Mapping *Scientometrics* (1981-2001)

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We investigate an integrated approach to scientometric studies with emphasis to the use of information visualization and animation techniques. This study draws upon citation and co-citation patterns derived from articles published in the journal *Scientometrics* (1981-2001). The modeling and visualization takes an evolutionary and historical perspective. The design of the visualization model adapts a virtual landscape metaphor with document co-citation networks as the base map and annual citation rates as the thematic overlay. The growth of citation rates is presented through an animation sequence of the landscape model. Issues concerning the visual-spatial design are discussed from a citation analysis point of view.

Introduction

Science mapping aims to reveal structures of scientific literature and underlying specialties using graphical representations. Theories of how specialties evolve and change started to emerge in the 1970s (Small & Griffith, 1974). Researchers began to focus on the structure of scientific literatures in order to identify and visualize specialties, although they did not use the term "visualization" at that time. Co-word analysis (Callon, Law, & Rip, 1986) and co-citation analysis (Small, 1973) are among the most fundamental techniques for science mapping. They are the technical foundations of the contemporary quantitative studies of science. Each offers a unique perspective on the structure of scientific frontiers. Researchers have found that a combination of co-word and co-citation analysis could lead to a clearer picture of the cognitive content of publications (Braam, Moed, & Raan, 1991a, 1991b).

In *Little Science, Big Science*, Derek de Solla Price (1963) raised some of the most fundamental questions that have led to the scientometric study today: Why should we not turn the tools of science on science itself? Why not measure and generalize, make hypotheses, and derive conclusions? He used the metaphor of studying the behavior of gas in thermodynamics as an analogue of the science of science. Thermodynamics studies the behavior of gas under various conditions of temperature and pressure, but the focus is not on the trajectory of a specific molecule. Instead, one considers the phenomenon as a whole. Price suggested that we should study science in a similar way: the volume of science, the trajectory of "molecules" in science, the way in which these "molecules" interact with each other, and the political and social properties of this "gas".

Our recent research has been focusing on issues concerning how to effectively incorporate information visualization tools into scientometric studies. As an integral part of our long-term research, our investigation emphasizes an interdisciplinary synergy that may involve fields of study such as information visualization and scientometrics. Can we provide domain analysts, science performance evaluators, researchers, students, and other knowledge workers something tangible and meaningful that they can readily incorporate it into their work process? Can we improve the way we learn about a new subject matter, the way we explore a knowledge domain, and the way we trace the history and evolution of a specialty? And ultimately, can we augment our ability to judge the significance of scientific work more efficiently and more accurately?

As part of our long-term research, the study reported here takes the field of scientometrics as a starting point. First of all, this is because our own interest in the field. Secondly, because the best predictor of the future is the past, a historical and reflective perspective may lead to insights into mapping the growth of an interdisciplinary field like scientometrics. Finally, there exist a number of studies of the field. These existing studies may provide a valuable point of reference for understanding the findings of this study. The flagship journal of the field is *Scientometrics*, published science September 1978. The present study is based on articles published in Scientometrics between 1981 and 2001, drawn from the Web of Science.

Scientometrics

Scientometrics is "the study of the measurement of scientific and technological progress" (Garfield, 1979b). Its origin is in the quantitative study of science policy research, or the science of science, which focuses on a wide variety of quantitative measurements, or indicators, of science at large. Typically input and output of science programs correspond to two major categories of indicators. Input indicators include the amount of research grants awarded to institutions and the number of people receiving scientific degrees; output indicators include the number of scientific articles published, the number of citations to each article, and the number of patents granted. Science policy and program evaluation studies have used such indicators to measure the scientific strength of various countries, regions, or research institutions. Domain analysts have used such indicators to describe the intellectual structure of a knowledge domain. Scientometrics is the demographics of the worldwide scientific community. As Garfield put it, "One can follow the growth or decline of various fields or identify where the action is."

Scientometric research has a strong application-oriented tradition (Garfield, 1979b; Raan, 1997). For example, scientometric studies may help governments and private sectors identify their competitive edges and make strategic plans for future research areas and allocate research funding to key research areas. Garfield (Garfield, 1979b) identified several publications appeared in the 1970s and contributed to the development of scientometrics, namely, the first Science Indicators published by the National Science Board in 1972 (Board, 1977), the *Evaluative Bibliometrics: The Use of Publication and Citation Analysis in the Evaluation of Scientific Activity* by Francis Narin and Computer Horizons, Inc. (CHI) in 1976 (Narin, 1976), which has been regarded as a good review source for anyone interested in scientometrics (Garfield, 1979b). Derek Price's 1965 article '*Network of Scientific Papers*' (Price, 1965) has been also regarded as a key event in the development of the field of scientometrics.

