Fitting the Jigsaw of Citation: Information Visualization in Domain Analysis

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Domain visualization is one of the new research fronts resulted from the proliferation of information visualization, aiming to reveal the essence of a knowledge domain. Information visualization plays an integral role in modeling and representing intellectual structures associated with scientific disciplines. In this article, the domain of computer graphics is visualized based on author cocitation patterns derived from an 18-year span of the prestigious *IEEE Computer Graphics and Applications* (1982–1999). This domain visualization utilizes a series of visualization and animation techniques, including author cocitation maps, citation time lines, animation of a high-dimensional specialty space, and institutional profiles. This approach not only augments traditional domain analysis and the understanding of scientific disciplines, but also produces a persistent and shared knowledge space for researchers to keep track the development of knowledge more effectively. The results of the domain visualization are discussed and triangulated in a broader context of the computer graphics field.

Introduction

When we first encounter a scientific discipline, or a subject domain, we often would need to have a good standing point and as many signposts as possible to guide ourselves through the field. On the other hand, more experienced researchers and domain experts would need effective ways to track the development of their own fields and extract crucial signs of the dynamics of a scientific discipline (Bush, 1945).

The World Wide Web (Web) has revolutionized the way we search for information. On today's Web we can easily access a vast amount of information on almost any subject. However, a profound challenge to many of us in the modern information society is to transcend the vast amount of information in scientific literature and access scientific knowledge at a higher level. The meta-knowledge, the knowledge of how particular knowledge structures have been perceived, should become an integral part of the scientific discipline involved, and it should be presented with simplicity and clarity for scholarly communication as well as public understanding.

Domain visualization is an exciting field of study that addresses these questions. It utilizes various modeling and visualization technologies to augment traditional approaches to the study of scientific disciplines. Works in this area are closely related to domain analysis, proposed by Hjorland and Albrechtsen (1995) in information science. According to this approach, the best way to understand scientific communication is to study the knowledge domains as thought or discourse communities. Knowledge organization, structure, cooperation patterns, language, and communication forms reflect the objects of the work of these communities and their role in society. Until now, there is a limited integration of domain analysis and information visualization.

The pioneering *Atlas of Science* (ISI, 1981) of the Institute of Scientific Information (ISI) and their latest work in visualizing science (Garfield, 1998; Small, 1999) have mapped the macrostructure of science. In contrast, instead of the entire science as a whole, domain visualization tends to focus on a specific domain or discipline such that one can explore the dynamics of a scientific discipline as an organic system, for example (White & McCain, 1998) on information science, and (Chen, 1999b) on hypertext. Most of these works derive high-level structures from document cocitation, author cocitation, and classification code cooccurrences.

As White and McCain have pointed out in 1998, citation analysis must not only identify the value of particular works, but also explain why some are more valued than others. Noyon, Mode and Luwel (1999) combined domain mapping and citation analysis in a bibliometric study to emphasize the evaluation aspect of bibliometrics.

In this article, we describe our approach to domain visualization through a series of applications of analysis and visualization of a knowledge domain: *computer graphics*. The key component in our approach is a domain-specific knowledge roadmap derived from literature analysis and

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visualization. As a semantic-rich, multifacet, and extensible structure of a knowledge domain, knowledge roadmaps provide a unique type of resources for a scientific discipline and its literature.

The rest of the article is organized as follows. First, we introduce the history of mapping science and intellectual structures reflected through contemporary literatures. Second, we focus on current challenges to domain visualization, especially citation analysis-based approaches. We then describe our approach, and illustrate it through a working example based on an author cocitation analysis of the prestigious *IEEE Computer Graphics & Applications* (CG&A). We analyze and triangulate our results through a variety of in-depth crossexaminations to obtain a relatively comprehensive picture of the subject domain and its specialties—subfields in a subject domain. We established some significant connections between citation indexing and domain analysis methodologies, including characterizing the nature of specialties based on citation contexts.

Related Work

More than 50 years ago, Vannevar Bush (1945) envisaged his visionary device Memex. A central idea in Memex is *trailblazing* in a vast information space. Making connections has been regarded one of the most fundamental tasks of knowledge work. Scientists frequently need to tie together different thoughts found in scientific literature. On today's Web, we surf from one document to another on existing hyperlinks provided by others. A trailblazer in Memex would build their pathways or trails in an ever-growing information space. To a considerable extent, the practice of citation in scientific literature has a similar nature.

Scientific literature is a huge jigsaw for the scientific community. To improve the integrity and accessibility of scientific literature, technologies have been developed for tracking the growth of scientific disciplines. Here we outline two most related work: one is the *classic citation indexing*, a well-established approach from the Institute for Scientific Information (ISI) (Garfield, 1970), and the other is a promising approach recently developed by researchers at NEC, known as *autonomous citation indexing* (Lawrence, Giles, & Bollacker, 1999).

Classic Citation Indexing

Originally, citation indexing was motivated to break the barrier in subject indexing. By drawing upon the profound practice of citation in scientific literature, it is intended that citation indexing can reveal the underlying, intrinsic structure of the body of scientific knowledge. ISI, best known for its Science Citation Index (SCI), has devoted to represent the structure of scientific literature for many years. Its pioneering *Atlas of Science* (ISI, 1981), based on document cocitation analysis, revealed the macrostructure of disciplines such as biochemistry and molecular chemistry. Recently, ISI is increasingly interested in the applicability of visualization technologies for mapping science as a whole (Garfield, 1998).

Autonomous Citation Indexing

More recently, researchers at NEC Research Institute have developed a Web-based citation database system called ResearchIndex, formerly known as CiteSeer, which allows users to search for various citation details of scientific documents available on the Web (Lawrence et al., 1999). ResearchIndex was designed to improve the accessibility of scientific literature using an autonomous citation indexing approach. Not only can users search the database on various bibliographic attributes of a document such as the author, article title, and journal title, but also use the *citation context* function to retrieve a list of highlights of excerpts from citing documents and access detailed statements of its perceived value. This function provides an invaluable tool for researchers to judge the nature of an influential article. In fact, we used this function to examine citation contexts and thereby identify the nature of each specialty.

ResearchIndex relies on various heuristics to locate scientific articles from the Web and extract citation data. ResearchIndex currently supports an experimental database for computer science, which already contains hundreds of thousands of records. It is certainly desirable to extend the coverage of the database continuously and turn it to a comprehensive source of reference.

Author Cocitation Analysis

Cocitation is a widely used to measure similarities and to derive intellectual structures, to name a few examples (Bayer, Smart, & McLaughlin, 1990; Braam, Moed, & van Raan, 1991; Chen, 1999b; Small, 1973; White & Griffith, 1981; White & McCain, 1998). Author cocitation analysis (ACA) aims to discover intellectual structures from author cocitation data (White & McCain, 1998). In ACA, instead of articles or journals, individual authors are used as data points in the literature. Authors are the unit of analysis. ACA provides invaluable information about how authors, as domain experts, perceive the interconnectivity between published works.

An in-depth author cocitation analysis was reported by White and McCain (1998) in 1998. They analyzed the domain of *information science* based on author cocitation data drawn from 12 key journals in the field. Their work clearly demonstrates the strength and potential of ACA. On the other hand, ACA is still a time-consuming task. In particular, incorporating information visualization techniques into ACA studies will significantly strengthen the role of ACA as a means of mapping scientific disciplines. Inspired by this landmark work, we exploit the potential of information visualization in ACA and in general methodologies of mapping scientific disciplines.

