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Disciplinary, Multidisciplinary, Interdisciplinary - Concepts and Indicators -

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Introduction

The production of knowledge is dominantly organized in disciplines. At the same time, multidisciplinary and interdisciplinary research is developing at the boundaries of the scientific disciplines. In this paper we compare disciplinary and non-disciplinary forms of knowledge production in terms of communication patterns. We will suggest an indicator for measuring the degree of interdisciplinarity, and this allows us to evaluate the development of interdisciplinary fields. The indicator is based on the patterns and intensity of the knowledge streams between research fields. The communication of knowledge within a disciplinary field is expected to differ from the communication of knowledge within a non-disciplinary field. The same holds for the communication between a disciplinary and a non-disciplinary research field with their respective scientific environments. Clarifying these patterns of knowledge communication improves our understanding of the nature and dynamics of non-disciplinary research, and we will illustrate that interdisciplinary fields develop towards disciplinary patterns.

Disciplinarity and interdisciplinarity

Interdisciplinarity is an important and a complex issue. It is important as modern society increasingly demands application-oriented knowledge, and the usability of scientific knowledge generally requires the combination and integration of knowledge form various scientific disciplines. Traditionally, the disciplines have been very dominant in the organization of the science system, in the reward system, and in the career system. Nevertheless, funding agencies are increasingly stressing the social relevance of research results, and consequently a new mode of application-oriented research is emerging, on top of traditional academic research. In other words, the science system is not only growing in size, but its structure and functioning are changing too: the locus of research, the patterns of collaboration, and the aims of the scientific enterprise. Gibbons et al (1994) analyzed these changes by contrasting two modes of knowledge production, and the distinction between disciplinarity and interdisciplinarity is in the core of their approach. The differences between the two modes can be summarized as follows.

Mode 1 is the production of traditional ‘disciplinary science’, in which the academic interest in ‘pure’ knowledge prevails. The aim is to produce theoretical knowledge of (physical and human) nature. The locus of Mode 1 is the university organized along disciplinary lines in faculties and departments. Consequently it is homogeneous in terms of organizational structures and practitioners, it is hierarchical, and relatively stable. Quality control is internal by peer review, and based on the journal system. In contrast, *Mode 2* is interdisciplinary and application-oriented knowledge production. The focus is not so much on discovering ‘laws of nature’ but on studying artifacts and the operation of complex systems. Examples are among others computer science, chemical engineering, and biotechnology. Mode 2 is heterogeneous, as a wider set of organizations and types of researchers are involved, operating in specific contexts on specific problems. Various different organizational forms co-exist within Mode 2, and research is not exclusively based in universities. The system of quality control is broader, and not only based on peer review of academic papers, and includes usability and social accountability. In that sense Mode 2 is heterarchical. Mode 2 knowledge production finds its roots in the intimate interaction between information and communication technologies (ICT), and advanced scientific and technological research and innovation. It is reflected and reinforced by large application-oriented and collaborative transnational research programs like the EU framework programs. Mode 2 is growing in importance, but not supplanting Mode 1 research, as it remains dependent on the development of disciplinary knowledge.

The notion of interdisciplinarity is a difficult one, as many related concepts exist with various interpretations: multidisciplinarity, crossdisciplinarity, pluridisciplinarity, interdisciplinarity, and transdisciplinarity. (Thompson 1990, 1995) These forms of *non-disciplinary* knowledge have in common that they are generally defined in contrast to what is seen as 'normal' – that is disciplinary – knowledge, and the prevailing classification of research in disciplines, sub-disciplines, and research fields is often taken for granted. Therefore we start with defining disciplinarity, before we try to define non-disciplinarity. A disciplinary research field can be defined as a group of researchers working on a specific set of research questions, using the same set of methods and a shared approach. (e.g., Kuhn 1962; Price 1965; Chubin 1983) Disciplinary research is 'normal problem solving' within a 'paradigm', and with hindsight is we can define the boundaries of disciplinary fields.

