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VARIOUS METHODS FOR THE MAPPING OF SCIENCE

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The dynamic mapping of science using the data in the *Science Citation Index* was put on the research agenda of science studies by *De Solla Price* in the mid 1960s. Recently, proponents of 'co-citation cluster analysis' have claimed that in principle their methodology makes such mapping possible. The study examines this claim, both methodologically and theoretically, in relation to other means of mapping science. A detailed study of a co-citation map, its core documents' citation patterns and the related journal structures, is presented. At these three levels of possible study of aggregates of citations, an analysis is pursued for the years 1978 to 1984. The many different statistical methods which are in use for the analysis of the respective datamatrices–such as cluster analysis, factor analysis and multidimensional scalling–are assessed with a view to their potential to contribute to a better understanding of the dynamics at the different levels in relation to each other. This will lead to some recommendations about methods to use and to avoid when we aim at a comprehensive mapping of science. Although the study is pursued at a formal and analytical level, in the conclusions an attempt is made to reflect on the results in terms of further substantial questions for the study of the dynamics of science.

Introduction

For more than twelve years now, the clustering of co-citations from the *Science Citation Index* as a database for the purpose of drawing a comprehensive and dynamic 'map' of science has been pursued with great tenacity in what we might call the Philadelphia programme for the study of the sciences. Recently, one of the founding fathers of this programme, Henri *Small,* acted as first author in two review articles in *Scientometrics* on this subject[1] in which the authors claim that their improved techniques for clustering the *Science Citation Index* with cocitations as basic units have been developed to a level of sophistication which in principle appears to make "a comprehensive mapping of science tractable within the present methodology".[2] Such a methodological breakthrough in achieving a global model of science could have major implications for science policies, as the previous success of more modest co-citation modeling has already shown.[3] If it becomes possible– as these authors hope, and still others are actually developing– to commercialize global models of scinece on floppy disks for personal computers with an inbuilt 'decision support system', the range

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of questions about science from science policy makers will gradually be transformed as well. Such a transformation would change in its turn the types of questions which can legitimately be dealt with concerning the dynamics of the sciences.

However, these authors are addressing not only science policy makers, but also science studies directly, when they list the questions to which they hope to contribute: What are the natural structural units of science? How are these structural units related to one another? What are the forces which determine these structural units and their interrelations? How does the structure of science change over time, both at a macro- and at a micro-level? [4] Their answer to these questions is that co-citations offer a correct operationalization of the structural units of science precisely *because* they can be used as units to produce comprehensive and dynamic maps of science. These maps can be generated at different levels by 'clustering the clusters', and by overlaying maps from different periods, even 'structural change in science' can be made visible. The proof of the pudding is in the eating!

At the science policy level, various attempts have been made to evalutate the usefulness of these co-citation maps. Although critical in tone, the conclusions have been mostly positive for the method. For example, a comprehensive evaluation of the ABRC recommends to the British Research Councils that the developments of co-citation analysis "would help increase the utility of their work."[5] In particular, the recommendation favored the building and accessing of wider models to allow comparisons between fields, and improvement of the general accessibility of the models to users.[6]

The emphasis in these policy-oriented studies has been on *validation of the outcomes* of the models.[7] Less attention has been paid to the methodological decisions which precede the model building, and which in some cases were taken already as early as 1974, when the programme to map science with co-citations was launched.

In this article, I will argue that precisely some of these methodological decisions, and particularly those with respect to the use of cluster techniques in this research programme, have been basically wrong, and that therefore the co-citation maps in their current form– however useful the pictures may be as bibliographic tools– do not represent or represent only very partially "the structure and the dynamics of science". To this end, I will make a precise analysis of a co-citation matrix and compare the results of this analysis with the results of an analysis of the related journal network.

Because the significance of journals and their relations can be much more easily grasped intiuitively than the meanings of co-citations– which are themselves relations!– and their relations, by using this indirect approach we will be able to point to one important limitation of the cluster methods commonly used in co-citation analysis, and to suggest alternative methods which may help overcome these limitations. Hence, in the conclusions we will suggest a set of standard analyses which make it possible to link the different levels of analysis which can be discerned, and we will attempt to reconceptualize these levels as dimensions in a model of the scientific enterprise. To this end, we will begin with a brief discussion of the theoretical interpretation of co-citations vis-à-vis citations and journals.

Design of the study

Co-citations are only one of several levels at which one can study the dynamics and the structural properties of aggregates of citations.[8] Journals, authors, research programmes, and citations themselves, all form networks which can be analyzed with various statistical techniques such as factor (or vector) analysis, cluster analysis, graph analysis, or multidimensional scaling. On the one hand, it has been emphasized that an understanding of the 'dynamics' of such structures presupposes that a calibrating baseline with respect to the notion of 'change' can be fixed,[9] and, on the other, it has been noticed that the relation between journal-journal maps and co-citation maps is still unclear.[10] One obvious approach to the question of what is changing in respect to what is stable, and at which level, would be to compare the many available studies at the different levels in this respect. A major problem in doing so, however, is that researchers use their own specific techniques, threshold levels, cut-off points, clustering methods, and graphic presentations without paying much attention to how one representation relates to another, or whether a study could be used for secondary analysis. Furthermore, because one usually needs access to the original ISI-tapes for co-citation analysis, it is difficult for an independent researcher to replicate a certain outcome with other methods in such a way that it becomes possible to compare his own results with those of other analyses. The introduction of fractional counting and other sophisticated techniques (to correct for differences in citation behavior between fields of science, etc.) has as a side-effect that the figures– which are sometimes given in the legenda– are also not easy to interpret.

Actually, I came to this question while engaged in a study of the development of journal-journal citations, when I noticed that despite clear results in the factor analysis, different clustering techniques led to rather different results.[11] Because of this, we decided to discard cluster analysis in that study, and to use factor analytic and multi-dimensional scaling techniques exclusively. Once the instrument for following 'the dynamics of science' at the level of journals had been developed, however, the question again arose of how to link the results which those of others who actually were and are using different forms of cluster analysis. The opportunity to overcome the problems of not having the funds necessary to replicate a co-citation study on the

ISI-tapes, nor being able to reconstruct an original data-matrix from the published articles– for the reasons noted above– was presented about when a Dutch governmental institute commissioned the ISI to perform an extensive co-citation analysis for the purpose of assessing Dutch national R & D-efforts.[12] In this study we were able to identify 37 core documents for co-citation analysis in 'chemical physics' without further help from ISI, and to replicate the study straightforwardly using the on-line facilities on DIALOG. A comparison of these data with the simple citation counts and with an analysis of journal-journal citation aggregates in the same field can lead to a better insight into the relevant dimensions in the mapping of science and their relations. By repeating the co-citation analysis, which was originally done for 1981 and 1982, also far 1978 (and 1979) and for 1984 (and 1985), we will be able to compare the dynamic properties of citations, co-citations, and journals in this field as well.

The programme of mapping science

The dynamic mapping of science using the data in the *Science Citation Index* was put on the research agenda of science studies by *De Solla Price* in the maid 1960s. About 1965 *Price* formulated some hypotheses about the structural properties of journals, publications, author's names, and citations, which could be operationalized within the framework of *Garfield*'s *Science Citation Index.*[13] A central idea ever since has been that these scientific databases reflect multidimensional spaces (of journals, etc.) which correspond to disciplines and specialties. What accounts for the structures of these spaces (the units of analysis) was, in the opinion of *Price,* still an open question. He pointed to three ordering mechanisms: 1. journals; 2. invisible colleges; and 3. the notion of a 'research front' versus accepted knowledge.

This latter element introduced the idea of qualitatively different layers of science, and hence pointed to the need of theorizing before we can say which variable is being indicated by what indicator. However, since the problem of describing structure is prior to that of describing dynamics, the focus in the scientometric enterprise has been on 'mapping' the relations among journal and 'invisible colleges'.

Journals

Price himself strongly advocated studying the relations among journals as the most fruitful entrance point for a study of the structure and dynamics of science.[14]

This line of research was developed in the early 1970s by *Narin* and his colleagues at Computer Horizons Inc. They worked on an experimental tape made by ISI for the development of what is now well known as the *Journal Citation Reports,* which consist of listings of the aggregate citations of journals to journals, and which since 1974 have formed a separate volume of the *Science Citation Index* and the *Social Science Citation Index*. *Narin* used the experimental tape of the last quarter of 1969 to construct hierarchies of journals.[15]

The results of this analysis exceeded expectations: a large amount of consistency was found between the citing characteristics of journals in the different scientific fields, with quite distinct boundaries between fields, and a few well known cross disciplinary journals (*Science* and *Nature*) as cross field information links. Within disciplines the journals form fully transitive hierarchies with very few relational conflicts. In a subsequent article[16] these authors tried to cluster the journals with the help of a computer programme. In this study they extensively reported on the problems involved in choosing the right clustering algorithm. Eventually they decided to combine nine different techniques for clustering and to define a similarity measure between journals which is essentially a linear combination of the outcomes of these different techniques. However, they had to admit that "the characteristics which two journals frequently clustered together have in common may simply be their difference from the rest of the set, rather than a similarity with each other."[17] Although by manipulating some parameters in a 'trial and error' way they managed to obtain some beautiful pictures,[18] by the end of this article the authors had to introduce an ad hoc hypothesis about the existence of non-cognitive (e.g., national) characteristics in order to explain their results. However, this hypothesis was no explanation of the problems they encountered. To understand what is at stake, we have to look more carefully at the datamatrices which form the input for their analysis.