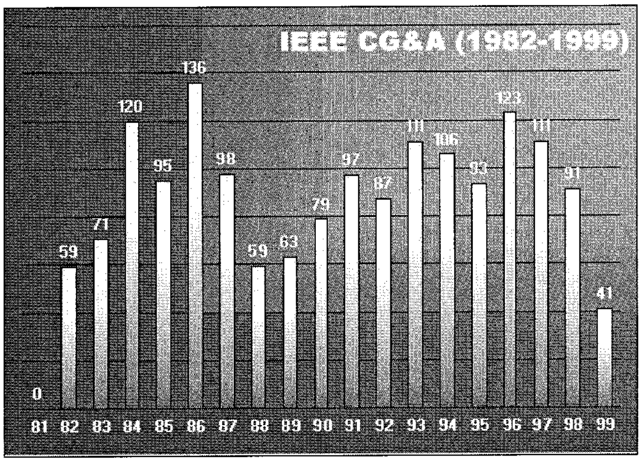

FIG. 1. Sampled data from IEEE CG&A (1982–1999).

TABLE 1. Descriptive statistics on the data.

Categories
The number of articles cited
The number of authors cited (first author only)
The number of citing authors
The number of authors cited more than five times
The number of valid author cocitation pairs

Visualization of Citation Data

Information visualization aims to uncover the secret of complex and dynamic systems, ranging from everyday-life data to abstract, intellectual structures (Chen, 1999a). A knowledge domain is often high dimensional in nature, comprising various contributing specialties. König (1998) summarizes a number of multivariate data visualization techniques.

In parallel to document visualization, higher order, more profound and intrinsic structures in scientific literature has been explored in the past. Butterfly, designed at Xerox PARC, provides an organic user interface to the SCI database (Mackinlay, Rao, & Card, 1995). The head of a butterfly represents a currently searched article. The wings of the butterfly represent the corresponding citing and cited articles.

Traditional author cocitation studies typically use multidimensional scaling (MDS) to depict the underlying patterns between authors. However, interpreting the nature of dimensionality in MDS is not always straightforward. Local details in an MDS map can be difficult to interpret.

To provide more details on local structures, we have explored the use of Pathfinder networks as a semantically rich and visually simple alternative to visualizing proximity data (Chen, 1999b). Pathfinder network scaling gives an analyst a greater control over extracting and representing the most salient structures defined by proximity data. We have incorporated Pathfinder network scaling into the traditional approach to author cocitation studies.

Preserving the high-dimensional integrity is a fundamental problem in high-dimensional data visualization. In our earlier studies, we color coded three most predominant specialties in author cocitation maps. Although such color mapping reflects the essence of the memberships of the most important specialties, many high-dimensional characteristics are not adequately represented. It is difficult to distinguish overlapped specialties and less predominant specialties. Existing studies have highlighted the following issues that must be addressed by mapping scientific disciplines in general: (1) mapping a knowledge domain in terms of specialties; (2) identifying specialties and characterizing their nature; (3) preserving high-dimensional properties of a knowledge structure; (4) incorporating trends of citation into cocitation structures; (5) introducing citation-context matching into domain mapping. In the rest of this article, we will illustrate our approach to mapping scientific disciplines with special respect to these issues.

Methods

In this article, we concentrate on domain visualization based on bibliographic data. A domain visualization process

TABLE 2. Top 20 most frequently cited sources in IEEE CG&A 1982–1999, 2(1)–19(3).

Rank	Citations	Type	Titles
1	1335	J	SIGGRAPH Computer Graphics. 1980–
2	769	J	IEEE Computer Graphics and Applications. 1981–
3	237	J	Communications of the ACM. 1958–
4	175	J	Computer Aided Design. 1968–
5	154	J	Computer Graphics and Image Processing. 1972–1982
6	142	J	Computer Aided Geometry Design. 1984–
7	132	J	COMPUTER GRAPHIC JUL
8	114	J	ACM Transactions on Graphics. 1982–
9	112	J	IEEE Computer. 1967–
10	81	J	Visual Computer. 1985–
11	69	P	Proceedings of Graphics Interface. Canadian Information Processing Society.
12	68	P	Proceedings of IEEE Visualization
13	61	B	Foley, J.D., & van Dam, A. (1982). Fundamentals of interactive computer graphics. London: Addison-Wesley.
14	48	B	Newman, W., & Sproull, R. (1972). Principles of computer graphics. Englewood Cliffs, NJ: Prentice-Hall.
15	48	J	IEEE Transactions on Pattern Analysis and Machine Intelligence. 1979–
16	46	J	IBM Journal of Research and Development. 1957–
17	44	B	Preparata, F.P., & Shamos, M.I. (1985). Computational geometry: An introduction. London: Springer-Verlag.
18	44	J	Computer Vision, Graphics, and Image Processing 1983–
19	43	P	Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE)
20	39	J	Computing Surveys. 1969–

Type of source: J—journal, P—proceedings, B—Books.

consists of several stages, including data collection, citation analysis, visualization, crossexamination, and virtual reality modeling. In particular, the following steps are undertaken:

(1) draw bibliographic data from the Science Citation Index
(2) identify bibliographic records corresponding to a set of source journals
(3) select the most representative author population above a citation threshold
(4) compute author cocitation counts
(5) generate author cocitation matrices
(6) identify the essential structure of the subject domain using factor analysis
(7) preserve the strongest semantic relations using Pathfinder network scaling
(8) superimpose high-dimensional features of author cocitation networks through animation
(9) map semantic models to spatial models
(10) incorporate citation history of individuals into the spatial-semantic model using color mapping
(11) present the spatial-semantic model as information landscape
(12) enable multiuser access to the domain through the information landscape.

Major steps in the procedure are explained in detail in the following sections.

Data Collection

The bibliographic data were drawn from Science Citation Index to cover all the articles published in IEEE CG&A, which was launched in 1981. SCI's records started from the second volume in 1982 through current issues in 1999. Extending the data to other journals indexed in SCI and SSCI will be straightforward. Figure 1 shows the distribution of articles published in the journal over the past 18 years. Other types of publications in the journal, such as editorial and report, were not included in the study.

Representative authors in the subject area were selected for subsequent analysis. A total of 10,292 unique articles were identified in the citation data; 5,312 unique first-author names were also identified (see Table 1). Authors who have been cited for more than five times by articles in the journal were selected for the subsequent cocitation analysis. This resulted in a total of 353 authors. Author cocitation networks of these top-sliced authors will be used to represent the core structure of the domain.

Most Cited Sources

Sources of citations, such as journals, conference series, and books, provide additional insights into communication channels associated with a particular subject domain. The top three most cited sources in IEEE CG&A were ACM SIGGRAPH Conferences on computer graphics, the journal itself, and *Communications of the ACM*. *ACM Transactions on Computer Graphics* and *IEEE Computer* were in the top 10. In addition to journals and conference proceedings, a few classic computer graphics books appeared in the list (see Table 2).

Most Cited Works

The top 20 most frequently cited works in IEEE CG&A included some of the most fundamental and influential works (see Table 3). The top three works were books that also appeared as most cited sources. Whitted's ray tracing paper in 1980 was the top-ranked journal article.

Most Cited Authors

To identify people who have shaped the field of computer graphics, we listed the top 100 authors who were cited the most by IEEE CG&A. To a reasonable extent, this list reflects the image of this field projected by major sources such as IEEE CG&A, ACM SIGGRAPH, and *Communications of the ACM*. The nature of their contributions to the field will become clearer in the author cocitation analysis and especially through matching citation contexts (Table 4).

Factor Analysis

Author cocitation counts were computed based on the 353 authors' citation records. Raw cocitation counts were transformed into Pearson's correlation coefficients as a means of measuring the proximity between authors' cocitation profiles. According to White and McCain (1998), it registers the likeness in shape of their cocitation count profiles over all other authors in the set. Self-citation counts were replaced with the mean cocitation counts for the same author.

A principal component analysis (PCA) was conducted on the 353×353 author cocitation matrix to identify salient dimensions that can explain the variance in the data. In information science, it is regarded that these dimensions correspond to groupings of research topics and subfields in scientific disciplines, i.e., specialties.