Research in scientometrics has also been reflective. A number of studies have analyzed the filed of scientometrics itself in order to identify trends in this interdisciplinary subject matter. Michael Moravcsik (1977) presented a review of scientometric literature (Moravcsik, 1977). Anthony van Raan (1997) analyzed the state of the art of scientometrics and characterized its application-oriented tradition. He envisaged that scientometrics could benefit significantly from a greater integration with knowledge discovery and data mining. Loet Leydesdorff (2001) identified some challenges of scientometrics and suggested that: "the state of the art of science studies is 'pre-paradigmatic:' it is an interdisciplinary area integrated only at the level of its subject matter, and an applicational area for various contributing disciplines."

The author co-citation analysis of information science by White and McCain (1998) identifies 12 specialties in information science. Some of these specialties are directly connected to the field of scientometrics. At the highest level in their maps, information science was represented by two prominent sub-domains: experimental retrieval and citation analysis. Experimental retrieval is beyond the scope of our current analysis. Our analysis of the field of scientometrics relies on its flagship journal *Scientometrics*. We interpret the domain structure identified in this study with reference to the findings in the author co-citation specialties described in (White & McCain, 1998).

A directly related study of *Scientometrics* was done by Olle Persson (2000). He retrieved 1,062 articles published in the journal from volume 1 to volume 44 between 1978 and 1999. Top-10 most cited publications include (Garfield, 1979a; Schubert, Glanzel, & Braun, 1989; Small, Sweeney, & Greenlee, 1985). He generated several maps to show a variety of structures, including journal co-citation, direct citation links among countries, shared citations among authors, and direct citations among authors. The provision of such results provides a valuable reference framework.

Procedure

This study is based on bibliographic data retrieved from the Web of Science. The data contain all types of documents published in *Scientometrics* between 1981 and 2001. The retrieval was finally updated on January 30, 2002. Each article must be cited for 5 times or more in order to be included in this integrated analysis. This threshold resulted in a total of 403 articles. We decided to apply our approach directly to the raw data with no human intervention, as we want to see to what extent our approach can handle various types of noise in such data.

In this study we have adapted an integrated procedure of citation analysis and information visualization, including Pathfinder network scaling, Principal Component Analysis (PCA), and visual-spatial models rendered in Virtual Reality Modeling Language (VRML). PCA, multidimensional scaling (MDS), and cluster analysis have been typically used in traditional co-citation analysis (Small, 1999; White & McCain, 1998). This method was subsequently extended to be integrated with Pathfinder network scaling in (Chen, 1999) more recently streamlined in (Chen & Paul, 2001) to become a tool that can facilitate both author co-citation and document co-citation analysis.

Table 1. Twenty five components, or factors, extracted by PCA from the co-citation structure of 403 articles.

Total Variance Explained

	Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	91.331	22.663	22.663	55.110	13.675	13.675
2	62.565	15.525	38.188	44.615	11.071	24.746
3	44.507	11.044	49.232	41.758	10.362	35.108
4	37.157	9.220	58.452	38.528	9.560	44.668
5	19.455	4.828	63.279	33.378	8.282	52.950
6	17.685	4.388	67.668	22.096	5.483	58.433
7	16.686	4.140	71.808	19.368	4.806	63.239
8	13.359	3.315	75.123	17.557	4.357	67.596
9	10.988	2.726	77.849	17.510	4.345	71.941
10	8.363	2.075	79.925	16.090	3.993	75.933
11	7.005	1.738	81.663	10.485	2.602	78.535
12	6.144	1.525	83.187	7.006	1.739	80.273
13	4.895	1.215	84.402	5.876	1.458	81.732
14	4.170	1.035	85.437	5.091	1.263	82.995
15	3.627	.900	86.337	4.979	1.236	84.230
16	3.349	.831	87.168	4.406	1.093	85.324
17	2.871	.712	87.880	3.466	.860	86.184
18	2.578	.640	88.520	3.331	.826	87.010
19	2.191	.544	89.064	3.261	.809	87.819
20	1.980	.491	89.555	2.756	.684	88.503
21	1.659	.412	89.967	2.750	.682	89.186
22	1.516	.376	90.343	2.417	.600	89.785
23	1.235	.306	90.649	2.053	.510	90.295
24	1.135	.282	90.931	1.859	.461	90.756
25	1.020	.253	91.184	1.723	.428	91.184

Extraction Method: Principal Component Analysis.