Non-disciplinary research then can be seen as ways of combining elements form various disciplines, as an interaction among two or more different disciplinary specialties, in order to answer practical questions and to solve practical problems. The interaction may range from communication and comparison of ideas, and the exchange of data, methods and procedures, to the mutual integration of organizing concepts, theories, methodology, and epistemological principles.[1] Without trying to define all the various concepts mentioned above, the basic difference between these various manifestations of non-disciplinary is the *level of integration* of the different disciplinary approaches they are based on.

- In multidisciplinary research, the subject under study is approached from different angles, using different disciplinary perspectives. However, neither the theoretical perspectives nor the findings of the various disciplines are integrated in the end.
- An interdisciplinary approach, on the other hand, creates its own theoretical, conceptual and methodological identity. Consequently, the results of an interdisciplinary study of a certain problem are more coherent, and integrated.
- In the older use of the term, transdisciplinarity is defined as an interdisciplinary meta-theoretical perspective, like structuralism and Marxism (Thompson 1990).
- More recently, Gibbons et al (1994) use the concept of transdisciplinarity in a different way. In their view, interdisciplinary approaches are characterized by an explicit formulation of a uniform, discipline-transcending terminology or a common methodology. A transdisciplinary approach goes one step further, as it is based upon a common theoretical understanding, and must be accompanied by a mutual interpenetration of disciplinary epistemologies. In this view, a transdisciplinary field has a homogenized theory or model pool.

Indicators for interdisciplinarity

A central characteristic of non-disciplinary research is that it is application oriented. As social problems change, non-disciplinary fields are expected to be constantly in flux. However, also disciplinary fields show considerable development and change. Anomalies emerge within the process of 'normal' puzzle solving, and once the existence of those anomalies is accepted, normal science may turn into crisis. Eventually radical changes occur, in which fields merge or break up. A reconstruction of the research field takes place, often a process of recombining elements of different disciplines, which results in the emergence of a new paradigm. In other words, contrasting disciplinary and extra-disciplinary research in terms of homogeneity versus heterogeneity, and stability versus flux, is not convincing. If these *global* characteristics cannot be used, it may be more fruitful to start with the differences on the *micro*-level, the level of communicative selections of individual researchers, and compare the resulting macro-patters that emerge from these communicative actions. (Fujigaki 1998)

How can we distinguish disciplinary from non-disciplinary fields using this micro-level approach? Researchers within a specialty communicate more with one another than with researchers in other communities, and they are expected to refer to one another's work significantly more frequently than to the work of outsiders. Scientific specialties can thus be considered as communication-networks (e.g., Griffith & Mullins, 1972; Shrum and Mullins 1988). The communication within a disciplinary network is much more intensive than the communication with researchers in other specialties (e.g., McCain 1990). On the other hand, within interdisciplinary fields the intensity of the internal discussion is expected to be less, and external communication more intensive, as interdisciplinary fields draw more intensively upon various other specialties than disciplinary research fields do. For multidisciplinary research fields, this is expected to be even stronger, as in these fields integration of the various perspectives is almost absent, and consequently, the level of internal communication is expected to be very low. We will use this hypothesis to study the difference between the various forms of non-disciplinary and disciplinary fields in terms of the different structures of the communication networks.

Communication patterns have been studied in terms of co-citations among authors or articles (e.g., Small and Griffith 1974; McCain 1986 and 1990). In a number of studies, it has been shown that journal-journal citations can be used as an operational indicator for the disciplinary organization of the sciences (e.g., Doreian and Fararo, 1985; Borgman and Rice, 1992; Tijssen, 1992; Leydesdorff & Cozzens, 1993). One may expect strong citation relations within and between journals

[1] We do not discuss here organizational forms of integration of research and teaching (Thompson 1990, 1995).

belonging to a discipline, and (much) weaker relations with other journals. Additionally, one expects that journals belonging to the same discipline relate (through citation patterns) to existing knowledge in a different way than other journals. As argued elsewhere (Van den Besselaar & Leydesdorff 1996) we study the communication patterns within a specialty not in relational terms – how much does a field depend on information from other fields – but in terms of the position the specialty has within the scientific landscape. Can we use this as an operational indicator to distinguish the various types of non-disciplinary research?