Typical of citation-studies–at various levels of analysis but also at the level of journals–is the large amount of *missing values* in the matrix. Journals within one specialty cite each other heavily, but between specialties only the major–and most of the time the leading–journals constitute the network. As a consequence, the interjournal citations of non-leading journals in different specialties are usually comparatively low. (To give the reader an impression of such a journal-journal matrix we refer to Table 1, which shows the matrix for the area which we will examine in detail in a later section.) It is exactly this typical structure of the matrix which makes it possible to find the relations which *Narin* and others have reported.[19] However, most cluster analyses, including the majority of the ones *Narin* used in his 'linear combination' (see above), commonly start by making a distance matrix from the datamatrix, using Euclidean metrics. Since missing values do not add to the Euclidean distance between two cases, those cases with large amounts of missing values end up with small distances among them, and when this is the cluster criterion (as for example in single linkage clustering), clustering starts at this end. Hence, as has been correctly noted by *Small* et al.,[20] what one is clustering is the hierarchical

Table 1
Journal-journal citations for 19 'chemical physics' journals in 1981

(CITED ↓)	CP1	CP2	CP3	CP4	CP5	PR1	PR2	PR3	PR4	MP1	MP2	SP1	SP2	SP3	CH1	CH2	CH3	CH4	VP1 (CITING →)
CP1	14532	2833	3745	2871	1866	1046	364	0	0	845	93	388	310	872	1982	325	170	49	923
CP2	910	2353	440	204	63	0	14	0	0	0	0	27	11	53	980	532	170	34	30
CP3	2651	770	1969	997	386	189	69	0	0	176	26	73	40	160	753	57	36	26	149
CP4	986	216	502	780	0	49	14	0	0	78	12	0	0	50	139	0	0	0	0
CP5	1100	211	459	316	1151	117	0	0	0	58	11	0	43	47	214	11	25	0	180
PR1	1048	60	243	166	138	3240	380	26	33	1529	292	80	146	597	0	0	0	0	46
PR2	759	94	247	99	74	1330	2782	1838	2044	410	344	1316	771	3805	0	0	0	0	22
PR3	0	0	0	0	0	56	572	3071	1987	0	229	0	0	0	0	0	0	0	0
PR4	0	0	0	0	0	52	423	1897	4059	0	81	0	0	97	0	0	0	0	0
MP1	444	0	158	132	63	1260	159	0	14	2325	307	18	0	0	0	0	0	0	27
MP2	56	0	37	0	0	121	18	23	14	84	426	23	12	56	0	0	0	0	15
SP1	188	0	98	25	12	25	318	0	0	0	24	1361	529	1817	0	0	0	0	0
SP2	157	0	57	19	28	69	209	14	22	0	21	522	1497	1297	0	0	0	0	0
SP3	610	75	188	79	55	270	1046	57	74	29	60	2217	1544	7854	68	9	0	0	0
CH1	1226	2198	913	366	136	0	21	0	0	20	0	0	12	661	15305	355	6914	3109	81
CH2	62	192	44	6	0	0	0	0	0	0	0	0	0	0	86	584	14	0	0
CH3	0	85	0	0	0	0	0	0	0	0	0	0	0	0	2157	20	4606	1674	0
CH4	0	0	30	0	0	0	0	0	0	0	0	0	0	0	2010	0	2372	2571	0
VP1	583	115	236	151	185	43	16	0	0	63	21	0	0	14	102	0	0	0	1265

position of journals and not their subject structure. Of course, if one stops clustering at a certain value, for example, by specifying the maximum size of the clusters or the number of clusters in advance, the results may very well show some other clusters which do represent subject areas, precisely because single linkage clustering starts with 'chaining' all the more marginal cases in the first cluster. Therefore, one can easily predict that a cluster analyst of citation data who uses these methods will get stuck with at least one major cluster which he cannot easily interpret, and it is interesting to take a careful look at the ad hoc hypotheses which have to be introduced to cover this failure of the method.

Actually, *Narin,* probably becoming aware of these problems, when he started to build his analytic version of the *SCI* on the basis of the 1973 tape, dropped the project on clustering journals in favor of a more pragmatic approach to delineating subsets of journals.[21]

Invisible colleges

Small et al. went on to say that "(t)he co-citation maps (. . .) are designed specifically to reflect subject similarities and disciplinary structures."[22] The theoretical notion which has guided the selections made to cluster the *SCI* in terms of co-citations is *Price*'s conjecture that there is an inherent maximum size limitation to an invisible college.[23] *Price* argued that in groups larger than about 100 members, interpersonal communication between the members becomes difficult if not impossible, leading to the breaking up of the group into smaller subgroups.[24] Proponents of co-

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Legend to Table 1

CP CHEMICAL PHYSICS
CP1 Journal of Chemical Physics
CP2 Journal of Physical Chemistry
CP3 Chemical Physics Letters
CP4 Chemical Physics
CP5 Molecular Physics

PR PHYSICAL REVIEWS
PR1 Physical Review A
PR2 Physical Review Letters
PR3 Physical Letters B
PR4 Physical Review D

MP MOLECULAR PHYSICS
MP1 Journal of Physics B: Atomic and Molecular Physics
MP2 Physica Scripta.

SP SOLID STATE PHYSICS
SP1 Solid State Communications
SP2 Journal of Physics C: Solid State
SP3 Physics Review B

CH CHEMISTRY
CH1 Journal of the American Chemical Society
CH2 Journal of the Chemical Society: Faraday Transactions
CH3 Journal of Organic Chemistry
CH4 Tetrahedron Letters

VP VARIOUS PHYSICS
VP1 Journal of Molecular Spectroscopy

citation analysis believe that such 'invisible colleges' as structural units of science, can be described by co-citation analysis. The detailed maps which they arrive at should therefore be validated at the level of the scientific enterprise. Co-citation analysis is then believed to produce a representation of the actual cognitive structure as it is perceived by practicing scientists.

The technique of co-citation analysis as introduced into science studies in 1974 by *Small* and *Griffith*[25] is fundamentally simple: by citing two documents in one article an author establishes a co-citation-link. One can count how many times this happens in a certain year very easily by using a Boolean AND in the search. So, for n cited papers, you get $n \times (n - 1)/2$ possible combinations (the lower triangle of a datamatrix), because the citations of A AND B are the same as the citations of B AND A.[26] Again, in empirical and sensible cases, most of the cells will be empty. For example, in the prototype study of 1974, non-zero values were found in only 1.2% of the cells.[27]

However, the authors of that study were very clear about their methodological purpose: without any *a priori* assumptions concerning the existence of specialties or 'invisible colleges' they wanted to prove that such structures–which had been hypothesized on other grounds[28]–did exist. At the end of their article they claimed that "the very existence of document clusters which, by definition, have a high degree of internal linkage, is strong evidence for the specialty hypothesis."[29] But this is a fallacious argument because a cluster analysis will always generate a cluster structure; the real question is to determine what the structure represents.

Probably in order to test their specialty thesis as strongly as possible, *Small* and *Griffith* chose 'single linkage clustering' as a basic technique. 'Single linkage clustering' will guarantee that any case including even one non-zero cell in a row (in many cases a value of 1) will cluster, but as a result, this technique is well known to produce 'straggling' clusters–the effect is called 'chaining'–because the purpose of the algorithm is to include the incidental points.[30] Tight 'minimum variance' clusters require other forms of cluster analysis. Hence, the effects we described in the former section (concerning journals) emerge *a fortiori*.

