

# Using the Self-Organizing Map for Measuring Interdisciplinary Research

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## Abstract

The prevalence and role of interdisciplinary research has been debated both among scholars and policy makers. Unfortunately, there is a lack of good tools for measuring how common such research is, and how important it is in the dynamics of science. In this paper we set out to develop a new tool for the measurement of interdisciplinary research; a tool that would use the self-organizing map (SOM) as its technological basis, and the WEBSOM method for a contents analysis of documents. Our focus is on the requirements that such an analytical tool would have to fulfil.

## 1. Introduction

Interdisciplinarity research is in many ways a contested phenomenon among scholars studying science. There is uncertainty about its prevalence; its basic forms; its significance for science; its quality; its relevance for society; and how it should be implemented. In this paper, we focus on the first two topics, the prevalence and significance of interdisciplinary research. There are presently two major ways of studying interdisciplinary research: through case studies and through scientometric measurement. The first methodology includes studies of: the formation of disciplines; the activity of research groups or institutions; trends in specific research areas; and the development of innovations. It also includes reviews of research programs and organizations in various areas. The second methodology covers surveys and bibliometric studies of interdisciplinary activity.

Taken together, the research based on case studies and scientometric methodology indicate that interdisciplinary research is indeed a common phenomenon, and that it is of great significance for the dynamics of science. Some of the research also suggests that there is a trend toward an increase in the crossing of disciplinary boundaries. However, there is no convincing method for demonstrating these things numerically. The case studies do not aim at measurements, and the scientometric methods have some problematic limitations. As an improvement to contemporary methodologies, we propose that the self-organizing map (SOM) is used as the basis for measuring interdisciplinarity. In what follows, we outline the requirements of such a tool.

The paper is structured as follows. In the next section, we review some of the reasons for why interdisciplinary research is thought to be common and important, respectively rare and of marginal importance. In section three, we review the methods by which various scholars have tried to establish the prevalence and trends of interdisciplinary research. We also discuss the limits of those methods, focusing particularly on the existing bibliometric methods. In

section four we propose that the self-organizing map (SOM) could be used to achieve a higher degree of validity in the analysis. We outline some of the principles for how the SOM could be used for this. Section five concludes the paper with a discussion about some of the challenges for further development of the SOM methodology discussed here.

## 2. The significance and prevalence of interdisciplinary research

Few issues are as contested as the significance and prevalence of interdisciplinary research. Opinions among scholars vary from Alan Leshner's claim (quoted in Johansson 2004, 27) that "disciplinary science has died" and that "most major advancements involve multiple disciplines," to Peter Weingart's (2000, 26-27) contention that scientific innovation takes place "primarily within disciplines, and it is judged by disciplinary criteria of validation." The two scholars should know what they talk about. Leshner is the CEO of the American Association for the Advancement of Science (AAAS), the world's largest science organization and the publisher of *Science*. Weingart, in his turn, has been the Director of University of Bielefeld's well known Center for Interdisciplinary Studies (ZiF). Still, Leshner and Weingart have contradictory views on the significance and prevalence of interdisciplinary research. For Leshner it is the engine of science; for Weingart it is merely an ideal, encouraged by science funders, but poorly mediated to the practice of doing science.

Both poles of opinion have their followers in the scientific community. Leshner receives support from scholars such as Klein (1993, 187), who maintains that disciplines permeate each other, and that "permeation occurs across the distance of discipline, from frontier to core." Similarly, Gibbons and his colleagues (1994, 5) argue that final solutions in modern scientific knowledge production (what they call Mode 2) "will normally be beyond that of any single contributing discipline." Stefik and Stefik (2004) agree, and point

out that collaboration across disciplinary boundaries is particularly important in radically new research, or what they denote breakthrough research.

Gibbons and the Stefiks are primarily talking about the natural, life and medical sciences, and about technological research. Wallerstein and his colleagues bring the same argument to the social sciences. They write that “the tripartite division between the natural sciences, the social sciences, and the humanities is no longer as self-evident as it once seemed,” and also contend that social science disciplines have become increasingly heterogeneous (Gullbenkian Commission 1996, 69; see also Dogan and Pahre 1990, and Camic and Joas 2004 for similar arguments). What about the humanities, then? Klein’s (1996, 133-172) study of literary studies shows that the subject of interdisciplinarity has recurred over and over again within that field. Moran (2002) comes to a similar conclusion in his analysis of literary studies: “it has never been a ‘pure’ discipline but a hotchpotch of contending aesthetic, theoretical and scientific discourses.”