Over the years, various indicators have been developed to describe *multidisciplinary* (Glänzel et al 1999), *cross-disciplinary* (Porter & Chubin 1985), and *interdisciplinary* (Thijssen 1992; McCain & Whitney 1994; Tomov & Mutafov 1996; McCain 1998) research. These indicators are generally defined in contrast to what is seen as normal – that is disciplinary – knowledge, and the *prevailing* classification of research in disciplines, sub-disciplines, and research fields is often taken for granted. This conventional classification in terms of disciplines reflects our conventional worldview, in which we distinguish the various 'natural domains'; and the disciplines are organized accordingly. Non-disciplinary research is defined as a derivate of the disciplines, and is seen as based on those. Consequently, indicators for non-disciplinary research are generally based on the relations with the disciplines, like the number of 'out-of-discipline citations'. (Porter & Chubin 1985)

We will use a slightly different approach, and will apply the same methodology for the delineation of non-disciplinary fields as for the disciplinary fields. As already emphasized, the method is used to describe research fields in terms of their position within scientific communication networks. If we use a similar approach for the analysis the communication networks of non-disciplinary fields, we can answer the question to what extent disciplinary, interdisciplinary, and multidisciplinary fields have different positions within scientific communication networks. In other words, we delineate the non-disciplinary field in the same way as disciplines, and then we will identify the specific way they are embedded within the network of related disciplines. By mapping research fields in various years, we are able to analyze the development of multidisciplinary and interdisciplinary fields. That is, if we do not take the existing disciplines are frame of reference, but *disciplinary behavior*, we are able to show how multidisciplinary fields may develop into interdisciplinary fields, and how the latter develop into disciplines. This implies that they become less dominated by the traditional disciplines in their environment, and become more internally coherent.

Methods and data

We use a method for delineating specialties as described elsewhe re. (Van den Besselaar & Leydesdorff 1996) It comes down to a factor analysis of the journal-journal citations matrix of the core journal of a specialty. The point of departure is the selection of a journal representing the specialty. For every year, we determine the relational citation environment of that journal, using a threshold of 1%. Lets assume that this core journal is cited N times and cites other journals M time. We include all journals in the analysis that cite the core journal at least N/100 times, or are cited by the core journal at least M/100 times. For the resulting set of journals we can make the journal-journal citation matrix, with the citing behavior as the variables. A factor analysis of this matrix results in factors consisting of journals that have similar citation patterns. The factor on which the core journal has it highest loading represents the field under study. The other factors represent a set of research fields that are related to the field under study. Our question is whether the various forms of (non-)disciplinary research fields are characterized by a different factor structures. In contrast to other studies, the notion of multi/inter/transdisciplinarity does not refer to the relation dimension, but to the positional dimension.

The factor structure is characterized by various relevant statistics.

- Column 2[2]: The number of journals within the relational environment.
- Column 3: The number of factors resulting from the factor analysis.
- Column 4: The rank of the factor that does represent the field under study.
- Column 5: The rank of the core journal within the factor it has its highest loading on.
- Column 6: The explained variance by the factor representing the field under study.
- Column 7: The explained variance by the first factor, if this is another factor than in column 6.
- Column 8: The nature of the specialties represented by the various factors.

The second and the third columns show how restricted the environment of the field under study is. The lower the number of journals and factors, the more selective the communication network is, and the more codified the communication. The fourth column shows the rank of the factor that represents the field under study. The lower this is, the less dominant the field under study is within its own communication network. This is reflected in column six which shows the explained variance of the factor representing the field under study. In case this factor is not the first one, we also give in column seven the explained variance by the first factor, to show how strongly other research fields dominate the communication system. The fifth column shows the rank of the entrance journal within the factor on which it has its highest loading. If this rank is low, the journal has often relative high loadings on other factors,

[2] This refers to the columns in the tables on the following pages.

implying that the entrance journal 'belongs' to different fields. This is an indicator for multidisciplinarity. The last column shows what factors have been delineated: the specialties that are relevant in the environment of the focal specialty. We preserve the order, so it remains visible what are the more and what the less important specialties.