The procedure is outlined here. Readers are referred to (Chen & Paul, 2001) for a detailed description. For case studies and a comprehensive account of the methodology, see (Chen, 2002; Chen, Cribbin, Macredie, & Morar, 2002; Chen, Kuljis, & Paul, 2001). First, we choose a threshold of 5 to include all publications in *Scientometrics* that have been cited for 5 times or more. Our program then selects publications that meets this criterion and computes document co-citations for selected publications. The co-citation strength is computed as Pearson's correlation coefficients to form a co-citation matrix. Annual citation counts are also collected as this stage for each publication above the threshold. The co-citation matrix forms the basis of a base map, a terminology commonly used in cartography. Factor analysis, namely PCA, is subsequently applied to the co-citation matrix in order to produce a thematic overlay. The purpose of such a thematic overlay is to highlight the density distribution of various specialties. Factor loadings are used to color code each publication in the thematic overlay. We have a built-in component to conduct PCA as well as an export facility to produce data files that can be readily opened in SPSS. Publications with zero variances are omitted from PCA. As a result, zero-variance publications appear as black-colored spherical nodes in the visualization model. We simplify the co-citation matrix using Pathfinder network scaling, which retains the strongest co-citation links with reference to the so-called triangle inequality condition (Chen, 1997, 1998; Schvaneveldt, 1990). Finally, the growth of citation rates is animated across the entire Pathfinder network to facilitate the identification of trends. The visualization-animation model is made available in VRML 2.0 for easy access on the Internet. Users can access such models through a VRML-enabled browser, for example Internet Explorer with a freely available VRML viewer.

Results

A total of 403 publications were above the 5-citation threshold. Among them, the earliest one was published in 1917 and the most recent one was published in 1999. The only article in 1999 is Wouters' thesis. The second most recent one was (White & McCain, 1998), published in 1998. The rest of articles were published in 1997 or earlier.

Overall

PCA identified 25 factors from the 403 by 403 co-citation matrix. In theory, each factor should correspond to a specialty. In practice, the big picture tends to be dominated by a few specialties and analysts often focus on specialties that matter the most. The large number of factors reflects the diversity of scientometrics. In our analysis, we focus on the three largest factors of significant specialties of the field. Table 1 shows the variance explained by the 25 factors.

Figure 1 shows a landscape view of the 20-year Scientometrics' citation space. The base map is a Pathfinder network of 403 articles cited by publications in Scientometrics. The thematic overlay highlights the distribution of various specialties. Each spherical node denotes one of the 403 articles. Its color indicates a combination of its factor loading from the most predominant three specialties. The height of the vertical bar above each spherical node is proportional to the total number of citations received. The color map of the bar reveals the historical patterns of citations associated with the underlying article: darker segments correspond to citations made in earlier days of the 20-year citing window; brighter segments correspond to more recent citations. In Figure 1, the topology of the network is dominated by a long west-east spin. The largest specialty (red, when shown in color[1]) is located in the middle segment of the spin and pointing to north, with the second largest (green) towards east and the third (blue) towards west. The third specialty, for example, features classic publications by Lotka, Bradford, Price, and Brookes. In contrast to Figure 1, Figure 2 uses a different thematic overlay to display the year of publication for each article. The entire range of publication years is mapped to black-white grayscale; black marks the earliest publication in the scene and white marks the most recent one in the scene. Figure 3 shows an birdseye view of the model. Several earliest publications cited by *Scientometrics* are labeled.

The 403 articles vary considerable in terms of the year of publication, from the earliest one in 1917 to the latest one in 1999. Table 2 and Table 3 show the most recent and the earliest ones in the dataset.

Table 2. The most recent articles cited more than 5 times by *Scientometrics* (1981-2001).

Authors	Year	Source	Times Cited
WOUTERS P	1999	THESIS	6
WHITE HD	1998	J AM SOC INFORM SCI	6
KATZ JS	1997	RES POLICY	11
MAY RM	1997	SCIENCE	11
LUUKKONEN T	1997	SCIENTOMETRICS	9
NARIN F	1997	RES POLICY	8
GLANZEL W	1997	SCIENTOMETRICS	6
INGWERSEN P	1997	J AM SOC INFORM SCI	6
VANRAAN AFJ	1996	SCIENTOMETRICS	14
LETA J	1996	SCIENTOMETRICS	8
DORE JC	1996	J AM SOC INFORM SCI	7
GLANZEL W	1996	SCIENTOMETRICS	7
MELIN G	1996	SCIENTOMETRICS	7

Table 3. The earliest articles cited more than 5 times by *Scientometrics* (1981-2002).