Contesting all these claims, however, Abbot (2002, 227) makes the case that “disciplines work surprisingly well as a cultural system” and predicts that “in fifty years, we will probably have a disciplinary system recognizably descended from the present one.” Scholars who reason along these lines agree with Weingart about the primacy of disciplines. Some even question the practical possibility of interdisciplinary work, arguing that “outsiders cannot properly practice an intellectual discipline just as foreigners find it difficult to assimilate into a national culture” (Bauer 1990, 114). Several studies show that interdisciplinary research can be difficult as a result of disciplinary boundaries (e.g., Wallén 1981; Messing 1996; Rabinow 1996; Jeffrey 2003).

Practitioners of interdisciplinary research often complain about the scepticism towards, and resistance to, interdisciplinarity within academia (see Klein 1990). Yet it is difficult to find public stances against interdisciplinary work, perhaps because of the fact that interdisciplinarity expresses a scientific norm shared by most scientists, that of originality. As Weingart (2000, 31) points out, “public pronouncements of scientists will regularly reflect an openness towards interdisciplinary research, since it is concurrent with the value of originality. And they will, conversely, contain denials of ‘discipline-mindedness’ except in connection with efforts to secure an innovation.” However, this does not mean that they endorse interdisciplinarity in their operations and practice. As is well known, the scientific norms do not organize practice in the way assumed by Merton (1973). Weingart’s (ibid.) conclusion is that “declarations by scientists about the desirability of interdisciplinary research cannot be taken at face value.”

### **3. Empirical study of interdisciplinary research**

For a long time, knowledge about interdisciplinarity relied mainly on accounts of first hand experience and case studies. This was problematic, because such studies cannot by themselves provide a basis for generalizations. When aggregated, however, the sheer number of anecdotes and case studies of interdisciplinary endeavors suggests that interdisciplinarity research is indeed possible and not that uncommon. The anecdotal and case study -based literature includes examples of interdisciplinary research in a large number of fields, including landscape research (Tress, Tress et al. 2003), space research (Bonnet 1999), and materials science (Cahn 2000); research institutions (Hollingsworth and Hollingsworth 2000; Maasen 2000; Scerri 2000; Höyssä, Bruun et al. 2004; Stefik and Stefik 2004); and large scale mission-oriented projects (Hughes 1998). This literature shows that a great number of scientific and technological breakthroughs have had their background in interdisciplinary modes of research (for more examples, see Rabinow 1996; Hughes 1998; Miettinen, Lehenkari et al. 1999; Hollingsworth and Hollingsworth 2000; Wilmot, Campbell et al. 2000; Stefik and Stefik 2004; Langlais, Bruun et al. 2004).

Historical studies of the emergence of new research fields, disciplines, and technologies, provide similar evidence. Consider, for instance, the influence of physics in molecular biology (Morange 1998); the interaction between physics and chemistry in research on high temperature superconductivity (Nowotny and Felt 1997); the involvement of a large number of disciplines in artificial intelligence, cognitive science and neuroscience (McCorduck 2004); and the interaction between history and sociology in historical sociology and sociological history (Dogan and Pahre 1990; Gulbenkian Commission on the Restructuring of the Social Sciences 1996). This historical evidence suggests that interdisciplinary communication and interaction often plays a key role in the emergence of new research fields, that is, in scientific renewal and development.

Yet another type of evidence consists of historical and contemporary *institutional* signs of interdisciplinary research activity, such as the changing emphasis on interdisciplinary research in policies and principles for organization, and the establishment of interdisciplinary programs, university departments, centers, institutes, networks, etc. The great number of previous and contemporary interdisciplinary institutions, reported by Klein (1996) and others (see chapters in Salter and Hearn 1996; Cunningham 1999; Roy 2000; Weingart and Stehr 2000), indicates that interdisciplinarity research is indeed a widespread phenomenon in academia. This evidence is suggestive but not conclusive, however. Institutional mappings may fail to identify the real character of the activities within those institutions. In-depth studies of research programs that characterize themselves as interdisciplinary may reveal that they are multidisciplinary rather than interdisciplinarity, or just fragmented in completely unconnected disciplinary work, as predicted by Weingart.