To determine the nature of each specialty, we examined the citation contexts associated with authors in the same specialty. We used *ResearchIndex* to retrieve detailed information about citation contexts for authors with the highest factor loading in each factor. For example, Whitted was the top-ranked author in the first factor identified by PCA. We searched the name of *Whitted*, and found that his most frequently cited work on the Web was CACM article in 1980, which has been cited for more than 50 times on the Web. It echoed its profile in IEEE CG&A. We examined a list of detailed citation examples of this particular article and determine what the nature of this author's contribution was. The profiles of leading authors in each specialty can be established in this way so as to characterize the corresponding specialty they belong to. The following excerpts from ResearchIndex illustrate this characterization process for Whitted's article:

Whitted, T. *An improved illumination model for shaded display*. Comm. ACM 23 (1980), 343-349.

Details Correct **Ray Tracing with Meta-Hierarchies** James Arvo - Apollo Systems Division of Hewlett-Packard - 300 Apollo Drive - Chelmsford, MA 01824 - arvo@apollo.hp.com, arvo@yale.edu ......and cons of this mechanism and suggest future research directions. **1 Introduction Ray tracing acceleration has received much attention in the decade since Whitted introduced his illumination model and established ray tracing as one of the preeminent algorithms for high fidelity image synthesis [Whitted 80].** Though virtually every aspect of the algorithm has been studied for potential optimization, perhaps the greatest emphasis has been on the problem of efficiently finding the first point of intersection between a ray and a complex environment. Following the taxonomy outlined in [Arvo 89] we can ......

[Whitted 80] Whitted, Turner. *"An Improved Illumination Model for Shaded Display,"* Communications of the ACM, 32(6), June 1980, pp. 343-349.

Details Correct **A Generic Algorithm For The Simulation Of Straight-Line Energy Flows Within A Geometric Environment** Marc Roelens - D'epartement Informatique Appliqu'ee - Ecole Nationale Sup'erieure des Mines de Saint-Etienne - 158, Cours Fauriel - 42023 Saint-Etienne Cedex 2 - France ......environment. The Constructive Solid Geometry methodology is used to model the environment. Properties can be attached to any object in this environment, either to the inside or to the boundary. An application in the field of computer graphics is described. INTRODUCTION **The ray tracing algorithm (Whitted 1980) is now a widely used algorithm in computer graphics.** Basically, it works as follows: for each point in an screen (a pixel), it constructs a ray starting from the eye and passing through that point. This ray, called a primary ray is intersected with the objects in the environment and the nearest ......

Whitted, T. 1980. *"An Improved Illumination Model for Shaded Display."* Communications of the ACM 24, no. 6 (June): 343–349.

Details Correct **Density Estimation on Delaunay Triangulations** Leif P. Kobbelt, Marc F. Stamminger, Hans-Peter Seidel - University of Erlangen, Computer Graphics Group - Am Weichselgarten 9. 7, 91058 Erlangen, Germany - Email: kobbelt@informatik.uni-erlangen.de ......requires lengthy computations and large memory. Nevertheless, the subtle indirect lighting effects which can only be captured by such methods are essential if realistic images are to be obtained. **Ray tracing is still the mostly used method in commercial rendering systems for high quality rendering [10, 3].** To some extend, indirect illumination can be computed by stochastically sending recursive rays (distribution ray tracing), but especially diffuse surfaces would require an exploding number of rays to get reasonable results without too much noise caused by the stochastic sampling scheme. Many ......

[10] T. Whitted. *An improved illumination model for shaded display*. Computer Graphics (Special SIGGRAPH '79 Issue), 13(3):1–14, August 1979.

Mapping the Knowledge Domain

Authors' citation profiles were transformed into author cocitation matrices, either for the entire sample period or for each year's data. Author cocitation networks were submitted to Pathfinder network scaling to highlight the most essential structural characteristics of the domain.

Resultant Pathfinder networks were rendered as a virtual landscape of the knowledge domain. We first placed the Pathfinder networks into the landscape and then incrementally superimposed additional information to develop a semantic-rich and coherent representation of the field. We included citation time series and depicted the results of factor analysis within the same model. These virtual-reality models allow users to zoom in and out and explore the structure.

The three-dimensional landscape reinforces the underlying semantics and helps users to draw their interpretations naturally. Authors in the center of the Pathfinder network tend to be ones who have made profound and fundamental contributions to the field, whereas authors located in areas remote to the center tend to be known for their special and unique works.

On top of the author cocitation network, the citation time series of each author over the 18-year span was color mapped to a stacked bar. Each section of the stacked bar was displayed in a unique color. The length of the section was proportional to the number of citations of this particular author in a particular year. Citations in recent years are in bright yellow, and citations in earlier years are in darker colors. By looking at the color towards the top of an author's citation bar, one would be able to tell whether this author's work is currently in its peak or it was out of fashion some years ago. Domain analysts will be able to identify rising stars, those authors with an extended range of bright

TABLE 3. Top 20 most frequently cited works in IEEE CG&A 1982–1999, vol. 2(1)–vol. 19(3).

Cites	Works
61	FOLEY_JD, 1982, FUNDAMENTALS INTERAC
48	NEWMAN_WM, 1979, PRINCIPLES INTERACTI
44	PREPARATA_FP, 1985, COMPUTATIONAL GEOMET
30	WHITTED_T, 1980 VOL. 23 P. 343, COMMUN ACM
20	FAUX_ID, 1979, COMPUTATIONAL GEOMET
19	MEAGHER_D, 1982 VOL. 19 P. 129, COMPUTER GRAPHICS IM
18	LORENSEN_WE, 1987 VOL. 21 P. 163, COMPUT GRAPH
16	LEVOY_M, 1988 VOL. 8 P. 29, IEEE COMPUT GRAPH AP
15	DREBIN_RA, 1988 VOL. 22 P. 65, COMPUT GRAPH
15	PHONG_BT, 1975 VOL. 18 P. 311, COMM ACM
15	BRESENHAM_JE, 1965 Vol. 4 p. 25, IBM SYST J
14	PORTER_T, 1984 Vol. 18 p. 253, COMPUT GRAPH
14	REQUICHA_AAG, 1982 VOL. 2 P. 9, IEEE COMPUTER GRAPHI
14	ROTH_SD, 1982 VOL. 18 P. 109, COMPUTER GRAPHICS IM
14	GOURAUD_H, 1971 VOL. 20 P. 623, IEEE T C
13	JACKINS_CL, 1980 VOL. 14 P. 249, COMPUTER GRAPHICS IM
13	DEBOOR_C, 1978, PRACTICAL GUIDE SPLI
13	FUCHS_H, 1977 VOL. 20 P. 693, COMMUN ASS COMPUT MA
12	KAJIYA_JT, 1986 VOL. 20 P. 143, COMPUT GRAPH
12	PORTER_T, 1984 VOL. 18 P. 253, COMPUT GRAPH

colors in their citation bars, or shooting stars, whose citation bars are largely covered by dark colors. This color mapping provides analysts and researchers a means of tracking the development of their domain. These maps also provide direct access points to bibliographic and full-text digital libraries. Researchers and analysts can use these maps directly in their citation analysis and domain analysis.

Results

Author Cocitation Analysis

Factor analysis identified 60 factors in the 353 × 353 author cocitation matrix, corresponding to 60 underlying specailties, or subfields. The first two factors explained 13 and 11% of the variance, respectively, whereas the top five factors accounted for 39% of the variance. Figure 4 shows the eigenvalues of the top five factors and the percentage variance explained (Fig. 2).

To discover the nature of the major factors, we listed the names of the top 30 authors for each top-5 factor (see Table 5). We then examined the citation profiles of these authors to establish why they were cited.

Specialties in Context

The nature of five most predominant specialties was identified as follows, based on crossexaminations of citation contexts for leading members of each specialty.

Factor 1: Rendering and Ray Tracing

The first factor is predominated by the names of several well-known computer graphics scientists in various classic rendering techniques, including Whitted's illumination model for ray tracing, Williams' classification of level of details, the Cook-Torrance lighting model, and the famous Phong shading model. Whitted's original article in 1980 is ranked as the second most cited work for a total of 30 times in the IEEE CG&A data.

