed after 1995 and 1996, which may use new and not included keywords, is disregarded and newer developments are not included. Another problem of the KWS strategy is due to homonymy and synonymy. For example, it is not possible to distinguish between AD as an abbreviation for Alzheimer’s disease or for Advertisement. Finally, the removal of the multidisciplinary categories was another design choice, because those categories made the distinction between other fields less clear, clouding the interdisciplinary developments. However, multidisciplinary JSCs can also be regarded as a bridge between fields and a basis for new interdisciplinary developments. Therefore, future research should focus on how to reintegrate them, or to use them as a source of information.

The current approach requires a qualitative selection process based on a judgement of resulting publications. Although this introduces a subjective element in the search, this also allows the process to include background knowledge which is difficult to express in quantitative terms alone. The use of background knowledge is witnessed by the small number of publications in some of the KWS pairs, which were chosen because both we and the experts recognised them to represent known research, without covering all publications associated with that research. At the same time, we also dismissed pairs as too old using this kind of background knowledge. Additional tools could be used to try to encode such background knowledge and use that in the search and inspection. For example, Buter et al. (2006) describes an interface between a (quantitative) cognitive science map, which encodes the content of a set of publications, and a qualitative, user-provided concept map that encodes background knowledge in the form of research topics.

Another extension which can be used in the inspection phase of the approach is to expand the number of publications by those which share an important part of the knowledge base (such as the best cited publications). Such an extended set could create a more complete picture of the focus of the research in the convergence. To establish coherence of the (expanded) publication sets and aid the search for focus in the research, visualisation tools can help, such as cognitive maps (Buter and Noyons,
2001, 2002a) or networks (Calero et al., 2006 and Takeda and Kajikawa, 2009).

### 7.4.2 On the nature of converging research

We close this discussion with thoughts on the nature of converging research, combining theory and results described above. The original idea of converging research Roco and Bainbridge (2003) was more of a conceptual, high-level nature, rather than a concrete phenomenon. It was based on the idea that a unification of the sciences based on a “unity in nature” (ibid, p.15) could enable new developments. This conceptual framework was put in more concrete terms in this paper by defining converging research as emerging interdisciplinary research areas. Also, there were no explicit or implicit restrictions put on the fields that could converge; and in principle any (exotic) combination was possible. However, many of the pairs found in Table 5 appear already related, even though they are different fields without shared journals or (initially without) shared keywords. For example, it appear not surprising that Multidisciplinary Chemistry may use results from Materials Science, Biomatertials; or that Biochemical Research Methods cites Electrochemistry. This also confirms earlier observations reported by Porter and Chubin (1985) who also found that the use of research results from distant fields is a rarity, using a limited set of journals and categories.

A possible reason for this is that such endeavours have an implicit risk for the researcher. So can importing knowledge from a completely different domain may be less productive (Palmer, 1999). Additionally, if a researcher ventures into a new community, there is a need to learn and conform to existing vocabulary, descriptions of tools as well as problems. Acceptance and recognition by a new community may also be a boundary for a successful cross-over. Successful convergence therefore requires a mode of working that has a common language or understanding as well as a way to provide recognition of researchers from both originating disciplines. A “unity in nature” is usually not enough. At the same time, (ibid) also notes that importing knowledge from other domains offers a better opportunity for knowledge base development, and provides researchers with the opportunity to distinguish themselves by applying methodology to a new problem domain or (vice versa) to attack a problem with new methodology. This is also what we see in our results: science-born applications of tools on problems, where both tools and problems can be imported. For instance, the jsc Computer Science, Theory and Methods imports problems from the jsc Telecommunications (related to networks), and applies its own methods in the converging research area. In the Bioinformatics converging research area however, the Genetics and Biochemistry fields import tools from Statistics, for instance in order to apply these tools to expression data from micro-arrays.

Such developments result from the creative “probing” efforts of researchers into new research directions, or caused by interdisciplinary developments related to tasks, processes, products, or use (Porter and Chubin, 1985). Those processes are part of normal science and are not necessarily indicative for Kuhnian paradigm shifts.
7.5 Concluding Remarks

The results presented in this paper show that converging research can successfully be identified using search strategies applied to publication and citation data. Although convergence was originally developed on a more conceptual level, the translation into detectable, scientific developments makes it an interesting evaluation tool, because it can highlight new interdisciplinary research developments with a novel character. These developments are interesting for at least two reasons: first, converging research areas are spontaneous, normal developments in science; and second, convergence occurs between fields that have some kind of conceptual distance between them. Especially the last point makes convergence a potentially valuable phenomenon, because combining knowledge domains requires creativity and effort, and is also not without risk. Therefore, to invest such effort and run such risks, potential benefits must appear valuable. At the same time, this also implies that most convergence was (and will be) found between fields that are not too distant from each other, since the effort to cross fields increases proportional to the conceptual distance between them.

We conclude that, even though our strategies still require more development and the process as a whole would benefit from additional tools, the quantitative core of our approach could serve as the basis for a monitor that would signal new converging developments. Such a monitor could be a part of a policy instrument to identify areas where tools and problems are combined in new and creative ways, some of which may help to address current social, economical and scientific issues.

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