At the same time, it should be observed that much interdisciplinary work is going on within the framework of the traditional, disciplinary department structure of universities (Dogan and Pahre 1990; Schild and Sörlin 2002). Such activities are difficult to register if attention is given to interdisciplinary institutions only.

A fifth type of information about the role of interdisciplinary research comes from more comprehensive studies of the behavior and experiences of scholars. The methods used in these studies range from surveys and interviews to bibliometric publication counts. Common for them all is that they base their evidence on large samples of scholars or scholarly outcome (in contrast to, for instance, case studies). Morrison et al. (2003) did a survey study of 144 academic staff across 15 disciplines in the Faculty of Science at a New Zealand university. They found that over 85% of the respondents were involved in one or more collaboration projects, but that most of the projects were disciplinary in orientation. Only 6% of all projects were interdisciplinary. On the other hand, over half of the staff (56%) considered interdisciplinary collaboration to be important.

A Korean study gave a different picture. Song (2003) analyzed 4,163 proposals submitted to the Korea science and engineering foundation (KOSEF) in 2000 and 2001. The applications represented twelve fields of research within science and engineering. KOSEF requests researchers to indicate primary, secondary, and tertiary research fields and to estimate individual weights of each field in their proposals. Song found that 35.8% of individual research proposals and 54.6% of collaborative proposals were interdisciplinary.<sup>1</sup> He also found that the average weight of non-primary disciplines was 11.3% in individual research plans and 19.4% in collaborative plans. The degree of interdisciplinarity varied across the twelve fields. Still, Song's conclusion is that interdisciplinary research "already prevalent in Korea." Another conclusion is that interdisciplinary research is more common in collaborative research.

Bruun et al.'s (2005) study of applications for funding to the Academy of Finland, and the funding decisions of that organization, produced results more consistent with those of Song than with those of Morrison et al. Like Song, Bruun and his colleagues used applications as empirical material, but their method for categorization was different. They classified the applications on the basis of a qualitative analysis of their contents. Bruun et al. found that more than 40% of a sample of 324 successful research applications proposed to do interdisciplinary (in the generic sense) research. In a closer scrutiny of 266 of those applications, they found that 17% of them promised to do multidisciplinary research, while 26% promised more integrated, or interdisciplinary (in the specific sense), research. The integrative approach was thus more common than the multidisciplinary

approach, and approximately one fourth of all the General Research Grant funding was allocated to such projects in 1997 and 2004.

Interdisciplinarity can also be assessed by analyzing publication activity. Dutch researchers have studied interdisciplinarity by creating publication-based research profiles for institutions such as research programs or institutes. Rinia et al. (2001), for instance, studied a sample of 17,760 publications from 185 physics research programs in the Netherlands. They used the ISI (Institute of Science Information) journal classification to categorize all publications. The publication categories were then used to create a research profile for each program. The research profile tells us how the publications of the program were distributed across (sub)fields. In this case, the more papers published in non-physics journals, the more interdisciplinary is the research profile. With this operationalization of interdisciplinarity, the average degree of interdisciplinarity of a physics program was 36%. More than a third of publications were thus published in non-physics journals.

Another research profile study, of a well known Nutrition and Food Research institute in the Netherlands, analyzed 1,395 publications published by institute researchers in 1987-1996 (van Raan and van Leeuwen 2002). The methodology for categorizing publications was the same as above. This time, however, the institute's output was broken down into research fields rather than aggregated to a number. The study showed that the institute's output was highly interdisciplinary in the sense that it was distributed across a large number of fields, and that, more significantly, it succeeded in having a high impact in twelve different fields. This does not tell us much about the interdisciplinarity of actual research activities, of course, but illustrates that multidisciplinary research environments can produce good quality work.

Bibliometric studies give further confirmation of the idea that the significance of interdisciplinarity varies across research fields. Qin et al. (1997) studied 846 scientific research papers that were randomly selected from the Science Citation Index for publications in 1992. They measured a paper's degree of interdisciplinarity with the number of disciplines represented by journals cited in its bibliography. Ulrich's International Periodicals Directory was used to obtain category information for the journals. The study shows that 76% of the papers were written by more than one author. The degree of interdisciplinarity (the number of cited disciplines) ranged from 1.78 in mathematics to 5.18 in agriculture. One third of the collaborative papers were produced by authors from departments in two different disciplines. Two thirds of collaborations were thus between scholars from the same discipline, or, to be more specific, from departments with the same disciplinary label. This did not, however, necessarily mean that work was strictly disciplinary. "Within-disciplinary" collaborative projects frequently cited journals from other fields. Qin et al.'s conclusion is that "limited scientist-scientist (in terms of affiliation) interaction still can involve

<sup>1</sup> The exactness of the numbers appears strange to us, considering the method that was used. Yet, we did not to manipulate the numbers reported by Song.