One of the most cited authors in IEEE CG&A, James Blinn, is also identified in this group. He has received a total of 91 citations, ranked as the third. Blinn has been an active author, and this partially explains why his citation profile is not in the top 20 of the first factor ranked by factor loading. Blinn's seminal work on implicit surface modeling is known through his popular blobby model. This factor, therefore, indicates a specialty that includes pioneering works in rendering and computer-generated images.

The most frequently cited work in the IEEE CG&A data is the book by Foley and van Dam, published in 1982, entitled *Fundamentals of Interactive Computer Graphics*. This book covers a wide range of topics in computer graphics, and it is difficult to associate it with particular specialties in the field. This observation is reflected by the fact that the corresponding factor loading for Foley does not enter the top 30 in the first five factors (Table 6).

Factor 2: Computer Vision

The second specialty revealed by factor analysis is labeled as *computer vision*. This group is characterized by a number of pioneering researchers in this subfield of computer graphics, including Tilove's set membership classification on intersection problems and detecting collision paths. Search on ResearchIndex has revealed a total of 263 citations of Ballard and Brown's book, entitled Computer Vision. These authors' works represent some typical research in computer vision (Table 7).

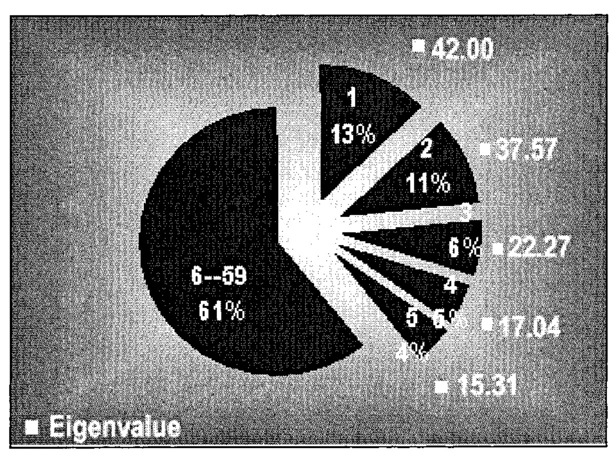

FIG. 2. Eigenvalues of the top five factors 1–5, explaining 39% of variance. The rest of factors explained 61% of variance.

TABLE 4. Top 100 most frequently cited authors in IEEE CG&A.

Rank	Citation	Name	Rank	Citation	Name
1	105	REQUICHA_AAG	51	26	RIESENFELD_RF
2	97	FOLEY_JD	52	26	TERZOPOULOS_D
3	91	BLINN_JF	53	26	WILHELMS_JP
4	70	BARSKY_BA	54	26	WILLIAMS_L
5	60	FUCHS_H	55	25	BARNHILL_RE
6	59	CATMULL_EE	56	25	MARCUS_A
7	59	CROW_FC	57	25	VOELCKER_HB
8	57	KAJIYA_JT	58	24	GOURAUD_H
9	53	HERMAN_GT	59	24	PORTER_TK
10	53	SEDERBERG_TW	60	24	ROSSIGNAC_JR
11	51	WHITTED_JT	61	23	BOYSE_JW
12	49	MAX_NL	62	23	GORDON_WJ
13	46	MAGNENATTHALMAN_N	63	22	COONS_SA
14	45	BADLER_NI	64	22	HALL_RA
15	45	NEWMAN_WM	65	22	HERBISONEVANS_D
16	43	MANTYLA_MM	66	22	KUNII_TL
17	43	PIEGL_L	67	22	PARKE_FI
18	42	COOK_RL	68	21	BARR_AH
19	42	ROGERS_DF	69	21	BARTELS_RH
20	41	FARIN_GE	70	21	CLARK_JH
21	41	KAUFMAN_AE	71	21	COHEN_ES
22	40	REEVES_WT	72	21	HOFFMANN_CM
23	40	SUTHERLAND_IE	73	21	MANDELBROT_BB
24	40	TILOVE_RB	74	20	BEZIER_PE
25	39	BRAID_IC	75	20	EASTMAN_CM
26	34	HECKBERT_PS	76	20	FUJIMOTO_A
27	34	MEAGHER_DJ	77	20	HANRAHAN_PM
28	33	BAUMGART_BG	78	20	REYNOLDS_CW
29	33	LANE_JM	79	20	VANNIER_MW
30	33	WEILER_KJ	80	20	VANWIJK_JJ
31	32	GLASSNER_AS	81	20	WOO_TC
32	32	LEVOY_M	82	20	WYVILL_G
33	30	FAUX_ID	83	19	AMANATIDES_J
34	30	FOURNIER_A	84	19	COHEN_MF
35	30	LORENSEN_WE	85	19	DREBIN_RA
36	30	PERLIN_K	86	19	GOLDWASSER_SM
37	30	PHONG_BT	87	19	YAMAGUCHI_K
38	30	ZELTZER_D	88	18	BLOOMENTHAL_J
39	29	ATHERTON_PR	89	18	CHIYOKURA_H
40	29	BOEHM_W	90	18	FARRELL_EJ
41	29	ROTH_SD	91	18	FEINER_S
42	29	SMITH_AR	92	18	KNOWLTON_KC
43	28	FORREST_AR	93	17	ARMSTRONG_WW
44	28	GOLDMAN_RN	94	17	BROWN_CM
45	28	NIELSON_GM	95	17	FRANKLIN_WR
46	27	ROBERTSON_PK	96	17	GOLDSTEIN_RA
47	27	UDUPA_JK	97	17	MYERS_BA
48	26	BRESENHAM_JE	98	17	POTMESIL_M
49	26	DEBOOR_C	99	17	TILLER_W
50	26	NISHITA_T	100	16	CARD_SK

Factor 3: Geometric Modeling and Computer-Aided Design

Several names in the specialty identified by factor 3 are related to the concept of spline. Splines are curve and surface representations defined with piece-wise polynomial functions. This group is dominated by the presence of computer-aided design and geometric modeling.

Bezier's name appears in the top 5 of this factor, whose name has been associated with a number of fundamental concepts in geometric modeling, including the famous Bernstein-Bezier patches and Bezier clipping. The Bernstein-Bezier representation has been extremely useful in characterizing multivariate spline bases. Bezier Clipping is an iterative clipping method that takes advantage of the convex hull property of Bezier curves, and clips away regions of the curve that does not intersect with the surface.

Bezier surfaces defined over a triangular domain are often called Bezier triangles. It was Sabin who first generalized Bezier to triangular B-splines. Sabin is on the top of the

TABLE 5. Factor membership. Top 30 authors ranked by factor loading of five most predominant factors, explaining 39: one percent of variance in the author cocitation profiles.