Authors	Year	Source	Times Cited
COLE FJ	1917	Sci Progr.	10
LOTKA AJ	1926	J Washington Academy	51
GROSS PLK	1927	Science	13
BRADFORD SC	1934	Engineering-London	30
VICKERY BC	1948	J DOC	7
BRADFORD SC	1948	Documentation	17
ZIPF GK	1949	Human Behaviour Principles	6
LEHMAN HC	1953	Age Achievement	6
GARFIELD E	1955	Science	6
SIMON HA	1955	Biometrika	10

Specialties

In the author co-citation of information science between 1972 and 1995, White and McCain (White & McCain, 1998) extracted 12 specialties from 120 most cited authors in the field. The largest 6 specialties are: experimental retrieval, citation analysis, online retrieval, bibliometrics, general library systems, and science communication. In order to determine the nature of major specialties identified in this study, we examine the titles of top-ten publications in each specialty. Tables 4-5 show the top-ten publications

[1]http://www.pages.drexel.edu/~cc345/ papers/asis2002.pdf

with strongest factor loadings in the three largest specialties.

Table 4. Specialty 1: Citations in Science Studies.

Factor Loading	Publications
0.874	Price D. J. D. (1965). Networks of scientific papers. Science, 149, 510-515.
0.857	Edge, D. (1979). Quantitative measures of communication in science: A critical review. Hist. Sci., 17, 102.
0.853	Garfield, E. (1955). Citation indexes for science: A new dimension in documentation through association of ideas. Science, 122, 108-111.
0.850	Leydesdorff, L. (1987) Various methods for the mapping of science. Scientometrics, 11, 291-320.
0.834	Amsterdamska, O., and Leydesdorff, L. (1989) Citations: Indicators of significance? Scientometrics, 15, 449-471.
0.834	Latour, B. (1987) Science in Action. Milton Keynes: Open University Press.
0.834	Small, H. G. (1978) Cited documents as concept symbols. Social Studies of Science, 8, 327-340.
0.830	Woolgar, S. (1991) Beyond the citation debate: Towards a sociology of measurement technologies and their use in science policy. Science and Public Policy, 18, 319-326.
0.829	Chubin, D. E. and Moitra, S. D. (1975) Content analysis of references: Adjunct or alternative to citation counting? Social Studies of Science, 5, 423-441.
0.827	Cozzens, S. (1985) Comparing the sciences: Citation context analysis of papers from neuropharmocology and the sociology of science. Social Studies of Science, 15, 127-153.

Table 5. Specialty 2: World and national science performance.

Factor Loading	Publications
0.836	Schubert, A., Glanzel, W., & Braun, T. (1989). Scientometric data files: A comprehensive set of indicators on 2649 journals of 96 countries in all major science fields and subfields 1981-1985. Scientometrics, 16, 3.
0.817	Frame, J. D. (1977) Mainstream research in Latin America and the Caribbean. Interciencia, 2(3), 143-147.
0.714	Frame, J. D., Narin, F., and Carpenter, M. P. (1977) The distribution of world science. Social Studies of Science, 7(4), 501-516.
0.696	Braun, T. et al. (1994) World science in the eighties: National performance in publication output and citation impact, 1985-1989 versus 1980-1984. 2. Life Sciences, Engineering, and Mathematics. Scientometrics, 31, 3-30.
0.696	Narin, F., and Frame, J. D. (1989) The growth of Japanese science and technology. Science, 245, 600-605.
0.695	Glanzel, W. (1996) Scientometrics, 35,291.
0.694	Braun, T., Glanzel, W., Maczelka, H., Schubert, A. (1994) World science in the eighties: National performances in publication output and citation impact, 1985-1989 versus 1980-1984 1. All science fields combined, Physics, and Chemistry. Scientometrics, 29(3), 299-334.
0.694	Noma, Elliot. (1986) Subject classification and influence weights for 3,000 journals. Report to National Institutes of Health and Advisory Board for the Research Councils (England). CHI Research.
0.690	Schubert, A. and Braun, T. (1986) Relative indicators and relational charts for comparative assessment of publication output and citation impact, Scientometrics, 9, 281-291.
0.687	Braun, T., Gomez, Y., Mendez, A., Schubert, A. (1992) International co-authorship patterns in Physics and its subfields, 1981-1985. Scientometrics, 24, 181-200.