We analyzed various fields over a longer period, mainly fields related to 'artificial intelligence': 'symbolic artificial intelligence', 'neural networks', 'cognitive science', 'robotics', and 'information science'. To create

a frame of reference, we analyzed the journals *Science* and the *Communications of the ACM*. We also studied 'science and technology studies' (Van den Besselaar 2000, 2001), and 'biotechnology', but because of lacking space we have not included them in this paper. However, the results for the two latter fields confirm the findings reported here. The period under study is 1982-1998, and we analyzed data for the even years. For some of the fields we use a shorter period, as the fields did not exist in the early years. The data were extracted from the Journal Citation Reports, the printed version for the earlier years and the CD-ROM version for the later years.

Findings

We analyzed various non-disciplinary research fields, in order to study the differences in their respective positions in the journal-journal communication network. The baseline for the analysis is formed by the application of the method on established disciplines. (Leydesdorff & Cozzens, 1993) This results in a clear and stable structure of not too many factors, all unambiguously representing a research field. Generally, the first (strongest) factor is the one that includes the core journal, and the core journal normally has a high loading on the factor. The other factors represent specialties in the vicinity of the specialty under study.

Table 1: Cognitive Science

Year	Number of factors	Number of journals	Rank of core factor	Rank of core journal	Explained variance	Explained variance factor 1	Main factors[2]
1982	7	21	1	3/8	26.2		CP (incl. CogS), P, CDP, Phil, AI (single)
1984	12	40	1	13/13	22.4		CP (incl. CogS), Phil, IS&CS, AI & PR, Communication
1986	11	29	1	8/8	21.5		CP, CDP, AI, EP, IS, Language, CogS
1988	11	27	3	4/4	8.6	13.1	CP, SN, AI (incl. CogS), EP, P, CS
1990	10	38	3	3/5	8.8	19.5	CP, CDP, AI (incl. CogS), BS, Linguistics, EP
1992	12	44	4	4/4	7.6	20.3	CP, AI, NN, CogS, EP, BS,
1994	17	61	5	4/4	5.4	18.2	CP, HCI/AI, EP, NN (inc SN), AI (incl CogS), CDP, Linguistics, CS/MIS
1996	18	71	12	3/3	2.9	15.8	CP, AI, NN, BBS, CDP, Instruction (incl. CogS), Ergonomics, CD.
1998	13	50	1	11/11	3.7	15.7	CP (incl CogS), AI, EP, SN, NN, CDP, HCI

1. Core journal is *Cognitive Science*. Threshold = 0.5%; this means that all journals are included with at least either 0,5% of the total number of references in that year to the core journal, or 0,5% of all citations by the core journal. Analysis: Principal component analysis, Varimax, Kaiser rotation.
2. AI = Artificial Intelligence, BS = Brain Research, CP = Cognitive Psychology, CDP = Child & Developmental Psychology, CS = Computer Science, CogS = Cognitive Science, EP = Educational Psychology, HCI = Human-Computer Interaction, P = Psychology, PA = Pattern Analysis and Vision, Phil = Philosophy & Discourse, NN= Neural Networks, IS = Information Science, SN = Science and or Nature etc.

The first research field we describe here is 'cognitive science', using *Cognitive Science* as entrance journal[3]. Table 1 summarizes the results of the factor analysis for *Cognitive Science*, for the period 1982-1998. The results are very different from the stable disciplinary pattern indicated above. First, we see the core journal loading on very different factors in the various years. In 1982, 1984, and 1998, *Cognitive Science* is part of 'cognitive psychology'. In 1988, 1990 and 1994, *Cognitive Science* is in the 'artificial intelligence' factor, in 1996 it is in an 'instruction science' factor, and in the other two years *Cognitive Science* is a factor of its own. Almost always, *Cognitive Science* is the journal with the lowest loading on its primary factor. At the same time, it shows considerable 'interfactorial complexity': it loads