*extensive* scientist-information interaction.” (p. 913, our italics)

In sum, then, there are many ways of studying interdisciplinarity in research. All methods have their strengths and weaknesses. The historical case studies and reviews of institutions give a lot of detailed information, but are limited in that they do not allow us to compare the prevalence or significance of interdisciplinary activity with that of disciplinary activity. The questionnaire-studies teach us a lot about attitudes or behaviour in one particular institutional context, but say little about the generality of the findings. Also, questionnaire-studies give little information about trends, unless repeated several times. The study of research applications teaches us a lot about the researchers' intents, but little about actual implementation. Again, it is unclear what generality the findings have, unless compared with other, similar studies. Unfortunately there have been no large-scale, comparative studies of interdisciplinarity, based on questionnaires or applications.

The easiest way of doing large-scale research on interdisciplinarity is to use bibliometric tools. The problem with the existing tools is, however, that they use metadata only, which implies that their operationalizations of interdisciplinarity are rather crude. Bibliometric metadata consists of the information that is attached to the publications that are studied: name of author, organization and country of author, key words, name of journal, etc. As mentioned above, a publication is considered to be interdisciplinary if, for instance, the organization of the author (e.g. a university department) belongs to a different disciplinary categorization than the journal in which the article in question is published. Thus a researcher in a biology department who publishes a paper in a physics journal is considered to have produced an interdisciplinary product, per definition. The problem here is that this presumes that there is a correspondence between the organizational category and the research of the scientist. In the example above, such assumptions are problematic if the author is a physicist employed by a biology department. A normal, disciplinary paper is then taken to be interdisciplinary. In other cases, the mistake can go in the other direction: an interdisciplinary product is perceived as disciplinary.

It can of course be argued that the problem of non-correspondence is cancelled when data is aggregated. Cases like the philosophical paper, produced at a technical university, and published in a sociological journal, are then considered to be exceptions—noise in the data. But it is precisely this issue that is under investigation here. Are they exceptions? And even if they were exceptions, what is their significance? Is a new area of research more likely to grow from the work of a biologist publishing in a biologist journal, or from a computer scientist publishing in a biologist journal? In the rest of this paper, we will focus on the development of a bibliometrical tool that would be more sensitive to the actual contents of publications, and that would allow us

to study not only the prevalence of interdisciplinary publications, but also their significance.

#### **4. A New Tool for Measuring Interdisciplinarity**

We envision a bibliometric tool that automatically analyses the contents of scientific publications, and that compares those contents with regard to similarity. The Self-Organizing Map (SOM) could constitute the basis of such a tool (Kohonen 2001). The SOM is a technique for a two-dimensional clustering of high-dimensional data, developed by Teuvo Kohonen in the 1980s. The SOM has been applied for a number of purposes, including the analysis of publication contents. In the latter case, the analysis uses word-use as a proxy for content. Thus, publications that use words in similar ways are considered to have similar contents. There are a few encouraging studies of the validity of such an approach (e.g., Pöllä et al. 2006), but more testing is needed. Although the SOM-technique was developed some twenty years ago, its application for research purposes is still at an early stage, particularly when it comes to content analysis. In the following, we rely on the WEBSOM method that was developed by Honkela et al. (1997) for the purpose of contents analysis (see also Kaski et al. 1998; Kohonen et al. 2000; Lagus et al. 2004).

The procedural steps of the WEBSOM method are as follows. The first task is to transform the texts into numerical data. This is achieved by treating them as high-dimensional data units, and by transforming them to vectors. The vectors are then used as input data in the SOM-analysis. How is this done in practice? One starts by defining each publication as a primary data unit, and the words used in them as a dimension for a property. A text with 500 different words, then, has properties in 500 dimensions. These properties can vary in each dimension, which means that the dimensions are, in effect, variables. To illustrate, in the present text, the word “SOM” constitutes one of its dimensions. If the text uses this word thirty-four times, the text has the property of having 34 instances of “SOM”. A vector can then be formed on the basis of the word-use in the text: each word constitutes a vector-dimension, and the number of times that the word is used constitutes the value of that dimension (Lagus 1997). When several texts are analysed, a data matrix must be formed of all the words used in the complete body of sample texts. Let us say that 100 texts are analyzed, and that they use 2,200 words altogether. Then each text is transformed to a vector with values in all of these 2,200 dimensions. In the case of a text with 500 words only, 1,700 dimensions get the value of zero.