Unfortunately, the original matrices for these analyses have never been published, so it is not possible to follow the arguments which guided these authors when they denominated the clusters. However, we can see the problems we might expect with single linkage clustering emerging when we follow the text: "The largest grouping by far, at all levels, is biomedicine. It is, however, a relatively loosely knit cluster with many sub-clusters and a low percentage connectedness (0.69%). Since, by definition, the links *between* clusters are weaker than links *within* clusters, a large cluster like this should break up as the co-citation threshold is raised. However, this step, which is successful for the other subject areas [which are less marginal–L.], is only partially successful for the biomedical grouping. (. . .)"[31] "With the exception of the papers which, at each level, were clumped in the large biomedical cluster, most groupings were readily recognized after a couple of paper titles were located; . . ."[32]

This was all in 1974, at the start of this programme and under the influence of a specific theoretical purpose. But the alarming thing is that these early methodological decisions about clustering have never been fundamentally revised, but only adapted incrementally to produce better representations. The noted (1985) reviews claim major improvements in the methodology being used in cluster analysis, making it now possible to generate *The Atlas of Science* by 'clustering the clusters' and by overlaying maps from different periods. These improvements, however, have only to do with limiting the maximum cluster size ('variable level clustering'[33]), and correcting for differences in citation behavior between specialties ('fractional counting'[34]). The basic statistical method is essentially still the same. More recent techniques to improve single linkage clustering, such as mode analysis,[35] have been discarded by the authors who argue that such techniques are not well suited for large databases such as the *Science Citation Index.*

This argument is correct in itself: if one has to break down an enormous amount of data, one needs one clustering method or another to accomplish this. This is good practice if one wants to construct a bibliographic retrieval system from the *Science Citation Index.* The *Atlas of Science* is a superior retrieval system in its graphical, and in the near future three-dimensional representations, which are produced by multidimensional scaling techniques. Because the programmes to generate these pictures have inherent limitations to the number of cases they can handle at present, it also makes sense to set a maximum cluster size. However, once all these decisions have been taken, it becomes very difficult to say what one is actually producing in the end in terms of 'maps of science'.

When we look more carefully at the major results from the cluster analysis-efforts in the mentioned review articles, we find the same types of ad-hoc hypothesis which we predicted in the conclusions of the former section. More than once, it is emphasized that the larger part of the structure of the natural sciences is "interdisciplinary,"[36] with chemistry "to be considered the model of an interdisciplinary science".[37] This result (produced by 'clustering the clusters' twice with single-linkage clustering) cannot be validated at all at the level of journal-journal citations; this is probably a direct consequence of problems with the clustering methods, despite the rigorous limitations which have been placed upon chaining. Nevertheless, without any further argument, the authors claim that this picture offers "a much more balanced representation of major scientific disciplines than was achieved in any of the previous clustering and mapping experiments."[38] Actually, in a later section, the authors conclude once again with a methodological argument for sticking to 'single linkage clustering' despite the recognized problems of chaining and isolates, when they state that they do *not* want to treat their database (the *SCI*) as a structured database[39] –which is precisely what it is, however. The project of establishing an analytical grid of journals and nations, as has been pursued by *Narin*'s Computer Horizons, is turned down in favor of an inductive approach using the database as a kind of garbage can. However, the structures then to be found have to be validated extensively, particularly when they are counter-intuitive. In our opinion, the results are an artifact of the applied method, which leads to 'interdisciplinary' clusters on the one side and to strong–and sometimes isolated–disciplinary clusters on the other.

"The Cancer Mission"

One serious attempt to study co-citation maps and what they might represent was undertaken by *Studer* and *Chubin* in their study of *The Cancer Mission.*[40] In the relevant chapter they explained again and again, on the basis of a factor analysis of the co-citation matrix, that co-citations represent both a cognitive and an institutional structure. As they concluded, the institutional component seems to be linked to identifiable institutes (laboratories) and *not* to 'invisible colleges'.[41] Moreover, they raised the hypothesis that "cocitation cannot be taken at face value as indicative of the intellectual state of a field, specialty, or problem domain. Cocitation clusters may simply be isolating the early institutional contexts of scientific developments, that is, the most 'coherent groups'[42] and, later, the most visible 'invisible colleges'."[43]

Studer and *Chubin* used factor analysis as a statistical method (as do the later studies of *Griffith* et al.[44]). Factor analysis (or 'vector analysis', as they call it) also in our opinion, leads to a clearer view of underlying structures if (and only if!) one is able to separate clear factors. At the end of their study, however, these authors had to admit that they had difficulties precisely in terms of this criterion in comparing between levels, because at none of the levels could the factor-structure be used as a baseline. Amazingly enough they did not consider seriously the journals involved, probably because as sociologists they were not concerned with documents and their interrelations but rather with their authors as units of analysis. In the next section, we will link the result of a co-citation analysis to that of a journal-analysis.

The empirical evidence

Following its publication of a study of the output of state financed medical research in 1983,[45] the Dutch Advisory Council for Science Policy (RAWB) decided to commission a comprehensive explorative study to the use of S & T-indicators for assessing national R & D-efforts.[46] As part of that study, a co-citation model for 1981 and 1982 was constructed by the ISI and assessed for the share of Dutch publications.[47] Although some provisions were taken in the initial steps of the construction of this database to restrict the analysis to areas which were relevant because of Dutch activities, the eventual analysis was done quite straightforwardly.[48] 'Maps of science' were produced and published. Ever since, these maps have been hotly debated by Dutch scientists and science policy makers, and serious efforts have also been put into several 'validation studies'.[49]

From the 3029 clusters, we selected 7 clusters in such a way that they (1) formed one 'supercluster',[50] (2) consisted of a considerable yet nevertheless manageable amount of core documents (namely 37), and (3) belonged to one of the areas on which the later RAWB-study focussed. Actually, 4 of the 7 clusters in our sample (covering 31 of the 37 core documents) are included in the map of atomic and molecular physics which is the most widely published part of the RAWB study, among others in *Scientometrics.*[51] (For a list of the clusters see Table 2).

Table 2

Cluster number	No. of core documents	Specialty
121	2	Collision broadening of principal series lines of metals by noble gases
231	2	Pressure broadening and shifting in microwave and infrared spectra
325	6	Rainbows in rotationally inelastic scattering
523	2	Spectroscopy and ionization studies in laser-produced plasmas
541	11	Effects of neutral non-resonant collisions on atomic spectral-lines and potentials
1010	11	Mechanisms of atomic resonance fluorescence
1871	3	Collisions of Rydberg atoms in molecules

A full list of the core publications, their cluster numbers, and their citation and co-citation ratios is given in Table 3. In the fourth and fifth column of this latter table the citation counts for these articles over 1981 + 1982 as indicated in the ISI/RAWB-study are compared with those we found on-line. Our results are on the average some 7% lower than those of the ISI, but overall the two distributions are highly compatible. (We probably missed a few citations because of differences in file handling between the ISI and DIALOG.)

Table 3
37 core documents

		clus nr	citations ISI/ RAWB	citations this study	co-citations (DIALOG)	co-cit/ cit
1	Alekseev VA, Sov Phys JETP, 22 (1966) 882	121A	18	17	20	1.18
2	Omont A, J Phys-Paris, 38 (1977) 1343	121B	33	32	35	1.09
3	Anderson PW, Phys Rev, 76 (1949) 647	231A	48	47	51	1.09
4	Tsao CJ, J Quant Spectrosc RA, 2 (1962) 41	231B	42	42	36	0.86
5	Arthurs AM, P Roy Soc Lond A Mat, 256 (1960) 540	325A	60	58	48	0.83
6	Bergmann K, J Chem Phys, 71 (1979) 2726	325B	25	24	41	1.71
7	Bergmann K, J Chem Phys, 72 (1980) 4777	325C	32	32	41	1.28
8	Buck U, J Chem Phys, 72 (1980) 1512	325D	20	19	33	1.74
9	McGuire P, J Chem Phys, 60 (1974) 2488	325E	66	64	65	1.02
10	Parker GA, J Chem Phys, 68 (1978) 1585	325F	58	58	58	1.00
11	Bates DR, P Roy Soc A, 267 (1962) 297	523A	39	36	17	0.47
12	McWhirter RWP, P Phys Soc Lond, 82 (1963) 641	523B	19	16	12	0.75
13	Baylis WE, J Chem Phys, 51 (1969) 2665	541A	57	55	140	2.55
14	Buck U, Z Phys, 208 (1968) 390	541B	23	20	79	3.95
15	Czuchaj E, Z Naturforsch A, 34 (1979) 694	541C	22	19	99	5.21
16	Hedges REM, Phys Rev A, 6 (1972) 1519	541D	35	33	90	2.73
17	Pascale J, J Chem Phys, 60 (1974) 2278	541E	59	53	131	2.47
18	Sando KM, Phys Rev A, 7 (1973) 1889	541F	20	18	62	3.44
19	Saxon RP, J Chem Phys, 67 (1977) 2692	541G	20	17	65	3.82
20	Smalley RE, J Chem Phys, 66 (1977) 3778	541H	23	17	63	3.71
21	Szudy J, J Quant Spec, 15 (1975) 641	541I	44	40	110	2.75
22	Tellinghuisen J, J Chem Phys, 71 (1979) 1283	541J	26	23	80	3.48
23	York G, J Chem Phys, 63 (1975) 1052	541K	26	23	78	3.39
24	Burnett K, Phys Rev A, 22 (1980) 2005	1010A	21	21	61	2.90
25	Burnett K, Phys Rev A, 22 (1980) 2044	1010B	23	23	66	2.87
26	Carlsten JL, Phys Rev A, 15 (1977) 1029	1010C	33	30	77	2.57
27	CohenTannoudji C, J Phys B Atom Mol Ph, 10 (1977) 345	1010D	48	44	79	1.80
28	Courtens E, Phys Rev A, 15 (1977) 1588	1010E	20	17	43	2.53
29	Grove RE, Phys Rev A, 15 (1977) 227	1010F	20	18	40	2.22
30	Mollow BR, Phys Rev, 188 (1969) 1969	1010G	65	60	104	1.73
31	Mollow BR, Phys Rev A, 12 (1975) 1919	1010H	22	19	45	2.37
32	Omont A, Astrophys J, 175 (1972) 185	1010I	38	33	80	2.42
33	Schuda F, J Phys B Atom Mol Ph, 7 (1974) L198	1010J	24	22	58	2.64
34	Wu FY, Phys Rev Lett, 35 (1975) 1426	1010K	22	20	39	1.95
35	Gallagher TF, Phys Rev A, 16 (1977) 1098	1871A	26	26	34	1.31
36	Jeys TH, Phys Rev Lett, 44 (1980) 390	1871B	26	26	35	1.35
37	Littman MG, Phys Rev Lett, 41 (1978) 103	1871C	27	26	29	1.12
			1230	1148	2244	1.95