[3] *Cognitive Science* (in italics) stand for the journal, and 'cognitive science' stands for the scientific specialty.

relatively strong on various other factors, representing specialties relevant for 'cognitive science'. This all shows that 'cognitive science' has not developed as stable communication system, but is very much in flux and instable. The set of specialties in its environment is relatively stable, but its own position within this communication system is not stable at all. We consider this as a typical 'multidisciplinary' pattern: 'cognitive science' has an object, but uses many disciplinary approaches without much integration. In that sense, multidisciplinary research is reviewing more than integrating various disciplines. This leads to the hypothesis that multidisciplinary journals have a similar position in the communication network as review journals have.

This we can actually test by repeating the analysis for a well-known review journal like *Science*, covering physics and the life sciences, and another journal like the *Communications of the ACM*, covering computer science. The test was done only for the more recent period (1994-1998), and the results are strikingly identical to the 'cognitive science' case. The last column (main factors) of table 2 shows that *Science* has its highest loading on different factors. At the same time, it loads as one of the lowest journals on its main factor (column 5: rank of core journal). However, also *Science* has a high interfactorial complexity, as it loads substantially on a stable set of other factors. *Science* is a journal with a moving position in its journal environment. Table three repeats the analysis for computer science, using the *Communications of the ACM* as core journal. The results are again identical. As a conclusion, two types of multidisciplinarity can be distinguished, one from below, representing a multidisciplinary research field (like 'cognitive science'), and one from above, representing the top journals in the field, reviewing the most relevant results of various disciplinary research specialties that belong to the larger field.

Table 2: Science[1]

Year	Number of factors	Number of journals	Rank of core factor	Rank of core journal	Explained variance	Explained variance factor 1	Main factors[2]
1994	8	32	1	9/12	24.3		CG (incl SN), BC, Imm, NS, Virol, Chem, GP, Phys
1996	9	36	1	8/12	21.3		CG (incl SN), BC, Imm, GP, PC, Phys
1998	10	33	4	4/4	7.8	21.2	CG, BC, GP, NS (incl SN), Imm, GP, PC, Phys

1. See note 1, table 1. Core journal is *Science*
2. CG = Cell & Gene, BC = Biochemistry, GP = Geophysics, Imm = Immunology, NS = Neuroscience, Phys = Physics, PC = Physical Chemistry, Virol = Virology

Table 3: Computer Science[1]

Year	Number of factors	Number of journals	Rank of core factor	Rank of core journal	Explained variance	Explained variance factor 1	Main factors[2]
1994	10	54	5	2/3	7.7	18.7	SW, PC, MIS, ThCS, CACM, AI, Pat Anal, OR, InSyst
1996	13	63	11	4/5	4.4	11.8	InfoSyst, SW, PC, ThCS, CT, AI, IS, Prog, OR, HCI/CS (incl CACM), PA
1998	10	49	3	2/8	12.5	14.2	InfoSyst, PC, IntRes (incl CACM), SW, ThCS, AI, IS, Prog, Management

1. See note 1, table 1. Core journal is *Communications of the ACM*
2. AI = Artificial Intelligence, IS = Information Science, CS = Computer Science, CogS = Cognitive Science, ThCS = Theoretical Computer Science, OR = Operations Research, HCI = Human-Computer Interaction, CT = Communication Technology, SW = Software, PC = Parallel Computing, Prog = Programming, IntRes= Internet Research.

The next case we analyze is ‘information science’, with the *Journal of the American Society for Information Science - JASIS* [4] as the core journal. Like in the other cases, the core journal is the one with the highest impact factor in the field over the period under consideration. The resulting pattern is completely different from ‘cognitive science’.