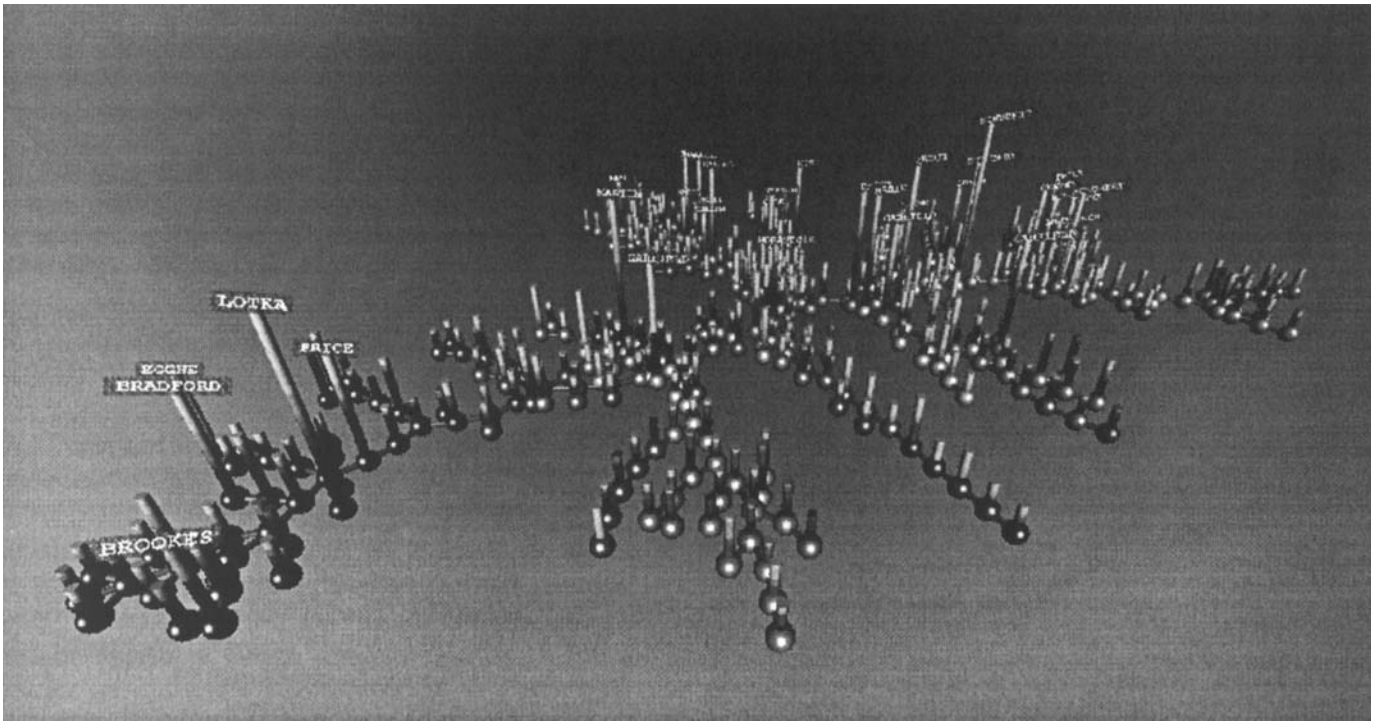

Figure 1: A landscape view of the 20-year Scientometrics' (1981-2001) citation space, containing 403 articles published between 1917 and 1999. Articles are colored by factor loadings on the largest three factors identified.