Table 4
Co-citation matrix for 37 core documents over 1981 plus 1982

cluster-number																																					
(121A)	0	13	0	0	0	0	0	0	0	0	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
(121B)	13	0	0	0	2	0	0	0	0	0	1	0	3	0	1	2	3	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	2	1
(231A)	0	0	0	25	0	1	1	0	3	0	0	0	2	1	2	1	0	1	0	0	2	0	0	2	2	2	1	1	0	1	0	2	0	0	1	0	0
(231B)	0	0	25	0	0	1	1	0	2	0	0	0	0	0	0	1	0	1	0	0	2	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
(325A)	0	2	0	0	0	2	3	5	17	13	0	0	4	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(325B)	0	0	1	1	2	0	16	7	5	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(325C)	0	0	1	1	3	16	0	5	7	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(325D)	0	0	0	0	5	7	5	0	10	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(325E)	0	0	3	2	17	5	7	10	0	20	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(325F)	0	0	0	0	13	9	8	6	20	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(523A)	1	1	0	0	0	0	0	0	0	0	0	12	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
(523B)	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(541A)	1	3	2	0	4	0	0	0	1	1	0	0	0	12	16	10	31	6	10	7	13	9	9	1	0	3	0	0	0	0	0	1	0	0	0	0	0
(541B)	0	0	1	0	0	0	0	0	0	0	0	0	12	0	19	6	10	4	2	4	9	6	3	0	1	1	0	0	0	0	0	1	0	0	0	0	0
(541C)	0	1	2	0	0	0	0	0	0	0	0	0	16	19	0	9	15	5	5	6	7	7	5	1	0	1	0	0	0	0	0	0	0	0	0	0	0
(541D)	1	2	1	1	0	0	0	0	0	0	1	0	10	6	9	0	13	10	3	4	14	5	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(541E)	1	3	0	0	1	0	0	0	0	0	0	0	31	10	15	13	0	4	11	8	10	10	13	0	0	0	0	0	0	0	0	1	0	0	0	0	0
(541F)	0	1	1	1	0	0	0	0	0	0	0	0	6	4	5	10	4	0	3	3	12	4	7	0	0	0	0	0	0	0	0	1	0	0	0	0	0
(541G)	0	1	0	0	1	0	0	0	0	0	0	0	10	2	5	3	11	3	0	9	3	10	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(541H)	0	1	0	0	0	0	0	0	0	0	0	0	7	4	6	4	8	3	9	0	2	13	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(541I)	0	1	2	2	0	0	0	0	0	0	0	0	13	9	7	14	10	12	3	2	0	5	6	5	4	5	0	2	0	2	0	6	0	0	0	0	0
(541J)	0	1	0	0	0	0	0	0	0	0	0	0	9	6	7	5	10	4	10	13	5	0	9	0	0	0	0	0	0	0	0	1	0	0	0	0	0
(541K)	0	1	0	1	0	0	0	0	0	1	0	0	9	3	5	10	13	7	7	6	6	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(1010A)	0	0	2	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	5	0	0	0	19	8	2	2	1	4	3	11	0	1	0	0	0
(1010B)	0	0	2	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	4	0	0	19	0	10	3	4	1	5	3	12	0	1	0	0	0
(1010C)	0	0	2	0	0	0	0	0	0	0	0	0	3	1	1	0	0	0	0	0	5	0	0	8	10	0	7	8	3	9	1	15	2	2	0	0	0
(1010D)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	7	0	9	6	22	8	6	11	4	0	0	0
(1010E)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	4	8	9	0	1	6	0	5	3	2	0	0	0
(1010F)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	6	1	0	8	7	2	7	4	0	0	0
(1010G)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	4	5	9	22	6	8	0	10	9	16	12	0	0	0
(1010H)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	8	0	7	10	0	3	8	2	0	0	0
(1010I)	0	0	2	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	6	1	0	11	12	15	6	5	2	9	3	0	2	2	0	0	0
(1010J)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	11	3	7	16	8	2	0	9	0	0	0
(1010K)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	4	2	4	12	2	2	9	0	0	0	0
(1871A)	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	13
(1871B)	1	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	14
(1871C)	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	14	0

Table 5

Varimax rotated factor matrix after rotation with kaiser normalization
(37 core documents isi/rawb-study)

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5	FACTOR 6	FACTOR 7	FACTOR 8	FACTOR 9
121A	-.02918	-.05634	-.01020	-.04880	-.08464	.13269	.10877	-.06257	[.76945]
121B	-.06137	-.13244	-.02712	-.12367	-.10202	.21746	.24320	-.06953	<-.58064 >
231A	-.01436	-.01414	-.00659	-.01873	.03629	<-.90720 >	.06956	.05357	-.03021
231B	-.01343	-.01917	-.00521	-.02305	.05093	.07690	<-.88288 >	.05578	-.01380
325A	-.00626	-.03626	.00520	[.38814]	.10569	.07301	.13903	.10568	.13866
325B	-.05653	-.01858	-.04053	[.31225]	.04622	-.00336	-.08013	.05620	-.02060
325C	-.02525	-.03745	-.04289	[.35042]	.06391	.01843	.03409	.07569	-.01245
325D	-.01483	-.04354	-.04253	[.42860]	.08805	.07290	.10686	.10088	-.00818
325E	-.06067	-.02850	-.04333	[.30793]	.02405	.04650	-.10875	.04188	-.11513
325F	-.01583	-.04519	-.03608	[.37750]	.06899	.05657	.11848	.08364	-.02856
523A	-.03360	-.04113	-.02785	-.04558	.17891	.08542	.08151	-.80775	.02993
523B	-.03647	-.05669	-.05229	-.06177	<-.81072 >	.06949	.07849	.18405	.03824
541A	-.02542	-.02742	[.26655]	-.02252	.02287	.11566	-.04790	.05796	-.02221
541B	.02118	-.03909	[.26963]	-.02756	.06804	.01683	.04320	.09535	-.05627
541C	-.02292	-.02079	[.28011]	-.02935	.06099	.04686	-.01934	.04752	.03778
541D	-.00986	-.04435	[.28004]	-.04449	.00112	.02908	-.01178	.10258	-.01289
541E	-.02119	-.02917	[.26726]	-.02132	.06784	-.02722	.10107	.03905	.04009
541F	.02752	-.05153	[.26851]	-.03927	.07078	-.03124	-.04059	.04643	.02501
541G	-.07282	-.00103	[.28491]	-.02316	.04019	.07640	.06902	.07030	-.01442
541H	-.08808	.00711	[.27425]	-.03349	.03754	.04413	.04766	.04322	.01190
541I	.13759	-.06107	[.26787]	-.04056	.07269	-.06093	.03151	.02570	.02631
541J	-.06232	-.01046	[.27916]	-.03847	.02888	.03844	.02941	.04553	-.00128
541K	-.06107	-.01217	[.29889]	-.02846	.05387	.02157	.05232	.04353	-.00376
1010A	[.49592]	-.11607	-.01522	-.00549	.02387	.02298	.03904	.03670	-.01206
1010B	[.43224]	-.06387	-.02210	-.01506	.01662	-.02613	-.00634	.01242	.00786
1010C	[.41414]	.03765	.00135	-.01629	.04816	.02836	.03831	.05205	.00248
1010D	.01155	[.35653]	-.01994	-.03154	.06010	.01173	.01376	.06168	.00241
1010E	[.31238]	.16138	-.01730	-.01308	.04674	.08375	.04804	.06228	-.01040
1010F	-.04249	[.40722]	-.01951	-.03331	.03235	.03584	.03979	.04460	-.01002
1010G	.10954	[.24532]	-.03613	-.03747	-.03307	.04511	.01498	-.01492	-.02167
1010H	.00600	[.37787]	-.01786	-.02624	.05250	.04196	.05825	.06143	-.00428
1010I	[.42978]	.01835	-.00349	-.01861	.03148	.06704	.00113	.04797	-.00891
1010J	-.07870	[.39633]	-.01643	-.03130	.03534	.02905	.03425	-.04679	-.00782
1010K	-.07527	[.42443]	-.00846	-.02659	.07293	.02633	.04497	.07882	.00028
1871A	-.09874	-.16205	<-.22258 >	<-.23856 >	[.22639]	.13105	.03033	[.27218]	-.03452
1871B	-.10216	-.14514	<-.20469 >	<-.22065 >	[.20180]	.03054	.10041	[.24912]	.15033
1871C	-.09692	-.16725	<-.22870 >	<-.24363 >	[.33888]	.08630	.12089	[.23424]	.00040