The next step is to pre-process the vector data. We will not go into the details here, but only mention two things that need consideration. First, some kind of normalization is needed. Second, words that are very common create background noise in the data, and need to be omitted. There are various techniques for this, such as comparing the sample texts with some neutral

body of texts, and then omitting words that occur frequently in both. A second method is to use word-lists for the exclusion of frequent words. A third method is to use some technique for the determination of superfluous words, such as entropy-based techniques that omit words that are evenly distributed across the texts. These procedures reduce the number of words available to the analysis, or in technical terms, the number of dimensions of the sample text vectors. In the example above, the number of dimension may be reduced from 2,200 to 1,300. Having pre-processed the data, the SOM iteration can be initialized.

The SOM consists of a two-dimensional map of evenly and symmetrically distributed cells in which each cell is represented by a vector. In contrast to the input vectors (the sample text vectors), the vectors on the map are called prototype vectors. The prototype vectors have equally many dimensions as the input vectors, 1,300 in our example, and may be set with random values. The purpose is now to map the information in the input data onto the SOM, so that the vectors on the map will reflect the topological organization of the data in the input space. This is more challenging than it sounds, because in the input space the topological organization is very complex, distributed in 1,300 dimensions. In the SOM map that will result, however, the same information is organized in two dimensions only, which allows visual inspection and comparison for human beings (who cannot compare high-dimensional data).

To make the significance of this transformation more obvious, we can think of each text as a profile of words and word-usage. In order to compare the texts on the basis of these profiles, we would have to take the profiles as a whole into consideration. In practice this is impossible for human beings. Normally, when people say that two texts are similar, they base their judgement on a small number of properties, such as the plot or the style of writing. People use these holistic properties to reduce the number of dimensions to be compared. Unfortunately, contemporary automatized content analysis techniques cannot make such holistic, or abstract, assessments of texts, and therefore have to use other techniques, such as the word-count proposed here. Is word count also a holistic assessment technique, or is it reductionistic, considering that words are very small units in the text? If only one or a few words were used, the technique would be highly reductionistic (claiming, for instance, that similarity can be analysed on the basis of a few key words). The SOM technique, however, uses the word-profile to get a *different* holistic assessment of the text than the human one: the profile of words and word-usage.

The mapping of input data onto the SOM works as follows. One of the input vectors is compared with all of the prototype vectors in terms of distance. This can be done with normal vector mathematics, which allows the measurement of distances between high-dimensional vectors. The prototype vector that is closest to the input vector is called the winner. The winner is adjusted according to the SOM algorithm so as to be a bit closer to the input vector in question. In addition to the winner, some of its neighbours are also

changed, but less so. These adjustments are called learning, and the rate with which adjustment is performed is called the learning rate. The learning rate and the size of the neighbourhood that learns are parameters that need to be determined before the mapping. When the learning has been accomplished on the map for the first input vector, a new input vector is selected, and the same process is repeated. The iteration continues until the map stabilizes, that is, until the introduction of new input data has little effect on the prototype vectors. There are two technical reasons for such stabilization: the learning rate is reduced and the neighbourhood size shrinks over time. Both of these are parameters that can be varied.

The input data has now been coded onto the map. The next step is to do a new mapping of input data. This time, however, the map does not change. The purpose of the second mapping is not to map information, but to map representation. The second mapping determines how prototype vectors represent input vectors. For instance, if text A was part of the input data, and *d* is the prototype vector that is closest to it, then *d* represents A. The SOM is thereby transformed to a representative map in which cells on the map represent one or several data units in the input space. This representative property is illustrated by labelling the cells according to the input vector that they represent, for instance with a few words from the title of the sample publication in question. The outcome is a two-dimensional map in which the labels of cells show how the input data is distributed (see Figure 1). There are many complexities in the labelling. If the SOM-analysis is done with a large number of sample texts, some kind of automatic labelling is needed. Labels need to be short and informative, so full titles cannot be used. Furthermore, if the input material is large, each cell on the SOM will represent several texts, which makes the task of labelling even more challenging.