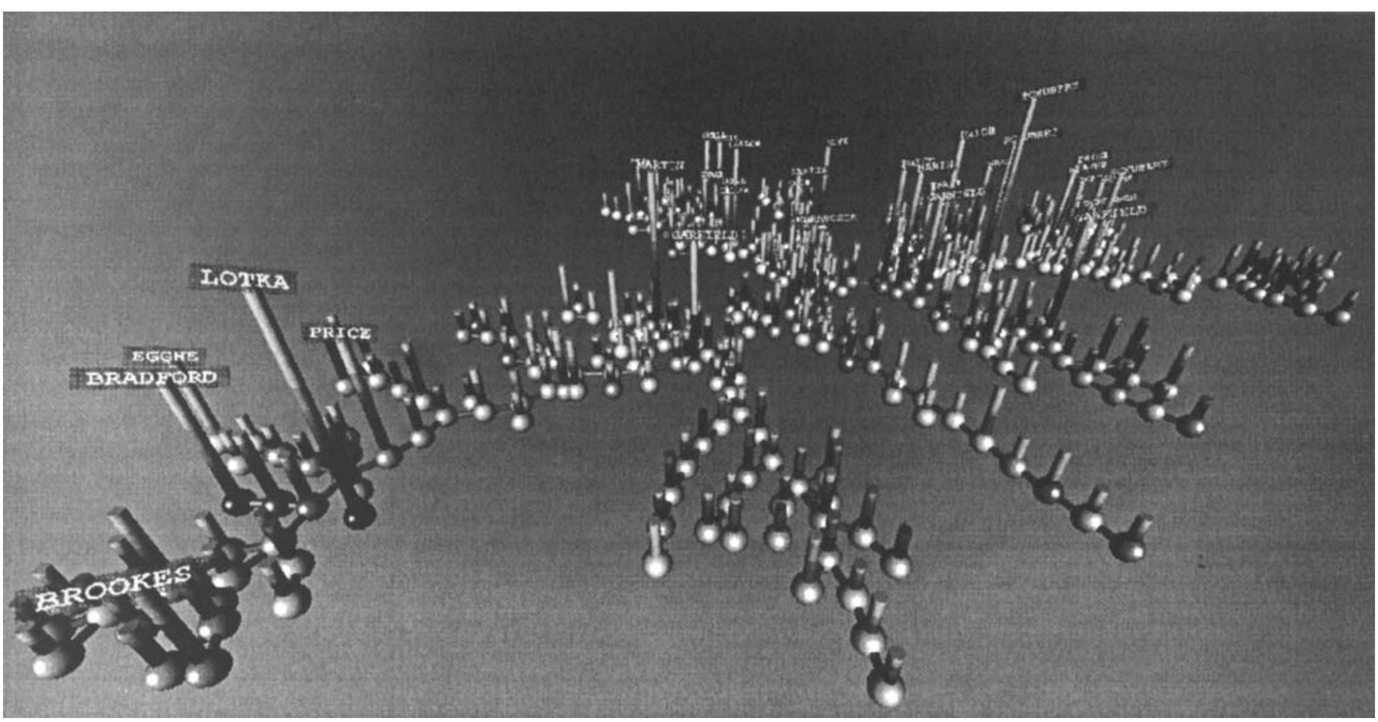

Figure 2: The same landscape view as Figure 1 except the articles are color mapped by the year of publication.