[ ] Factor Loading
< > Negative Factor Loading

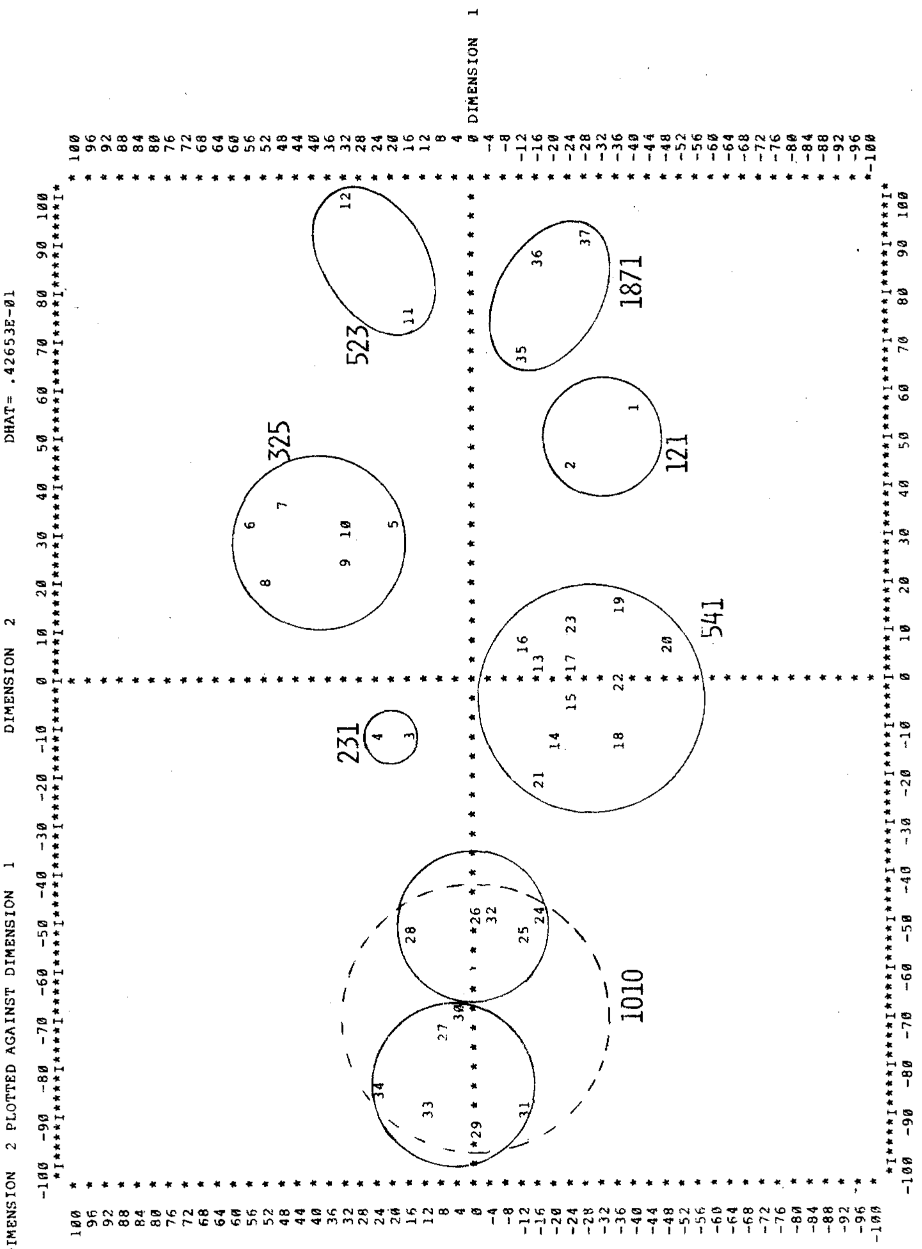

Fig. 1. Minissa for co-citations of 37 documents from rawb-study over 1981 plus 1982

Column 6 of this table presents the total co-citations for the respective core document as found on the DIALOG installation. The last column gives the ratio between co-citations and citations for each document. This column reminds the reader that a co-citation necessarily refers to a citation, but that there may be many co-citation links to the same citation. (See also note 26.)

Because the ISI/RAWB-study measures only the sum of normalized co-citations ('strengths'[52]) for intercluster links, it is not possible to calculate the full co-citation-matrix from these data. Hence, we will use the results from our own DIALOG-search from now on.[53] By searching for all possible pairs of core publications with an AND-operator, the co-citation-matrix as presented in Table 4 can be reconstructed. (Because our treatment of this matrix will now become more formal, we will indicate the core documents according to their cluster number and an alphabetical indicator according to their sequence number within the cluster.)

Visual inspection of the matrix does indeed reveal a cluster structure. However, further analysis reveals that there are not seven but eight clusters: cluster 1010 consists of two clusters.

Actually, when we do a factor-analysis[54] of this matrix, the two main factors (explaining together 59.5% of the common variance) are precisely the two groups of variables which have to be distinguished within cluster 1010 (Table 5).[55] Factor-analysis further reveals factorial complexity for cluster 1871, and clear cluster structures for clusters 541 and 325. The other clusters are more diffuse being connected with later factors which explain only minor parts of the common variance.

In Figure 1 the same data-matrix is used as input for multidimensional scaling, which produces a proportional picture of the distances between these 37 core documents in terms of co-citation-scores, with remarkably low stress.

The related journal structure

If we want to analyze the related journal structure, there are two ways to proceed. The 37 core documents involved have been published in 11 important journals all of which still exist, although sometimes under different names.[56] The *Soviet Physics JETP*, however, from which one of the core publications comes, is not covered in the Citing Journal Package of the *Journal Citation Reports* and was therefore left out of consideration here. Of the remaining 36 core documents, 11 have been published in the *Journal of Chemical Physics*, 9 in *Physical Reviews A*, and 2 in *Physical Review* (before the division of this journal into different parts in 1970). The other 8 journals contain only 1 or 2 of the core publications each. Therefore, we can also proceed by taking the *Journal of Chemical Physics* and *Physical Reviews A* as entrance journals for the analysis of a journal-journal network, using a method of analysis which we have developed elsewhere.[5 7] If we pursue this strategy we find a related journal network of the 19 journals listed in the legend of Table 1. The reader should notice that we are now dealing with two sets of journals in each of which the relations among the elements are defined at different levels: at the one hand, we have 10 journals which are related among eachother through co-citations of documents which have been published in these journals, and at the other hand, we have a related journal network of 19 journals which represents the relevant subject area at the level of journal-journal citations. The two sets have an intersection of 4 journals corresponding to 27 of the 37 original core documents.

We will now use both sets of journals to answer specific questions. The journal-journal-structure of the 10 X 10 matrix of related journals, leads to a factor structure which is difficult to interpret and sensitive to the choice of parameters in factoring and in finding solutions (such as orthogonal versus oblique).

If we construct the same journal-journal citation-matrix for other years, we of course do find a very similar matrix with about the same results of the analysis (see Table 6 for the Pearson correlations between these matrices, which are above 0.99).

Our interpretation of these results leads us to conclude that we are looking here at very stable relations among some important journals. However, the structure of these relations cannot be explained by variance *within* these data-matrices, because the elements (journals) have here been selected for their relations at a different level of analysis (i.e., of co-citations). Part of the structure among these core-publication

Table 6
Pearson correlation coefficients for the journal-journal citations among the 10 related journals

	1978	1981	1984
1978	1.0000 (0) P=******	.9977 (100) P= .001	.9967 (100) P= 0.001
1981		1.0000 (0) P=******	.9984 (100) P= .001
1984			1.0000 (0) P=******

journals may be determined by the other relations of these journals. Therefore, if we want to analyse the relations among them, we must take into account a full set of the journals which form a network at the level of journal-journal-citations, and not only those selected because they are related to a network at the level of co-citations.