Authors	F1	Authors	F2	Authors	F3	Authors	F4	Authors	F5
Whitted_T	0.895	Tilove_RB	0.876	Sabin_MA	0.819	Gordon_D	0.663	Badler_NI	0.635
Williams_L	0.890	Wesley_MA	0.873	Boehm_W	0.776	Frieder_G	0.651	Zelter_D	0.600
Lee_ME	0.886	Voelcker_HB	0.866	Bartels_RH	0.774	Udupa_JK	0.649	Mandelbrot_B	0.597
Kay_DS	0.885	Brown_CM	0.861	Bezier_PE	0.774	Cook_LT	0.649	Reynolds_CW	0.578
Max_NL	0.878	Boyse_JW	0.859	Deboor_C	0.770	Artzy_E	0.628	Parke_FI	0.577
Cook_RL	0.875	Woo_TC	0.857	Coons_SA	0.765	Goldwasser_SM	0.627	Armstrong_WW	0.572
Warn_DR	0.874	Mantyla_M	0.851	Goodman_TNT	0.759	Chen_LS	0.627	Gordon_D	0.570
Hourcade_JC	0.874	Lee_YT	0.845	Riesenfeld_RF	0.754	Reynolds_RA	0.623	Thalmann_D	0.564
Phong_BT	0.862	Markowsky_G	0.834	Joe_B	0.754	Fuchs_H	0.622	Wilhelms_J	0.557
Hall_RA	0.858	Morgan_AP	0.829	Schoenberg_IJ	0.747	Dev_P	0.601	Udupa_JK	0.556
Bouknight_WJ	0.857	Veenman_P	0.826	Derose_TD	0.745	Rhodes_ML	0.598	Cook_LT	0.555
Atherton_P	0.856	Wordenweber_B	0.824	Farin_G	0.732	Keppel_E	0.572	Calvert_TW	0.546
Crow_FC	0.853	Weiler_KJ	0.820	Nielson_GM	0.726	Herman_GT	0.566	Baecker_RM	0.543
Kajiya_JT	0.845	Baumgart_BG	0.810	Tiller_W	0.712	Glenn_WV	0.557	Artzy_E	0.542
Nishita_T	0.840	Okino_N	0.795	Goldman_RN	0.711	Vannier_MW	0.554	Magnenatthalman_N	0.540
Gardner_GY	0.829	Wilson_PR	0.780	Faux_ID	0.693	Farrell_EJ	0.537	Frieder_G	0.540
Heckbert_P	0.827	Spur_G	0.779	Cohen_E	0.687	Crow_F	0.472	Paul_RP	0.538
Potmesil_M	0.822	Yamaguchi_F	0.777	Hagen_H	0.682	Srihari_SN	0.427	Burtnyk_N	0.537
Rubin_SM	0.818	Braid_IC	0.770	Forrest_AR	0.680	Hersch_RD	0.417	Reynolds_RA	0.531
Blinn_JF	0.818	Woodwark_JR	0.767	Gordon_WJ	0.676	Drebin_RA	0.416	Goldwasser_SM	0.527
Peachey_DR	0.818	Gossard_DC	0.767	Versprille_KJ	0.666	Kaufman_A	0.394	Chen_LS	0.519
Flume_E	0.816	Kedem_G	0.761	Lane_JM	0.630	Danielsson_PE	0.375	Stern_G	0.518
Hanrahan_P	0.815	Fitzgerald_W	0.761	Barnhill_RE	0.626	Sproull_RF	0.372	Dev_P	0.511
Amanatides_J	0.800	Hanna_SL	0.749	Klass_R	0.588	Levoy_M	0.357	Hodgins_JK	0.507
Goral_CM	0.799	Miller_JR	0.747	Piegl_L	0.539	Meagher_D	0.348	Girard_M	0.502
Duff_T	0.797	Carlson_WE	0.735	Barsky_BA	0.536	Meagher_DJ	0.322	Witkin_A	0.498
Glassner_AS	0.792	Eastman_CM	0.730	Pottmann_H	0.533	Hoehne_KH	0.319	Korein_JU	0.497
Fujimoto_A	0.791	Rossignac_JR	0.730	Bohm_W	0.528	Christiansen_HN	0.318	Rhodes_ML	0.494
Greene_N	0.788	Carlbom_I	0.711	Bezier_P	0.526	Schwartz_EL	0.309	Herbisonevans_D	0.487
Goldstein_RA	0.787	Doo_D	0.693	Rogers_DF	0.517	Hohne_KH	0.290	Vannier_MW	0.487

membership list according to factor loading on this factor (Table 8).

Factor 4 Image Processing

Ray tracing and direct projection are two basic methods for generating directly rendered images. In ray tracing, viewing rays are sent through each pixel and integrated through the volume. In direct projection, each cell of the volume is projected onto the screen. In contrast to the ray-tracing specialty identified by factor 1, factor 4 corresponds to a group of researchers often associated with direct projection. The first two names ranked in this factor, Dan Gordon and Gideon Frieder, are frequently cited for their work in direct project. This specialty also includes research-

TABLE 6. Specialty identified by factor 1.

F1	Web[a]	Titles	Context of citation
0.895	79	Whitted, T. (1980). An improved illumination model for shaded display. Communications of the ACM, 23, 343–349.	Ray tracing, Whitted illumination model
0.890	30	Williams, L. (1983). Pyramidal parametrics. SIGGRAPH 83, 1–11.	Mip-mapping, level of detail
0.878	29	Nelson Max et al. (1990). Area and volume coherence for efficient visualization of 3D scalar functions. Computer Graphics, 24(5), December 1990. San Diego Volume Visualization Conference Proceedings.	Ray tracing, volume rendering
0.875	30	Cook, R.L. and Torrance, K.E. (1982) A reflectance model for computer graphics. ACM Transactions on Graphics, 5(1), 51–72.	The Cook-Torrance lighting model
0.862	34	Phong, B.T. (1975). Illumination for computer generated pictures. Communications of the ACM, 18(6), 311–317.	Phong shading
0.818	50	Blinn, J.F., & Newell, M.E. (1976). Texture and reflection in computer generated images. Communications of the ACM, 19(10), 542–547.	A seminal paper on implicit surface modeling, i.e., the popular blobby model.

[a]Citations on the Web as indexed by Research Index.

TABLE 7. Specialty identified by factor 2.

F2	Web	Titles	Context of citation
0.876	21	Tilove, R. (1980). Set membership classification: A unified approach to geometric intersection problems. IEEE Transaction on Computers, C-29, 874–883.	A generic set membership classification determines whether a point/line lies inside, outside or on the boundary of a Constructive Solid Geometry (CSG) model.
0.873	70	Lozano-Perez, T., & Wesley, M. (1979). An algorithm for planning collision-free paths among polyhedral obstacles. Communications of the ACM, 22. 560–570.	Configuration space representation of a motion-planning problem (robot).
0.866	7	Voelcker, H. (1993). A current perspective on tolerancing and metrology. Manufacturing Review, 6(4), 258–268.	Determining the range of possible boundaries of a part given tolerance specifications.
0.861	263	Ballard, D.H., & Brown, C.M. (1982). Computer vision. Englewood Cliffs, NJ: Prentice-Hall.	Computer vision.
0.859	12	Boyse, J.W. (1979). Interference detection among solids and surfaces. Communications of the ACM, 22(1), 3–9.	Detecting and analyzing collisions between a moving and a stationary object.

ers in image processing, especially in processing brain images and contour interpolation. Interpolation between contours is a general problem in computer graphics. This problem has been dealt with by algorithms that address the correct mapping or correlation of contours points at one level with those at an adjoining level. This specialty is therefore characterized as image processing (Table 9).

Factor 5: Modeling the Nature

An examination of the citation contexts associated with the top 5 scholars in this factor reveals that they are all related to the modeling of the nature, including human figures, facial expressions, flocking behaviors of birds, coastlines, and mountains.

The human body model consists of 69 articulated parts, 138 degrees of freedom, and 70 joints. The Jack human–body animation system, developed at the University of Pennsylvania's Center for Human Modeling and Simulation, is a landmark work in computer graphics and especially in the simulation and animation of realistic movements of human figures. Parke's parametrized facial modeling approach is also a predominant player in this specialty group. This specialty group also includes Reynolds' pioneering work in simulating flocking behavior in birds. Research in related areas has frequently referred to this model.

Fractals, coined by Mandelbrot, have been used to describe spiky, irregular or variegated objects, such as coastlines, mountains, and crystals. A common example is the computation of the length of a shoreline. The shoreline becomes longer and longer as the resolution of the map increases as one has to account for every new visible creek for higher resolutions. Zipf's Law, which is also explained in Mandelbrot's book, qualifies that the degree of popularity is exactly inversely proportional to rank of popularity. A number of citations to Mandelbrot's work applied this law to the modeling of behavioral patterns such as accessing documents on the Web. The relatively predominant position of fractals in factor 5 suggests that this specialty shares some common interests in modeling of the nature, especially human figures, facial expressions, animal behavior, coastlines, and mountains (Table 10).