After labelling, the actual analysis of the map can begin. What kind of information does it contain? As said before, its primary function is to give a two-dimensional representation of the topology of the input space. Texts will thus not be evenly distributed in the SOM, but will be grouped according to similarity in content (word-usage profile). Texts with similar contents will cluster in specific regions of the map. This visual illustration of clustering is improved by the fact that the map is non-linear: vector distances do not correspond to metric distances. A distance of three cells on the map can represent very different vector distances, depending on the values of the vectors. Visual aids have been developed to correct for the non-linearity. Thus, in many SOMs, large distances are illustrated with dark shades of gray and small distances with light shades of gray. Lightly coloured regions thus represent input data that is closely related, for instance in terms of content, while dark regions signify distance (see Figure 1). Using a three-dimensional metaphor, one can think of the light regions as valleys in which you can fly through the air between locations, and the dark areas as hills that have to be climbed when moving from location to location.

The SOM allows us to analyze the topology of contents in the samples texts. On the basis of the hierarchical model of scientific knowledge production, discussed in section 2, we would expect a SOM based on a large and heterogeneous body of scientific articles to have a disciplinary organization. There should in other words be a clear clustering around research fields, and these clusters should themselves be clustered in a way that allows us to find the established disciplines at higher levels of the hierarchy. The rhizome-model, on the other hand, predicts that boundaries between research areas will be diffuse, and that the connections between lower level clusters (research fields) and higher level clusters (disciplines) are complex. In order to do this investigation, the SOM itself would have to be hierarchically organized. What we mean is that by clicking on a cell on the map, one should be able to get a new SOM of the documents represented by that cell. It would also be important to be able to select several cells, and to get a new SOM of all the publications represented by those cells. The latter is important to be able to check for artificially produced hierarchies (a hierarchical SOM may produce an impression of hierarchically organized science, unless we can check for this effect).

We have chosen the SOM for the analyses of this paper since the SOM is robust and understandable. According to Laine (2003) these are important properties of systems intended for non-mathematicians. Robustness allows versatile types of data to be analyzed without pre-treatment. The SOM is robust since it makes no assumptions of the probability distributions of the data. The algorithm tolerates e.g. outliers and non-linearities. The SOM is understandable as the training concept of the SOM is simple and can be explained to the common user in minutes. The user is not required to understand probability mathematics or linear algebra.

Visual analysis needs, of course, to be supplemented by numerical analysis. We would need values for the degree of clustering of any region selected on the map. One should also be able to analyse clustering on the basis of metadata. For instance, we may be interested in the degree of clustering of the publication of author A or institute I. These measures correspond to the measure of degree of interdisciplinarity (see previous section), but in reversed form. A high degree of clustering would indicate strong specialization, while a low degree of clustering suggests an interdisciplinary profile. The clustering of a researcher or an organization can be compared with the clustering of other researchers or organizations, to see for instance how the researcher's publication profile compares with those of other researchers in his field. Such comparisons lay the foundation for a relative measure of specialization respectively interdisciplinarity. The good thing with these measures is that they are not dependent on any operationalization of specialization or interdisciplinarity from the analyst's side, but are based on an analysis of the topology of contents. The task of the analyst is then to draw the line between specialization and interdisciplinarity, and to distinguish

different categories of the two. There will probably be a continuum from very specialized to very broad.

Numerous other analyses are possible by using metadata to investigate distributions on the map. One could study the clustering of, for example, biology journals, sociology departments, or Finnish chemists. Comparisons of clustering could also be made between, for instance, psychology journals based in the US and Europe; Norwegian and Danish economists; Indian and Chinese information technology departments; or top-level and mediocre universities. One could also compare productive scientists with less productive scientists. Which group tends to be broader in its publication profile? Time is a particularly important type of metadata. If publications from different years are included, the SOM becomes, in effect, a time-space projection. The map as a whole does not represent the topology of contents at any particular year, but over a time continuum. With a large body of sample texts, we should thus be able follow how people, organizations, journals or whole nations move on the map over time. Do they become more specialized or more interdisciplinary? One should also be able to identify the origin of new clusterings. Are such origins to be found within older research fields or are they typically constituted by publications that move "outside the lines" (Salter and Hearn 1996). The temporal dimension allows us to analyse historical trends, and to project the future. Publication-based SOM-analysis could in other words be highly useful, both for development of theory and for policy purposes.