As is clear from table 4, ‘information science’ is much less a multidisciplinary field, but was already dominating its own environment in 1982. With an exception for the 1988 data, this position has increased since then. So our concept of interdisciplinarity is confirmed in this case: information science behaves disciplinary, despite its interdisciplinary nature if classified in terms of traditional disciplinary categories.[5] In all years but one, the factor representing ‘information science’ is the first factor. The journals belonging to this ‘information science’ factor are very similar in all years, as are the other factors (the relevant specialties) resulting from the analysis. The core journal (*JASIS*) generally is one of journals with the highest loading on the factor. And, the level of interfactorial complexity is small. Finally, the variance explained by the factor that represents ‘information science’ is high and increasing (column 6: explained variance), which means that the focal specialty increasingly dominates its environment. Despite the fact that ‘information science’ is generally seen as an interdisciplinary field, it shows a stable communication pattern, in which it is the dominant specialty. In other words, here we have an interdisciplinary field with strong ‘disciplinary’ characteristics.

Table 4: Information Science[1]

Year	Number of factors	Number of journals	Rank of core factor	Rank of core journal	Explained variance	Explained variance factor 1	Main factors[2]
1982	8	22	1	1/1	17.9		IS, CS, LIB, SN, STS
1984	17	47	1		14.3[3]		
1986	16	45	1		14.9[3]		
1988	21	46	3		6.8[3]		
1990	10	30	1	2/9	22.2		IS, Online, SN, LIB, CS, Sciento.
1992	9	30	1	5/8	21.6		IS, CS, LIB, SN, Sciento, SSS
1994	10	33	1	1/10	24.9		IS, CS, LIB, Sciento, SN, Respol,
1996	9	31	1	3/10	23.9		IS, LIB, CS, SN, PA, MI, Sciento & Respol
1998	7	30	1	3/13	35.5		IS, LIB, CS, MI, Sciento

1. See note 1, table 1. Core journal is *Journal of the American Society of Information Science (JASIS)*
2. IS = Information Science, LIB = Various Library Science, CS = Computer Science, STS = Science & Technology Studies, Sciento = Scientometrics, SSS = Social Studies of Science, SN = Science and or Nature etc, PA = Pattern Analysis, MI = Medical Information, AI = Artificial Intelligence.
3. The explained variance of the non-rotated solution, which is higher than of the rotated solution.

What we expect to find are other non-disciplinary fields with communication patterns between the fully multidisciplinary ‘cognitive science’ and the almost disciplinary ‘information science’. A good case to illustrate this is ‘artificial intelligence’. [6] Table 5 shows the main results of the factor analyses of the AI-data, for the 1982-1998 period. In the early years, the factor representing AI has a low rank (column 4: rank of core factor), and explains only a small part of the total variance (column 6: explained variance), which means that other specialties dominate the communication environment of ‘artificial intelligence’. The factor representing AI in 1982 was heterogeneous, indicating the multidisciplinary nature of the field. However, during the development of the field, we see the rank of the AI-factor rising (column 4), and starting in 1988, it is the strongest factor in its own environment. Second, the explained variance rises considerably, showing that a large part of the total variation in the dataset in the later years is explained by the AI factor. In other words, ‘artificial intelligence’ is strongly dominating its communication network in the later period. Thirdly, the number of research fields (column 2: number of factors) relevant for AI has decreased, and this shows that AI is more and more becoming a codified specialty. The other relevant factors are on ‘pattern analysis’, ‘theoretical computer science’, ‘robotics’, ‘medical applications of AI’, ‘CAD’, and ‘brain & behavioral science’. Compared to earlier years this set has become smaller and less diverse, and this too shows the increasingly disciplinary nature of AI. Fourthly, the journals in the AI-factor are increasingly restricted to theoretical and applied AI journals, which means that the AI-factor is becoming less heterogeneous over the years. Finally, the combination of applied and theoretical journals indicates the transdisciplinary nature of the field.

[4] *JASIS* changed its name in 2001 into *JASIST*. The T stands for ‘technology’.

[5] Also the ‘biotechnology’, which generally is classified as transdisciplinary has in a similar manner a ‘disciplinary’ structure.

[6] See for a more in depth discussion of ‘artificial intelligence’ Van den Besselaar & Leydesdorff (1996).