Table 11 lists the major journal titles associated with each factor. These journals together also gave some clues about the nature of groupings. However, at this level of categorization, many interesting details were lost.

TABLE 8. Specialty identified by factor 3.

F3	Web	Titles	Context of citation
0.819	26	Doo, D., & Sabin, M. (1978). Behaviour of recursive division surfaces near extraordinary points. Computer-Aided Design, 10(6), 356–360.	An algorithmic generalization of classical spline techniques enabling control meshes with arbitrary topology.
0.776	16	Boehm, W., Farin, G., & Kahmann, J. (1984). A survey of curve and surface methods in CAGD. Computer Aided Geometric Design, 1(1), 1–60.	
0.774	66	Bartels, R.H., Beatty, J.C., & Barsky, B.A. (1987). An introduction to splines for use in computer graphics and geometric modeling. San Mateo, CA: Morgan Kaufman Publishers Inc.	Splines, referring to curve and surface representations defined with piece-wise polynomial functions
0.774	2	Bezier, P. (1972). Numerical control. Mathematics and applications. New York: Wiley.	
0.770	20	deBoor C. (1978). A practical guide to splines. New York: Springer-Verlag.	Polynomial spline interpolation and approximation

TABLE 9. Specialty identified by factor 4.

F4	Web	Titles	Context of citation
0.663	3	Gordon, D. (1985). Image space shading of 3-dimensional objects. Computer Vision, Graphics, and Image Processing, 29, 361–376.	Volume rendering
0.651	13	Frieder, G., Gordon, D., & Reynolds, A. (1985). Back-to-front display of voxel-based objects. IEEE Computer Graphics and Applications, 5(1) 52–60.	Volume rendering, direct projection
0.649	13	Raya, S.P., & Udupa, J.K. (1990). Shape-based interpolation of multidimensional objects. IEEE Transactions on Medical Imaging, 9, 32–42.	Brain image segmentation.
0.649	4	Batnitzky, S., Price, H.I., Cook, P.N., Cook, L.T., & Dwyer S.J., III. (1981). Three-dimensional computer reconstruction from surface contours for head CT examinations. Journal of Computer Assisted Tomography, 5, 60–67.	Reconstruction from surface contours
0.628	4	Artzy, E., Frieder, G., & Herman, G.T. (1981). The theory design, implementation and evaluation of a three-dimensional surface detection algorithm. Computer Graphics and Image Processing, 15, 1–24.	A method to extract the faces shared by a voxel of the object and a voxel of the background.

An informative way to reveal the dynamic structure of a field is to trace the presence of institutions in the citation networks. Figure 6 shows 13 the publication profiles of 13 most productive institutions. Each of them has produced more than 10 article-type publications in IEEE CG&A (blue bars). The red bars represent the number of editorials published from authors affiliated with these institutions. The inset shows the time series of the number of articles published each year by authors affiliated with CalTech (1st) and Microsoft Research (13th). Blinn, formerly at CalTech and now at Microsoft Reseach, has published 35 articles in CG&A over 11 years. The second most productive author was Kunii, University of Tokyo, who has 17 CG&A articles over 7 years. Glassner, formerly University of North Carolina and now Microsoft Research, has 16 CG&A articles over 10 years. Such information would be useful for researchers to follow up the works of these leading researchers in the field (Figs. 3 and 4).

The next figure shows the most productive institution of each year over the 18-year history of CG&A. CALTECH has peaked seven times, Microsoft Research twice, and the University of North Carolina also twice.

Mapping the Knowledge Domain

A Semantic Space

Figure 6 shows a semantic map of title terms based on 1,640 articles published in IEEE CG&A. The structure of the network was derived from patterns of how these terms have been used in these titles. We used techniques such as Latent Semantic Indexing (LSI) and Pathfinder network scaling in the modeling and visualizing the semantic map. Each word in the map was colored to reflect its relative predominance. Words in red tend to connect to more popular subjects, for example, *spline*, *shading*, and *volume* (Figs. 5 and 6).

Author Cocitation Network

Figure 7 reveals the structure of an author cocitation network derived from the IEEE CG&A data. First, we used factor loading of the three most significant factors to color the network. The central area is in red, which corresponds to the most predominant factor. The green area to the left indicates the second most predominant factor of the field. The blue area to the right represents the third factor. The nature of these factors will be explained shortly. Note that

TABLE 10. Specialty identified by factor 5.

F5	Web	Titles	Context of Citation
0.635	36	Badler, N.I., Phillips, C.B., & Webber, B.L. (1993). Simulating humans: Computer graphics animation and control. New York: Oxford University Press.	Jack™, an animation system that provides human figures capable of realistic motion through model-based inverse kinematics.
0.600	12	Badler, N.I., Barsky, B., & Zeltzer, D. (1991). Making them move. San Mateo, CA: Morgan Kaufmann Publishers Inc.	Creating natural-looking skin and deformations across joints is a particularly difficult problem, and this is where many animal models fail.
0.597	228	Mandelbrot, B. (1982). Fractal geometry of nature. New York: Freeman.	Fractals, defined by self-similar structures, are used to model coastlines.
0.578	48	Reynolds, C.W. (1987). Flocks, herds, and schools: A distributed behavioral model. Computer Graphics, 21, 25–34.	Simulated flocking behavior in birds.
0.577	10	Parke, F.I. (1982). Parametrized models for facial animation. IEEE Computer Graphics, 2(9), 61–68.	The Parke facial model approximates the surface of a human face including eyes, eyebrows, lips, and teeth. The surface can be deformed using 50 parameters and moving the vertices of the polygon network in different ways.

TABLE 11. Representative journal titles for each factor based on top 50 members' citation records (factor loading range).

F1 (0.895–0.621)	F2 (0.876–0.570)	F3 (0.819–0.290)	F4 (0.663–0.175)	F5 (0.635–0.260)
409 COMPUTER GRAPHICS	108 IEEE COMPUTER GRAPHI	87 COMPUTER AIDED GEOME	92 IEEE COMPUTER GRAPHI	128 COMPUTER GRAPHICS
98 COMMUN ACM	53 COMPUTER GRAPHICS IM	41 IEEE COMPUT GRAPH	88 COMPUT GRAPH	77 IEEE COMPUTER GRAPHI
48 IEEE COMPUT GRAPH	43 COMPUTER GRAPHICS	38 COMPUT AIDED DESIGN	49 FUNDAMENTALS INTERAC	47 COMPUTER GRAPHICS IM
31 COMPUTER GRAPHIC JUL	20 COMM ACM	33 IEEE COMPUTER GRAPHI	45 COMPUTER GRAPHICS IM	17 P GRAPHICS INTERFACE
29 ACM T GRAPHICS	19 COMPUTER AIDED DESIG	27 COMPUTER GRAPHICS IM	14 MATH ELEMENTS COMPUT	15 P IEEE
24 THESIS U UTAH SALT L	17 IBM J RES DEV	26 COMPUTATIONAL GEOMET	13 P IEEE	14 COMPUTER GRAPHIC JUL
16 COMPUTER GRAPHICS IM	11 COMPUTER	17 CURVES SURFACES COMP	12 PROCEDURAL ELEMENTS	13 COMMUN ACM
	10 P IEEE	16 PRACTICAL GUIDE SPLI	11 IBM J RES DEV	11 IBM J RES DEV
		14 MATH ELEMENTS COMPUT	10 P SPIE	
		13 ACM T GRAPHIC	7 VOLUME VISUALIZATION	
		12 PROCEDURAL ELEMENTS	6 P SOC PHOTO-OPT INST	
		11 THESIS SYRACUSE U SY	5 VISUAL COMPUTER	
		10 NUMERICAL CONTROL MA	4 SCIENTIFIC AMERICAN	

the entire network has not been completely covered by color areas, suggesting that authors outside the colored areas must be characterized by high-dimensional factors. Journals associated with each factor were colored by the same coloring scheme and listed next to the network.