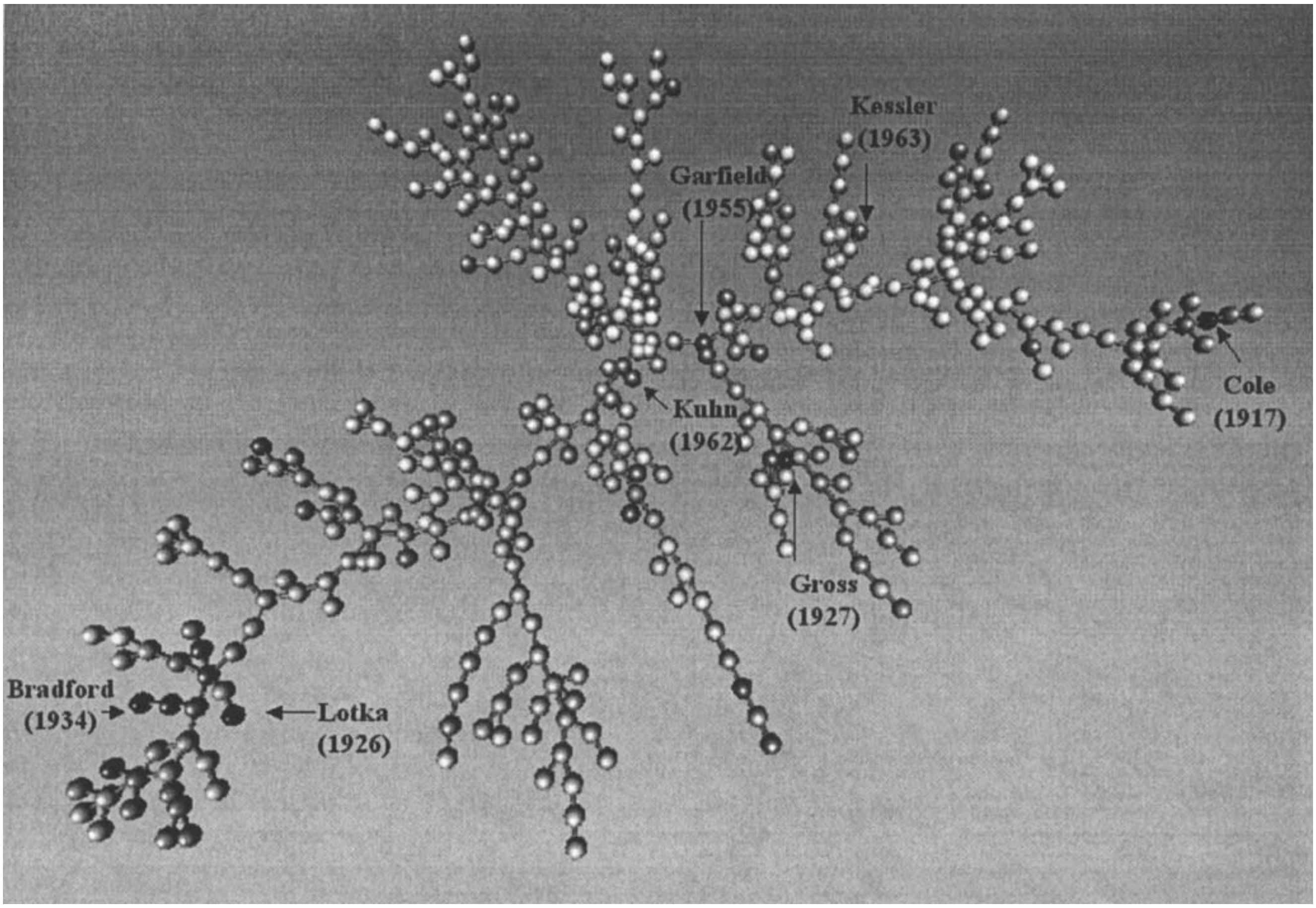

Figure 3: Some of the earliest publications in the citation space of Scientometrics.

Table 6. Specialty 3: Evaluation research outputs.

Factor Loading	Publications
0.728	Hagstrom, W. O. (1971) Inputs, outputs, and the prestige of university science departments. Sociol. Educ., 44, 375.
0.700	Narin, F, et al. (1976) Structure of the biomedical literature. JASIS, 27, 25-45.
0.696	S M Lawani and A E Bayer (1983) Validity of citation criteria for assessing the influence of scientific publications: New evidence with peer assessment. JASIS, 34(1), 59-66.
0.659	Koenig, M. E. D. (1983) JASIS, 34, 136.
0.658	Anderson, R. C. (1978) JASIS, 29, 91.
0.657	Vinkler, P. (1986) Management systems for a scientific research institute based on the assessment of scientific publications. Research Policy, 15(2), 77-87.
0.645	Koenig, M. E. D. (1982) Determinants of expert judgment of research performance. Scientometrics, 4(5), 361-378.
0.631	Lindsey, D. (1989). Using citation counts as a measure of quality in science: Measuring what's measurable rather than what's valid. Scientometrics, 15, 189-203.
0.623	Hicks, D. (1986) R&D Management, 16, 211.
0.608	Fox, M. F. (1983) Publication productivity among scientists: A critical review. Social Studies of Science, 13, 285-305.

In a conventional co-citation study, we typically cluster publications, or authors in the case of author co-citation, and then aim to characterize the nature of major clusters as surrogates of specialties. In this study, we suggest an alternative way to interpret such groupings. Principle Component Analysis (PCA) extracted factors and each factor reveals insights into some underlying specialty.

Because the commonality among publications in a specialty is essentially determined by co-citation patterns, they can be considered as multiple facets of a specialty. One could imagine an author citing one publication from a specialty is likely to cite other publications from the list identified by PCA.

The Growth

Figure 4 shows six snapshots taken from the 20-year animation sequence from 1981 through 2001. The snapshots run from left to right in the first row and continue from the left of the second row. The first frame shows few citations at the beginning of the citing window of *Scientometrics*. The second frame shows the growth of some citations in the branch towards east. This region corresponds to a number of Eugene Garfield's early publications. The third frame shows further growth in this area, indicating instrumental roles of citation indexing. The fourth frame shows the significant growth in areas corresponding to specialty 1 and specialty 2. The fifth frame shows the growth of specialty 3 and citations to some early publications from Lotka and Bradford. Finally, the sixth frame represents the snapshot of an accumulated citation base of *Scientometrics* over the last 21 years.