However, when we analyze the journal-journal-citations of the 19 journals which form the related journal-*network*, we find a very nice factor structure (Table 7). Five factors emerge which can all be easily recognized as the specialties involved, and all these factors explain a considerable part of the common variance. A first factor, explaining 33.6% of the common variance, stands for 'chemical physics'. 'Solid state physics' is the second factor; 'molecular physics' the fourth, and more general journals on 'physics' and 'chemistry' constitute the third and fifth factor, respectively. The last factor still explains more than 11% of the common variance.

Hence, this is in itself a clear structure. However, more than the ten journals directly related to the co-citation core-documents, this structure changes gradually from year to year: of the 19 journals included in 1981, only 16 still belong to the network in 1982, when 2 other journals have to be included if we adhere strictly to the methods for journal selection which were described in our earlier article.[58] Because we now have a sharp factor analysis revealing a clear structure in the data, we can proceed to test the different methods of cluster analysis which we discussed above: a good clustering technique should enable us to reproduce the same structure.

Table 7
Varimax rotated factor matrix after rotation with kaiser normalization
(19 'chemical physics' journals in 1981)

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5
CP1	[.44631]	.03597	.02607	.05800	-.01942
CP2	[.35418]	-.00552	.02119	-.04992	[.23287]
CP3	[.43863]	.01551	.00682	.02105	.01917
CP4	[.43837]	-.00118	.00092	.02508	-.03621
CP5	[.40434]	-.01059	-.01153	.00895	-.08749
PR1	.03731	.03983	-.04324	[.58869]	.02876
PR2	.03862	[.35031]	[.35428]	.16261	.06589
PR3	.00001	-.03934	[.63899]	-.03114	-.00728
PR4	.00241	-.04926	[.62460]	-.06261	-.01720
MP1	.02490	-.07268	-.13880	[.59011]	-.00296
MP2	-.06375	-.01733	.18752	[.48446]	-.02803
SP1	.00691	[.54514]	-.03127	-.03322	-.00990
SP2	-.01071	[.50954]	-.10363	-.06065	-.04380
SP3	.00179	[.54511]	-.02229	-.00383	.01527
CH1	.06544	.01546	.02449	.01671	[.55050]
CH2	[.17676]	-.06484	-.04020	-.14967	[.14522]
CH3	-.04022	-.01055	-.01763	.00293	[.55181]
CH4	-.06276	-.02043	-.03368	-.00409	[.52442]
VP1	[.28015]	-.07438	-.05077	-.06834	-.15446

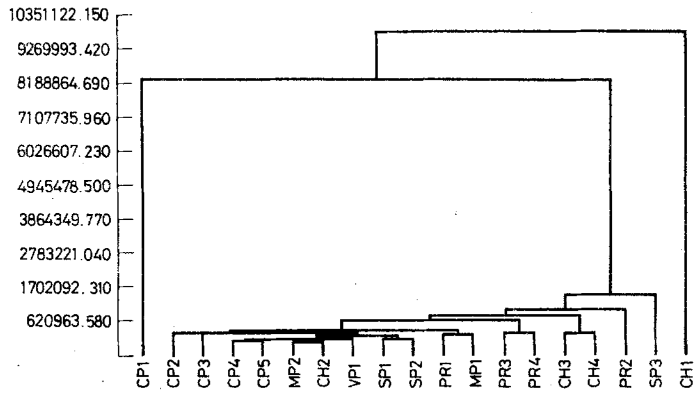

Fig. 2. Single linkage clustering of 19 chemical physics journals in 1981

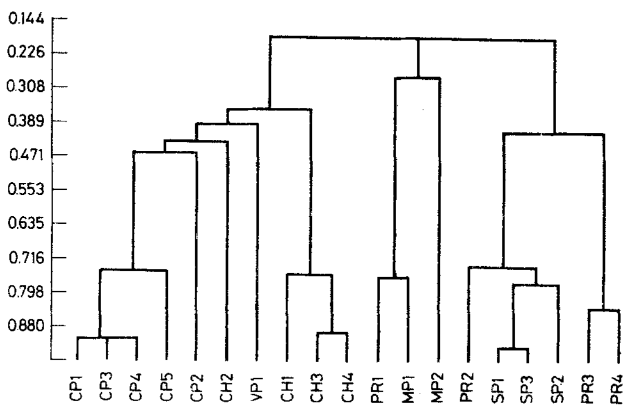

Fig. 3. Single linkage clustering from pearson correlation matrix

Figure 2 presents a dendogram using the single linkage clustering method for these data. In this dendogram we see a nice example of the growth of the first cluster as a consequence of the use of this method, by chaining. Only at the very last end do the leading 'chemical physics' and 'chemistry' journals show up as separate clusters. It also becomes clear how arbitrary any cut-off point (by variable level clustering) would be in this case.

The main point, however, is that nothing of the clear structure found in the factor analysis can be retrieved in this manner. As explained above, the reason for this is the large amount of missing values as has been demonstrated in Table 1.

If we change the similarity coefficient to a Pearson correlation, we immediately get a better picture (Fig. 3), but we only find a full representation of the journal-

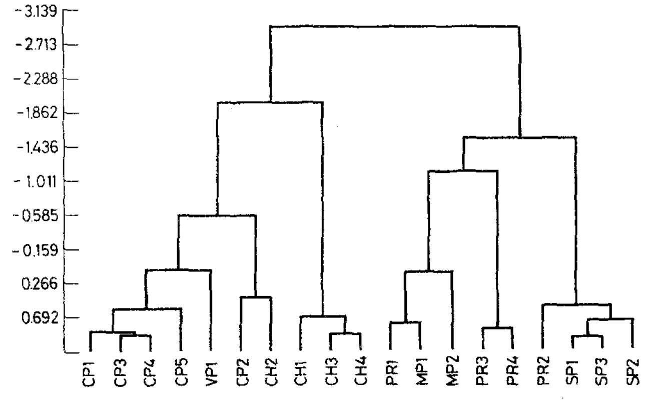

Fig. 4. Wards' method for 19 chemical physics journals in 1981 (pearson correlation)

journal structure revealed by the factor analysis if we also change the clustering method to Ward's mode of analysis (Fig. 4). In this dendogram, we find a nice division between physics journals (to the right) and chemical journals (to the left), leading to ever finer substructures of science. The links can also be traced, as revealed by the factor analysis among the different parts of *Physical Reviews* and the different specialties in physics.[5 9]

The clustering of co-citations

The advantage of the journal-structure is that its factorial structure is easy to interpret. The factors that emerge correspond to the cognitive structures among the disciplines and specialties involved, and the split is almost complete. Hence, the designation of the various factors does not give rise to serious problems. Since such a sharp split among factors is normally not the case for results of the factor analysis of a co-citation matrix, it becomes already more difficult to identify the relevant factors. Therefore, a researcher may choose not to use factor analysis for the interpretation of her data. However, despite this problem of interpretation, we can maintain that methodologically speaking, as with the journal-journal-citation matrices, cluster analysis of co-citation matrices should reveal underlying structures which are compatible with and complementary to the results of factor analysis.

If we now compare the results of factor analysis and cluster analysis (with single linkage clustering and simple Euclidean distances) on the co-citation matrix, which was generated as we discussed above, we (1) loose in the results of the cluster analysis