Animation of High-Dimensional Specialties

To reveal the high-dimensional nature of the field, authors in each specialty were highlighted in turn in a sequence of animated frames. Areas associated with the current specialty will become brighter. The glowing area helps users to identify the position of a specialty in the global context of the entire network (Fig. 8).

Domain Landscape

To allow analysts and users to access and exploit the results of our modeling and visualization, we adapted the information landscape metaphor in the user interface design. Figure 7 is a screenshot of an information landscape, which includes the current IEEE CG&A model and two models we generated earlier based on ACM Hypertext conference proceedings and ACM CHI conference proceedings. The landscape model provides a semantic-rich and multifacet representation of the knowledge domain. It integrates several significant structures such as author cocitation networks, citation time series, high-dimensional specialties. The three-dimensional landscape invites users to explore trends and peaks of citations, clusters of authors, and shortest paths connecting two different areas.

Discussions

Domain visualization opens many opportunities for us to explore the dynamics of a knowledge domain at various levels. Domain analysts can follow hyperlinks from authors in the landscape to corresponding citation contexts in ResearchIndex to examine in detail how a particular article has been cited and perceived by fellow researchers. Information retrieval users can follow a different type of hyperlinks that connect authors' names to a list of their articles so that one can access the full-text version of a useful article via its author. Citation analysts can study both citation and cocitation patterns directly within the landscape model. For new researchers, the persistent landscape will give them a standing point to jump-start their own mental image of the field or as a reference framework to form their own understanding of the knowledge domain.

Significance of the Results

The significance of the results of a domain visualization of a particular knowledge domain can be assessed in several ways. In this article, three perspectives will be considered in order to triangulate the results: (a) the context of citation; (b) the ACM Computing Classification System (CCS); and *c) survey articles in the given field of study.

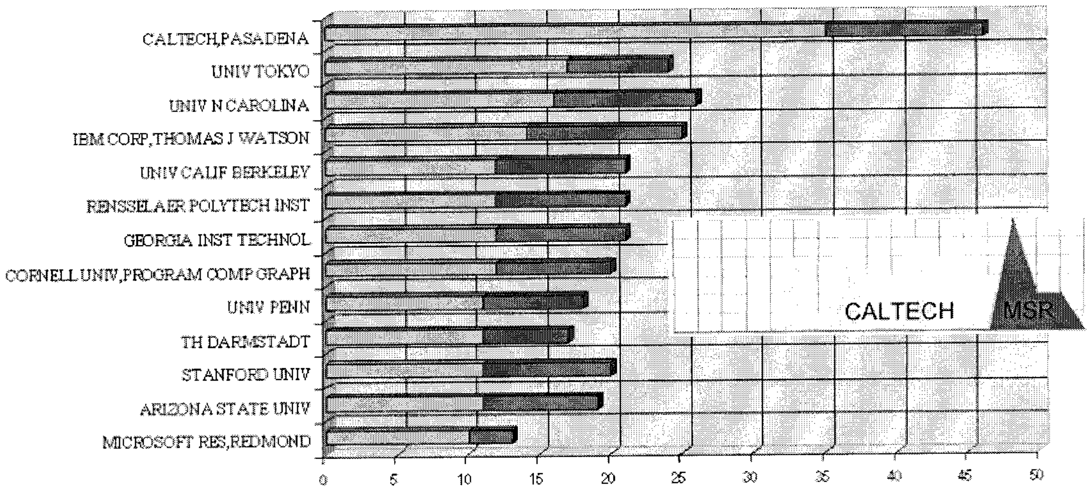

FIG. 3. Institutions that have produced more than 10 article-type publications in IEEE CG&A. The inset shows the records of Caltech and Microsoft Research.

In this article, we use crossexaminations of citation contexts through ResearchIndex to determine the nature of a specialty. We did not use the ACM Computing Classification System (CCS) or subjective review articles during the domain visualization process. Now, to analyze the significance of these results, we will find out to what extent our interpretation of the results will make sense in the context of the ACM CCS and the latest reviews of computer graphics.

Factor analysis reveals that the field of computer graphics consists of 59 factors in terms of author cocitation patterns, whereas the first five factors explain 39% of variance. The five most predominate factors are: (1) Rendering and Ray Tracing; (2) Computer Vision; (3) Geometric Modeling and Computer-Aided Design; (4) Image Processing; and (4) Modeling the Nature.

The animation of the high-dimensional specialty space has shown that the top five factors sum up the most representative parts of computer graphics.

According to the ACM CCS, computer graphics is classified under the Computing Methodologies with eight level-3 categories:

I.3.3 Picture/Image Generation
I.3.4 Graphics Utilities
I.3.5 Computational Geometry and Object Modeling
I.3.6 Methodology and Techniques
I.3.7 Three-Dimensional Graphics and Realism

CCS descriptors at the fourth level are comparable to the factors identified in our study. For example, factor 3 *Geometric Modeling and Computer-Aided Design* corresponds to CCS I.3.5: *Computational Geometry and Object Modeling*, which includes descriptors such as constructive solid geometry and splines. CCS I.3.7: *Three-Dimensional Graphics and Realism*, includes the largest number of common descriptors to the top five factors identified.

I.3.7 Three-Dimensional Graphics and Realism
- Animation
- Color, shading, shadowing, and texture
- Fractals
- Hidden line/surface removal
- Radiosity
- Raytracing
- Virtual reality
- Visible line/surface algorithms

To assess the significance of the results from our domain visualization, we also examine a set of latest review articles appeared on ACM Computing Surveys in 1996 on various aspects of computer graphics (see Table 12).

We acknowledge the limitation of using a single journal to map a subject domain, although the methodology is generic and extensible to include other sources of data. We are currently extending the study of computer graphics to several predominant journals in the field, such as ACM Transactions on Graphics. The scope and the readership of IEEE CG&A will have a significant impact on the domain image derived based on author cocitation patterns. This citation-based domain image may differ from subjective reviews of domain experts. On the other hand, subjective reviews provide an alternative perspective for us to judge the coverage of our findings.

Watt (1996) cited a total of eight articles in his review. The authors of three of these articles can be found within the top 10 members of factor 1, namely, Whitted, Cook, and Phong (see Table 5). This reinforces our interpretation of the memberships based on citation contexts and the classification of this factor as ray tracing and rendering.

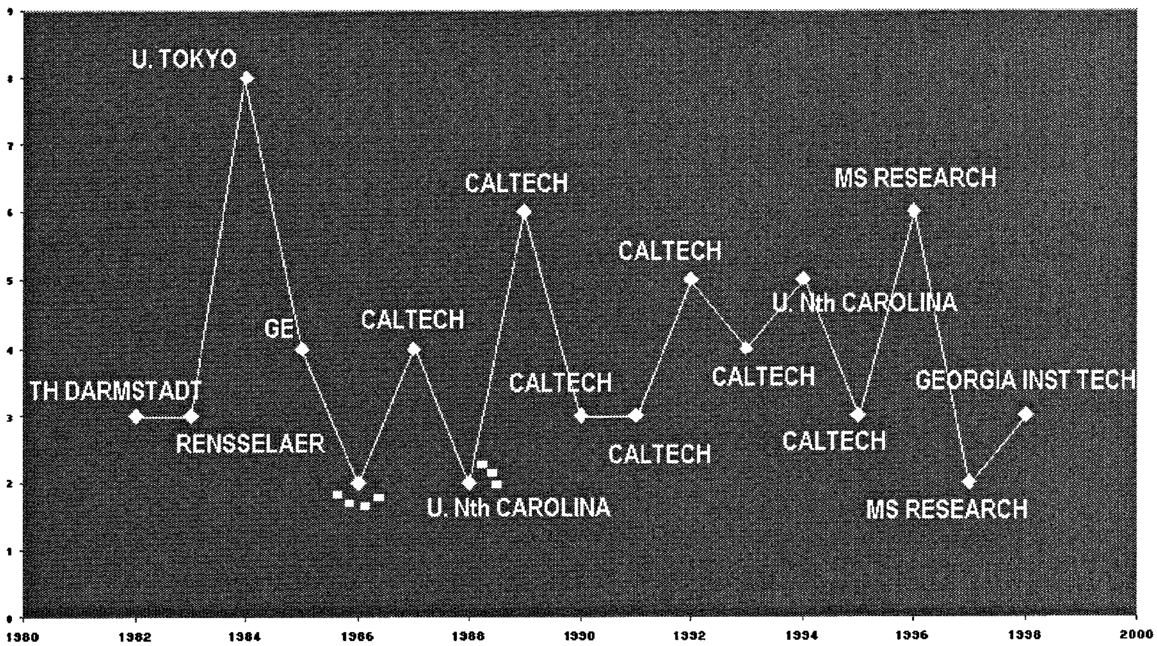

FIG. 4. The most productive institution of each year over the last 18 years of CG&A.