What does this case teaches us? Here we see a specialty that exhibits multidisciplinary communication patterns in the early eighties, and over the years the field seems to undergo a process of integration. In other words, it changes from a multidisciplinary field into an interdisciplinary or transdisciplinary field with a fairly high level of integration. The communication network of 'artificial intelligence' is increasingly similar to a disciplinary one.

Table 5: Artificial Intelligence[1]

Year	Number of factors	Number of journals	Rank of core factor	Rank of core journal	Explained variance	Explained variance factor 1	Main factors[2]
1982	6	17	3	3/3	13.5	23.1	CS, PA, AI (CogS), HCI, Psy
1984	14	52	6	1/3	4.2	11.1	CogS, CS, PA, SN, ThCS, AI
1986	13	43	2	1/6	10.7	14.5	CS, AI, ThCS (LP), PA, CogS
1988	11	43	2		11.8[3]	13.7	PA, AI, CogS, Softw, CS, Rob, Statistics
1990	13	42	1	2/9	18.7		AI, PA, CogS, CS, CAD, Rob
1992	13	51	1	1/19	22.1		AI, PA, Softw, ThCS (LP), Rob, CS, OR
1994	9	59	1	6/22	37.9		AI, PA, CS, ML, ThCS, Fuzzy sets, Simulation
1996	10	40	1	2/23	42.7		AI, Rob, LP, PA, OR
1998	8	46	1	1/23	38.9		AI, PA, LP, CS, NN, AI Med

1. Core journal is *Artificial Intelligence Journal*.
2. AI = Artificial Intelligence, CS = Computer Science, CogS = Cognitive Science, PA = Pattern Analysis and Vision, ThCS = Theoretical Computer Science, LP = Logic Programming, Rob = Robotics, OR = Operations Research, NN= Neural Networks, CAD = Computer Aided Design, SN = Science and or Nature, ML = Machine Learning
3. The explained variance of the non-rotate d solution, which is higher than of the rotated solution.

Table 6: Robotics[1]

Year	Number of factors	Number of journals	Rank of core factor	Rank of core journal	Explained variance	Explained variance factor 1	Main factors[2]
1984	24	61	3		5.5[3]		
1986	22	51	6		4.3[3]		
1988	12	35	3		8.6[3]		
1990	8	24	4	2/5	11.2	18.6	PA, Control, Sensors, Rob, Astronaut, CS
1992	6	26	2	3/6	19.8	25.2	PA, Rob, Automatica, AI, CS, Mechanics
1994	10	51	2	1/9	20.1	23.8	Automatica, Rob, PA, AI, NLD, Mechanics,
1996	9	45	1	2/14	27.6		Rob, Automatica, PA, Astronaut, Mechanics
1998	8	35	1	4/12	26.5		Rob, Automatica, PA, Mechanics,

1. See note 1, table 1. Core journal is International *Journal of Robotic Research*
2. PA = Pattern Analysis, Rob = Robotics, CS = Computer Science, AI = Artificial Intelligence
3. The explained variance of the non-rotated solution, which is higher than of the rotated solution.

Table 6 shows the results of the factor analysis for 'robotics' over the period 1984-1998, as the *JCR* did not include relevant robotics journals in 1982. 'Robotics' shows a similar development as 'AI', although the development has not gone that far (yet). The environment of 'robotics' is consisting of a stable set specialties, and the 'robotics' factor itself is also quite stable. In contrast to 'AI', the 'robotics' factor is only since 1996 the first factor, and the communication network of robotics was dominated by other specialties until 1994. Nevertheless, the explained variance by the 'robotics' factor started to increase four years earlier, and in 1998 the 'robotics' factor is explaining a substantial part of the variance. In sum, 'robotics' is developing from a multidisciplinary field in the early eighties to an interdisciplinary field in the late nineties.