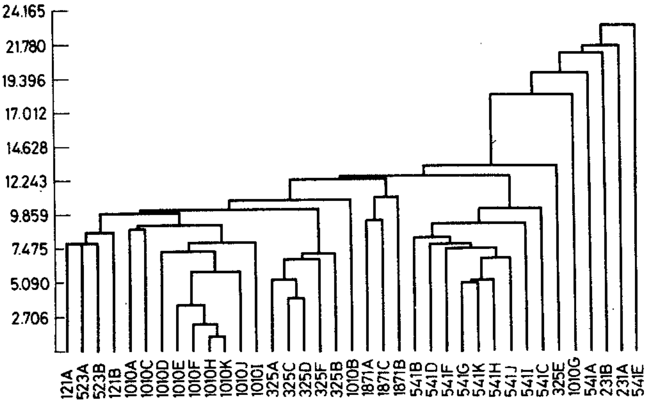

Fig. 5. Single linkage clustering of co-citations for 37 publications

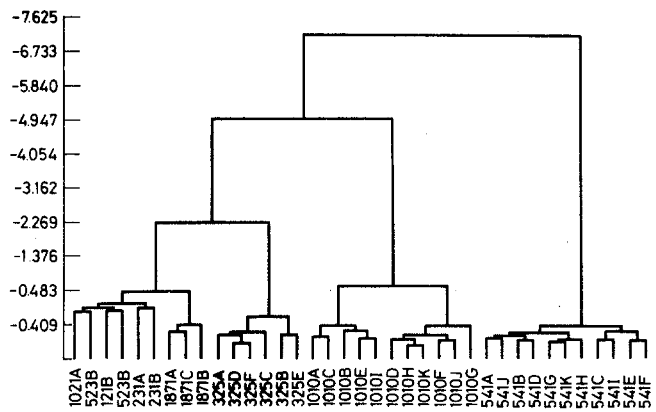

Fig. 6. Ward's method clustering of co-citations with pearson correlation matrix

(see Fig. 5), important parts of the cluster structure as revealed by the factor analysis (Table 5); (2) do not get any evidence for division into 7 or 8 clusters; and (3) although we happen to avoid 'chaining' in this case, we do find uninterpretable isolates at the upper end. Although the factorial structure (Table 5) was already less clear than in the case of the journal network, the results of the cluster analysis do not show this structure at all.[60]

Again, simply by switching to Ward's method of analysis on the basis of a Pearson correlation matrix, we can construct a dendogram which gives a full representation of the structure revealed by the factor analysis (Fig. 6). From this picture, we also can judge the relative importance of the split within cluster 1010 as compared with the fine-structure in, e.g., cluster 325. However, this latter fine-strucutre was not revealed by the factor analysis. Therefore, in this case and using this methodology, cluster analysis is even more rewarding than factor analysis.

The argument here against the use of single linkage clustering on these citation data, taking at first the journal-journal network as a kind of base-line, may seem circular. However, the argument is not circular but indirect: because we can to some extent interpret the results of the factor analysis of data matrices of journal-journal citations, we can demonstrate in this instance how devastating for the results the choice of the wrong clustering method may prove to be, and thus we can illustrate what we argued analytically about single linkage clustering in earlier sections of this paper. Once this argument was presented, we still needed to show–as we have done in this section–that the same effects emerge when we use a co-citation data matrix.

Stability and change

As was noted in the introductory section, a third element of the programme of mapping science was to include the time dimension: once a comprehensive mapping of science was achieved, this structure was to be depicted dynamically 'to show structural change'.[61]

Studer and *Chubin* (1980) added a methodological appendix to their monograph[62] in which they focus on the question of whether one can measure change without a stable base-line. They point out that relationsips between units of analysis in science can be analyzed in networks at many levels: for example, we have networks of authors, of references, of citations, of institutes, of journals, etc. The aim of their study was to look for 'confluence' at different levels as a criterion for an accurate description of the development of 'the cancer mission' over time. However, at the end of their study they were forced to conclude that the priority (or the relative weight) of the different indices remained a problem.[63] They concluded that "the methods, like the networks, are tools for understanding, not ends in themselves".[64] Although this conclusion is of course correct, it is also a rhetorical *ultimum refugium* which leaves us with a feeling of dissatisfaction. Elsewhere,[65] we have indicated that we can indeed find a 'baseline'–the claim is that aggregated journal-journal-citations and their development over time can be used as such; but this answer raises all the more urgently the question of *how* indicators at the other levels can be linked to this 'baseline'.

As noted above, in this case the related journals of the core documents show a very stable distributions of citations among them. The Pearson correlations between

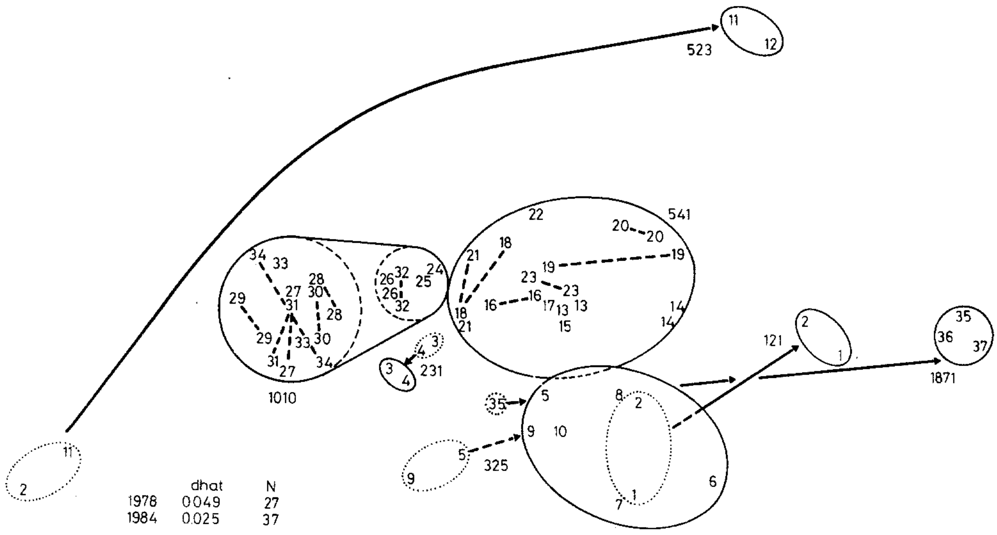

Fig. 7. Superposition of co-citation clusters for 1978 and 1984

these distributions do not differ substantially from 1.00 ($p = 0.001$). Hence, we considered this case as offering a good opportunity to explore how the citations and co-citations of these same documents develop over time.

Figure 7 presents a superposition of the multidimensional scaling for the co-citation data-matrices for 1978 (plus 1979), and 1984 (plus 1985[66]). Here, we are dealing only with 27 of the 37 core documents, since ten of them were not published before 1978. The major clusters in this case maintain stable distances from one another, while only a few smaller ones move around this stable structure.[67] Particularly spectacular is the shifting of cluster number 523, which consists of two publications from 1962 and 1963 on 'Spectroscopy and Ionization Studies in Laser-Produced Plasmas'. We wondered whether someone could find an interpretation for this change.

If we focus again on the 27 documents which exist over the whole period, we can trace the development of several distributions attached to these sets, including their citations, their co-citations, and their related journals. Table 8 presents some aggregate values, and in Table 9 the Pearson correlations between distributions are compared for these three dimensions for (1978 + 1979), (1981 + 1982) and (1984 + 1985).

The relations between the co-citation matrices are very high, and even higher than the relations among the distributions of citations of the same documents. However, if we correct by the pairwise deletion of missing data for stability which is brought about by *not* being co-cited together (the zeroes), we find correlations of the same order (0.75 over a period of six years). Of course, these are highly cited and co-cited

Table 8
Aggregated values for citations and cocitations for the ISI/RAWB-set of documents (n = 37) in (1981 + 1982) and (1984 + 1985*)

citations	1148	760
co-citations	2244	882
(co-cit/cit	*1.95*	1.16)

Aggregated values for citations and cocitations for (1978 + 1979), (1981 + 1982) and (1984 + 1985*) for the same set of core documents (n = 27)

	1978/9	1981/2	1984/5
citations	874	877	622
co-citations	1294	1324	638
(co-cit/cit	1.48	1.51	1.03)

*1985 is only included till week 50, the DIALOG-search having been done on January 30, 1986.

Table 9
Pearson correlation coefficients for different dimensions intersection 1978, 1981 and 1984

	1978	1981	1984
RELATED JOURNALS	1.0000	.9977	.9967
(N= 10)	(0)	(100)	(100)
	P=******	P= .001	P= .001
CO-CITATIONS	1.0000	.8661	.8472
(N=27*26/2)	(0)	(351)	(351)
	P=******	P= .001	P= .001
CO-CITATIONS WITH DELETION OF MISSING VALUES	1.0000	.8010	.7479
	(0)	(94)	(77)
	P=******	P= .001	P= 001
CITATIONS	1.0000	.8242	.7496
(N= 27)	(0)	(27)	(27)
	P=******	P= .001	P= .001

documents–the latter being precisely the reason why they were selected (for 1981 + + 1982).

Since we know from the literature that co-citation links sometimes change considerably over time, we were rather surprised by the stability of this set of co-citation links. In their attempt to describe 'change' in Collagen Research, *Small* et al.[68] never found more than 53% continuity between two succeeding years, and in several cases only continuities below 15%. Of course, these authors have deliberately chosen a completely different approach, clustering the whole database each year *de novo*. Moreover, part of the difference may have to be explained in terms of the fields involved, but the high turnover is also most certainly an effect of the inadequacy of the results of single linkage clustering. This method systematically underestimates the structure in these data.