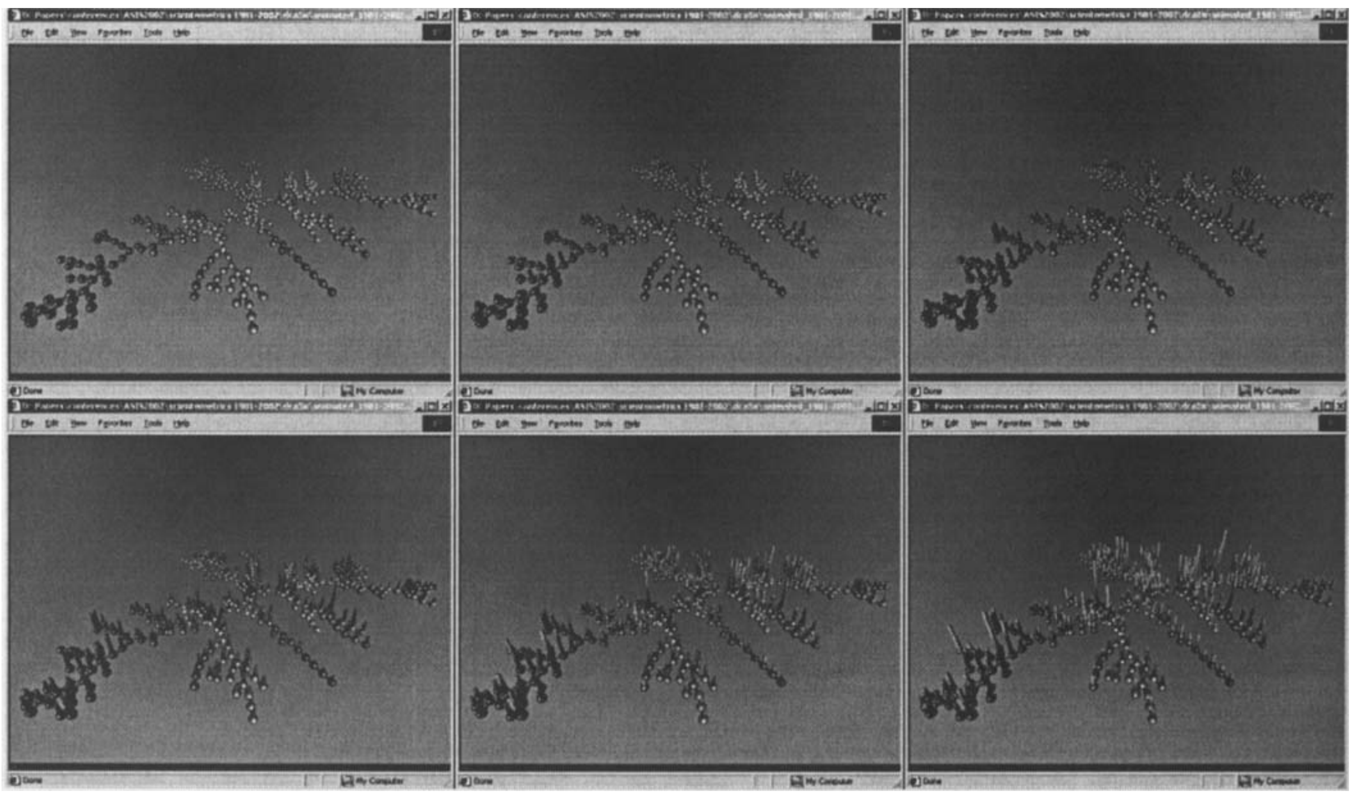

Figure 4: A sequence of snapshots taken from an animation of the citation space.

Discussions

From a designer's point of view, a few issues should be addressed in future studies. For example, although the citation space visualizes and animates the growth rates of scientific publications, not all publications are created equal: earlier publications may have more chance to get more citations than later publications. Aging patterns of journal articles were studied by McCain and Turner (McCain & Turner, 1989). They found two types of aging patterns: aging slowly or aging quickly in terms of how soon the citation rate of a publication starts to decline. They examined the context of each citation of publications in molecular genetics and ranked the significance of citations in several categories. "Methods" publications were consistently ranked higher than publications cited for research results and theoretical implications. Such findings suggest that one may gain more insights by looking deeper into the type of intellectual contributions reflected in the context of citation.

Another issue is concerned with the base map of the citation space. Because not all publications appeared in the same year, viewing the growth of their citations within the same framework may not be optimal. First, in the current version of our method, all publications are visible throughout the entire animation sequence, regardless the year of publication. This may create an illusion that all the publications are actually available in each year shown in the corresponding animation frame. This is why we have generated a visualization in which the nodes are not colored by their specialty memberships; instead, they are colored by the year they were published. One can tell whether a high citation rate of a publication is due to its thematic impact, or simply due to the fact that it has been around for a long time. Alternatively, one can restrict all publications in the scene to a single year of publication and generate a series of annual snapshots. Another option is to add specific visual-spatial attributes to the visualization so that one can distinguish the age of each publication.

In both author co-citation analysis and document co-citation analysis, one of the most challenging tasks is to identify the nature of each underlying specialty. Such identification, in an ideal world, calls for intimate knowledge of the discipline in question, sound judgments of evasive evidence, and a command of abstraction and classification skills. The provision of complementary views may largely facilitate a wider group of analysts to accomplish such tasks. By comparing and contrasting various aspects of specialties visualized in author co-citation maps and document co-citation maps, one may gain valuable insights into the dynamics of a discipline.

Conclusion

In this article, we have analyzed and visualized the citation image of Scientometrics over the last 21 years (1981-2001). An animation of the evolution of this 403-article citation image over the 20-year span appears to provide a promising instrument for probing more directly into the changes of the invisible college underlying the field of scientometrics. Our long-term research will continue to pursue visualization-augmented approaches to scientometric studies, experiment with a wider range of source data, and incorporate research findings from the scientometrics community as well as information visualization and other relevant fields of study into the practice of the strong application-oriented discipline.

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