‘Neural networks’ research is the last case we analyze here. As ‘neural networks’ is a younger research field, we only cover the period 1988-1998. *Neural Networks* is used as the core journal for this analysis. The pattern resulting from the factor analysis is quite identical to one we found for ‘robotics’, although ‘neural networks’ in its current stage of development is still is more multidisciplinary and less interdisciplinary. First of all, we do find a ‘neural networks’ factor in all the years. This shows that more than in the case of ‘cognitive science’, ‘neural networks’ is becoming an identifiable field. However, in the early years different journals belong to the ‘neural networks’ factor, which only becomes more stable in the later years. The ‘neural network’ factor is first or second in the 1990s, but the explained variance is not very high. This means that the communication network is equally influenced by various other specialties. Summarizing, ‘neural network research’ still is in a multidisciplinary phase, and not yet very much integrating the various disciplinary perspectives in a coherent interdisciplinary framework.

Table 6: Neural Networks[1]

Year	Number of factors	Number of journals	Rank of core factor	Rank of core journal	Explained variance	Explained variance factor 1	Main factors[2]
1988	16	47	6		4.1[3]		
1990	11	31	4	2/2	7.0	15.4	SN, NS, CogS, NN, Optics, PA
1992	14	45	1	4/5	9.9		NN, NS, SN, PA, Ph, BC, CogS
1994	15	57	2	1/8	10.9	12.3	NS, NN, SN, PA, Inf Sci, SP, BC, P, CS
1996	17	53	1	3/8	10.8		NN, NS, Ph, AI, SN, PA, Optics, Robotics, OR
1998	12	48	2	4/7	10.6	14.3	PA, NN, NS, SN, CS, SP, BC, Ph.

1. See note 1, table 1. Core journal is International *Neural Networks*
2. NN = Neural Networks, NS = Neuroscience, BC = Biology & Cybernetics, SP = Signal Processing, CS = Computer Science, CogS = Cognitive Science, EP = Educational Psychology, P = Psychology, PA = Pattern Aanalysis, Ph = Physics, SN = Science and or Nature etc
3. The explained variance of the non-rotated solution, which is higher than of the rotated solution.

4. Conclusion and discussions

The analysis leads to the following findings:

1) Multidisciplinary fields are dominated by the disciplines in the environment. Consequently, multidisciplinary fields have a different type of factor solution than disciplinary fields. Typically, the multidisciplinary field is represented by a factor with a *lower rank* explaining only a small part of the *total variance* of the journal-journal citation environment.

2) Multidisciplinary fields may develop into (inter)disciplinary fields, and this is indicated by a changing factor solution through the years. We found several examples of this: ‘robotics’, ‘artificial intelligence’, and ‘neural networks’.

3) Developed interdisciplinary fields are characterized by a communication system that is very similar to the patterns of disciplinary fields. The main difference seems to be the larger number of journals and specialties (factors) in the communication system of interdisciplinary fields.

4) Interdisciplinary and transdisciplinarity modes of knowledge production often are not very much dependent on the traditional disciplines. The relations are bi-directional and symmetrical, similar the science-technology relationship, as in the cases of ‘artificial intelligence’ and ‘information science’.

The picture of the science system that reflects the ‘given’ natural and social domains is only one of the possible classifications, although a powerful one.[7] Nevertheless, the boundary crossing non-disciplinary research activities seem to develop – at least in some cases – towards a disciplinary pattern. For example, *information science* is not an interdisciplinary specialty emerging in between traditional disciplines, but a different perspective on reality, a different projection of reality to make it accessible for specific type of research. It uses elements of the various disciplines, but organizes them in a specific way. The so emerging fields are only ‘interdisciplinary’ from the perspective of the traditional disciplines, but have a similar communication network as disciplines. We expect these so called interdisciplinary fields to operate in the same way as the traditional disciplines.

In this paper we have only analyzed formal communication through scholarly journals. One may argue that especially in application oriented research also other, more fluid forms of knowledge communication are important, like conferences,

[7] See Bowker & Star (1999) on the politics of classification.

professional associations (e.g., Van den Besselaar & Leydesdorff 1996), and practical collaboration in applied projects. Investigating the roles of this other forms of organizing knowledge flows in non-disciplinary fields may further clarify the nature of Mode 2 knowledge production.

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