Conclusions

With respect to our initial question of whether various methods for the mapping of science can be compared and eventually related, the above results lead to the conclusion that although they are less stable than inter-journal citation structures, citation and co-citation structures are both stable at the same level for this set of documents–which was chosen precisely for its co-citation characteristics! The two dimensions–or three if we take journals into account as well–are rather independent of each other, and each may have its own dynamics. 'Confluence', the criterion introduced by *Studer* and *Chubin*[69] may be a useful methodological criterion in the study of the rise of a specialty, but in our opinion it is a special case. On the basis of our more abstract comparisons of the developments of the structures in the relevant datamatrices, we are inclined to draw the conclusion that the levels seem to be rather independent of one another, both in what they indicate and in their development over time.

The differences are apparent both at the conceptual level–what do citations, co-citations, and journals represent in terms of the dynamics of sciences–and at the level of organization of the data: citations indicate one variable of a document, co-citations indicate symmetrical relations between two documents, and journal-journal citations indicate asymmetrical relations among journals. As we have shown, however, several statistical methods can be used to compare one with another. When we want, however, not only to compare and to describe the various dynamics of aggregates of citations, but also to link the different types of analysis, we are in need of a theory.

We have already mentioned *Price*'s seminal conjecture about the notion of 'accepted knowledge' versus the 'research front' as another structural element of these multidimensional spaces. We now know that this means not only that there is a dynamic introduced by the social production of knowledge, but also that there are hierarchies within each level at which we can analyse the other elements of a given structure. That has been shown to be the one argument, why single linkage clustering leads to unsatisfactory results on citation-matrices in general: the *Sciences Citation Index* and the different levels at which we can study aggregates of citations should not be conceptualized as a garbage can with individual elements, but as highly structured networks with specific hierarchical relations which can only be understood from a theoretical point of view. The use of single linkage clustering focuses the analysis on individual points of accidental linkage, which from a theoretical point of view might be within the statistical margin of error. However 'validated' the outcomes of such analyses may be, they turn the process of 'justification' upside down: the structure they find is found despite their efforts to ignore it.

I think that it is precisely the force of the structure of science which makes scientometrics, and more generally science studies, relevant also for sociometrics and general sociological theorizing. More than in other subsystems it may be possible here to develop 'indicators' for the different variables in a model. Moreover, we now possess a large body of case studies and partial theories. In recent years, an awareness has emerged that serious attempts should be made to connect the more qualitative kind of sociological theorizing, with its increasing focus on the cognitive aspects of science, with the more quantitative approach of scientometrics, characterized by its increasing awareness of the relevance of institutional factors.[70] This is, however, an even larger progamme than the one proposed by *Studer* and *Chubin:* it implies a model of science not only at its various internal levels, but also in relation to important external factors (such as funding).[71]

The development of this type of theorizing is a long-term academic goal, as opposed to the short-term need for science policy indicators in the political arena. To reach this goal, the various indicators need to be reinterpreted as operationalizations of variables, among which the relations can be specified in attempts to construct (parts of) a model, and eventually these models will have to be tested.[72]

In the meantime, we are cought in a dilemma: the relevant science policy question—can we specify the conditions under which science policy can be effective at different levels of the science systems and to what degree—can only be answered in a more comprehensive model. Because the development of such a model can only be a long-term goal, science policy makers in need of legitimation will probably have to be satisfied with ever more beautiful graphs from computers, claiming that these represent the structure and the dynamics of science. There exists a market and there is a technology available: as S & T-students, we should know then what to expect!

But I should like to caution researchers against the unreflective use of different statistical methods which sometimes—such as in the case of cluster analysis—provide results that are largely dependent on the choice of options offered by the computer programme. Or, to phrase it more dramatically: if someone presents a multidimensional scaling picture of a part of science, there remains always the technical question of how the lines drawn between the different points can be legitimized–even if the position of the various points is only a graphical representation of the cases and variables. This problem cannot be circumvened by 'validation' through interviews with experts: experts tend either to condemn them out of hand or to rationalize the pictures presented to them, whether they are bibliometric or scientometric.

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19. See also: F. NARIN, *Evaluative Bibliometrics,* Computer Horizons, Inc., Cherry Hill, 1976.
20. "There is little similarity however between the journal influence maps and co-citation maps because the former are intended primarily to show hierarchies of journal quality, and only secondarily of subject similarity." (*Op. cit.,* note 1, p. 324.)
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26. Using this–generally accepted–procedure, higher order relations (such as three or four articles being cited together) are as such left out of consideration, as the 'zero-order' relation which the co-citation constitutes in itself is also omitted (J. OBERSKI, personal communication). The latter order however, returns in a certain sense as the problem of the zero and non-zero cells in the matrix.
27. *Op. cit.,* note 25, p. 22: "Of the 1,677,196 pairs that might have been created from 1832 items (the number of possble pairs is $^1/_2\, n(n-1)$, where n is the number of documents), only 20 414 appear, i.e. co-citation shows only 1.2% 'connectedness' for this set of documents. This is evidence of the looseness of the overall structure."
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29. *Op. cit.,* note 25, p. 35.
30. 'Chaining' describes the phenomenon where areas of high density are linked together to one supercluster by accidental in-between points. This is a problem specific to single linkage clustering. Cf. B. EVERITT, *Cluster Analysis,* Social Science Research Council, Heinemann Educational Books, London etc., 1974.
31. *Op. cit.,* note 25, p. 26.
32. *Ibid.,* p. 28.
33. *Op. cit.,* note 1, p. 395; see also: J. A. HARTIGAN, *Clustering Algorithms,* John Wiley, New York, 1975, pp. 191–215.
34. *Ibid.,* p. 393 f.; see also: D. DE SOLLA PRICE, D. BEAVER, Collaboration in an invisible college, *American Psychologist,* 21 (1966) 1011.
35. Cf. EVERITT, *Op. cit.,* note 30, p. 33.
36. *Op. cit.,* note 1, p. 333 f.
37. *Ibid.,* p. 337.
38. *Ibid.,* p. 333.

39. *Ibid.* p. 338.
40. *Op. cit.* note 9.
41. *Ibid.*, pp. 204 ff.
42. *Op. cit.*, note 28.
43. *Op. cit.*, note 9, p. 223.
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47. See also: *Op. cit.*, note 3.
48. *Ibid.*
49. *Accent*, KNAW, Amsterdam, 1986; J. OBERSKI, *Cocitaties Clusteranalyse en Natuurkunde*, NIKHEF/FOM, Amsterdam, 1986.
50. A 'supercluster' is defined as the set of all clusters having 'co-citation links' with at least one document in the core cluster.
51. *Op. cit.*, note 3, p. 350–352.
52. The co-citation strength is defined as $1000 \times C_{ij}/\sqrt{C_i^* C_j}$. In the RAWB-study 'strengths' below 300 are left out of consideration.
53. It is, however, possible to calculate from our co-citation-matrix the interactions as expressed in 'strength', and to check the result against the results of the ISI-study. The two matrices obtained in this way correlate almost completely ($r > 0.99$).
54. Because the results are not very sensitive for the various parameters, the default values in SPSS have been chosen.
55. We can put cases and variables on a par because the matrix is symmetric.
56. Two core documents were published in *Physical Reviews* before its split into various sections in 1970. The analysis here has been restricted to *Physical Review A*, in which nine other core documents have been published. One core document was published in the *Proceedings of the Physical Society London. A.*, which split in 1968 into the various sections of the *Journal of Physics*. For substantive reasons, we limit the present analysis to the *Journal of Physics, B.* In the case of the *Zeitschrift für Physik* and its sections *A* and *B*, we took the aggregate of the three citation scores, because here it is more difficult to argue for a further restriction of the analysis.
57. *Op. cit.*, note 8.
58. *Ibid.*, p. 107.
59. Both here and in the factor analysis the *Journal of Molecular Spectroscopy* shows up as a core 'chemical physics' journal. In the qualitative analysis it had mistakenly been included under the category of 'various physics'.
60. In this study, the cluster structure had in fact not been produced by ISI through single linkage clustering but by a much simpler counting technique.
61. *Op. cit.*, note 1, p. 339.
62. *Op. cit.*, note 9.
63. "But can one be used as a baseline to calibrate our understanding of another?" *Ibid.*, p. 269.
64. *Ibid.*, p. 270.
65. See also: *op. cit.*, note 8, p. 122.
66. 1985 is only included to week 50. (The DIALOG searches were done on January 30, 1986.)
67. In 1978/9, cluster 1010 is indeed one cluster. In 1984/5, the internal structure as discussed for 1981/2 above, is again present, although the position of document nr. 28 (1010E) has changed.

68. H. SMALL, E. GREENLEE, *op. cit.,* note 4.
69. *Op. cit.,* note 9, p. 270.
70. See a.o.: S. E. COZZENS (Ed.), Funding and knowledge Growth, Theme Section *Social Studies of Science,* 16 No. 1, (1986) 9–150.
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