The usage of metadata to analyse the contents of the SOM requires both visual and numerical tools. Visual tools allow the analyst to see the distributions on the map, for example how the distribution of the publications of some particular organization moves over time. Such a tool would have to be advanced in the sense that it should not only show distributions in the year that is investigated, but also allow comparison with earlier distributions. This can be done, for instance, but letting historical and contemporary (the focus year) distributions be visible at the same time, but make distinctions by using different shades or colour for different years.

## 5. Discussion

This paper has proposed a new method for measuring interdisciplinarity. We started by discussing a range of opinions about the prevalence and significance of interdisciplinary research, and settled for a broad definition of the term. We then reviewed some of the empirical approaches to the study of interdisciplinarity. The review concluded that there are many different methodologies, and that all of them are limited either in scope or precision. Our own proposal, discussed in the previous section, uses the self-organized map and the WEBSOM method of contents analysis to achieve both scope and precision.

How does our concept relate to other efforts of mapping science? The idea of studying the structure of

science is not new. Early studies focused on networks or clusters of authors, papers, or references. Later studies expanded the approach to co-word analysis, to achieve a greater semantic relevance. As visualization techniques have improved and computing capacity increased, samples have become larger and maps more complex. (Boyack et al. 2005) The focus in most previous mapping exercises, if not all of them, has been on *the map as the object of analysis*: maps show us the structure of science. Our proposal, however, uses a different approach. We do not define the map as the object of analysis, but rather as a space for meta-data behaviour. Meta-data behaviour is the true object of analysis, in our model. The map constitutes, instead, a space in which the meta-data events unfold. This puts some pressure on contemporary techniques for clustering and visualization. Our proposal goes beyond presently existing techniques, but may not be unrealistic in the near future.

At the core of the proposed concept is learning from data. According to Laine (2004), key features in such a system are supervised operation, robustness and understandability. A tool created for bibliometric analysis should allow the user to guide the search towards areas of interest (supervision), should operate well with heterogeneous text corpuses (robustness), and be usable to a wide range of users (understandability).

These three criteria apply to three levels of development: algorithm, software and service model development. On the algorithm level, we need to choose and develop statistical methods that comply with the three criteria mentioned above. The SOM is such an algorithm. On the software level, we need to create a human-computer –interface that is intuitive and leads the user towards results that he or she considers to be interesting. The SOM, as a visualization tool, provides the user with the grand view, and immediately allows the user to zoom into a given field of clustering of publications. In the present paper, we have proposed a number of solutions that are yet to be implemented. The underlying technologies exist for most of the propositions, for example, implemented in the public domain SOM-Toolbox created for Matlab ([www.cis.hut.fi](http://www.cis.hut.fi)), but they need to be brought together in a new way. In the phase of implementation, it is important to remember that the concept has to serve real organizations. The needs of potential users, such as scholars interested in the mapping of science and policy makers, must be considered. We require an interdisciplinary project comprising domain experts of various academic and non-academic fields and computer science experts.

If such a project is successful, we gain a system that allows analysis of past developments, and to some extent, prognosis of future application areas. According to Hargadon (2003), breakthroughs happen when existing knowledge is combined in new ways, and a new team pursues the generated vision. The concept proposed in this paper allows new theoretical combinations to be identified, and their technological strength and potential for application to be estimated. What remains to be done is, in the terminology of

Stefik and Stefik (2004), to follow the problem to its roots.

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FIGURE 1: SOM of fifty-one publications (scientific papers). The symbols refer to the authors who produced the texts. Two disciplinary corpuses of text were investigated, A and B. In other words, A and B indicate the disciplinary orientation of the author. Numbers identify particular authors. B1 is thus author 1 from the disciplinary context of B. A second number identifies a particular text (in cases when individual authors have produced several texts). Thus, B28 refers to text 8 by author B2. This map is a draft version: the two number-system has not been used consistently (some of the texts by B2 are indicated with B2 only). In the final map, the two-number system will be omitted, since the identity of particular texts is not

important for the readership. A few words need to be said about the colouring, too. Light areas indicate that publications are close to each other, even if the distance may be (relatively) long on the map. Dark areas indicate longer-than-metric distances. When investigating the distribution of text corpuses A and B, we see that they occupy distinct regions on the SOM. This seems to verify that the methodology is able to make adequate categorizations on the basis of contents. An unpublished analysis of the distribution of texts by B1, suggested that there was a high correspondence between the groupings made by the SOM and those made by B1 himself. Source: Pölla et al. 2006.