The review article of three-dimensional computer graphics (House, 1996) cites two authors in Factor 1 and one in Factor 3.

The review by Ebert (1996) of modeling techniques indirectly corresponds to Factor 3. Kaufman's (1996) review of volume visualization echoes Factor 4.

One of the coauthors of the computer animation review article (Thalmann & Thalmann, 1996) appears as the eighth in Factor 5 (see Table 5). Among the seven articles cited in their review, Balder_NI appears on the top of Factor 5 ranked by factor loading. This supports our classification of factor 5 as *Modeling the Nature*.

This initial evaluation suggests that the predominant factors identified indeed provide a meaningful picture of computer graphics as a field. Using the ACM CCS and review articles in the field as triangulation frameworks is

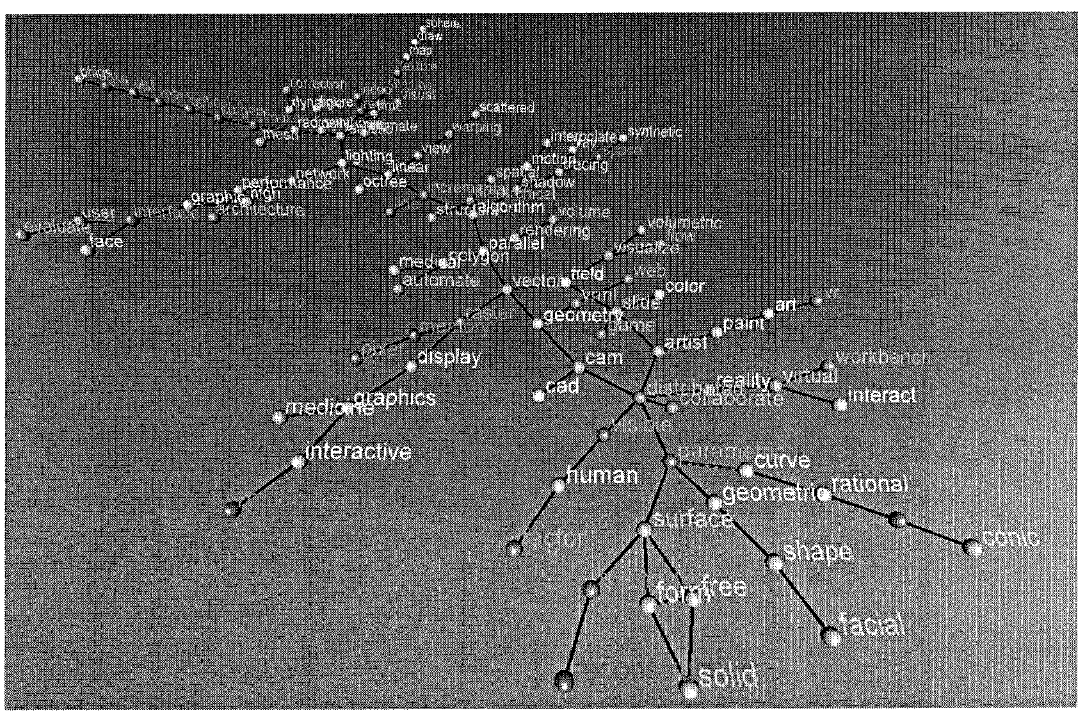

FIG. 5. A semantic map derived from the titles of 1,640 articles (terms = 106, links = 221).

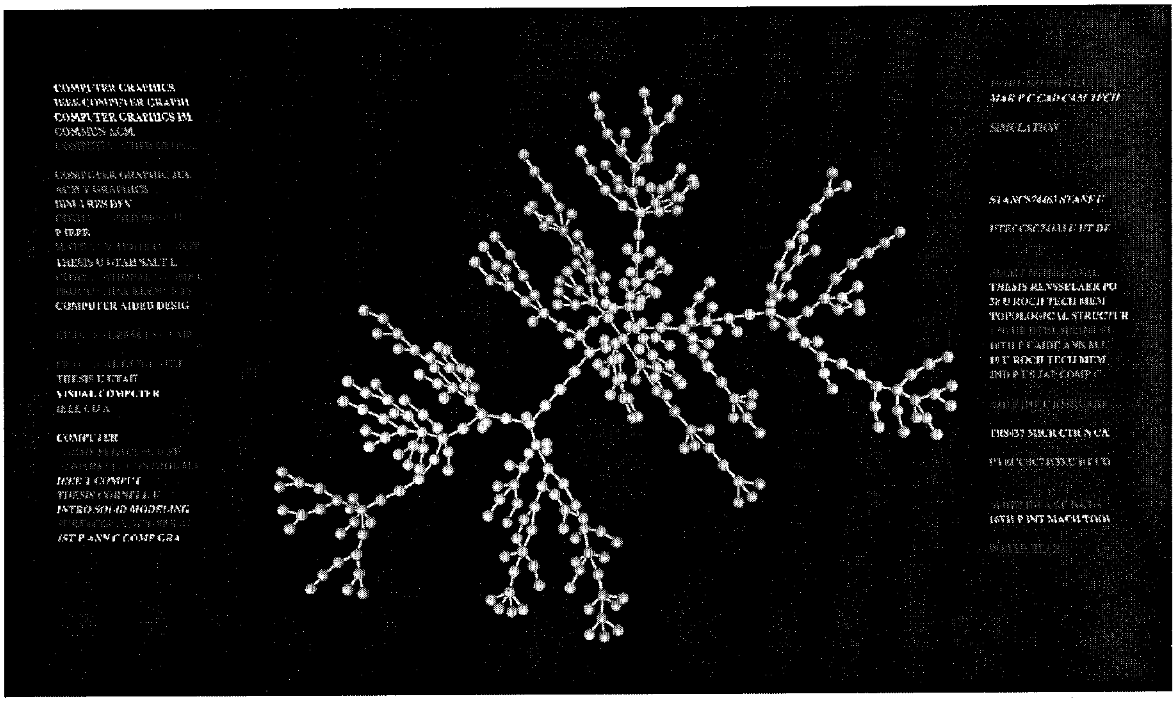

FIG. 6. The complex author cocitation network is divided by predominant factors into subfields of expertise (Pathfinder network ($q = 352$, $r = \infty$), $N = 353$, $E = 355$).

particularly appealing, as they compliment to the domain visualization approach based on citation analysis. The results of domain visualization prompt a different perspective for scientists to reflect their knowledge of the underlying subject domain.

Conclusions

In this article, we have described a visualization approach to domain analysis. We have applied this approach to the modeling and visualization of computer graphics. As a test drive, we analyzed the IEEE CG&A data. Because our data were directly drawn from SCI, there is a great potential of applying this methodology to other subjects and knowledge domains.

We have introduced the use of several techniques in a harmonic way, especially including Pathfinder networks, factor analysis, visualization and animation of high-dimensional abstract spaces. We have also highlighted the con-

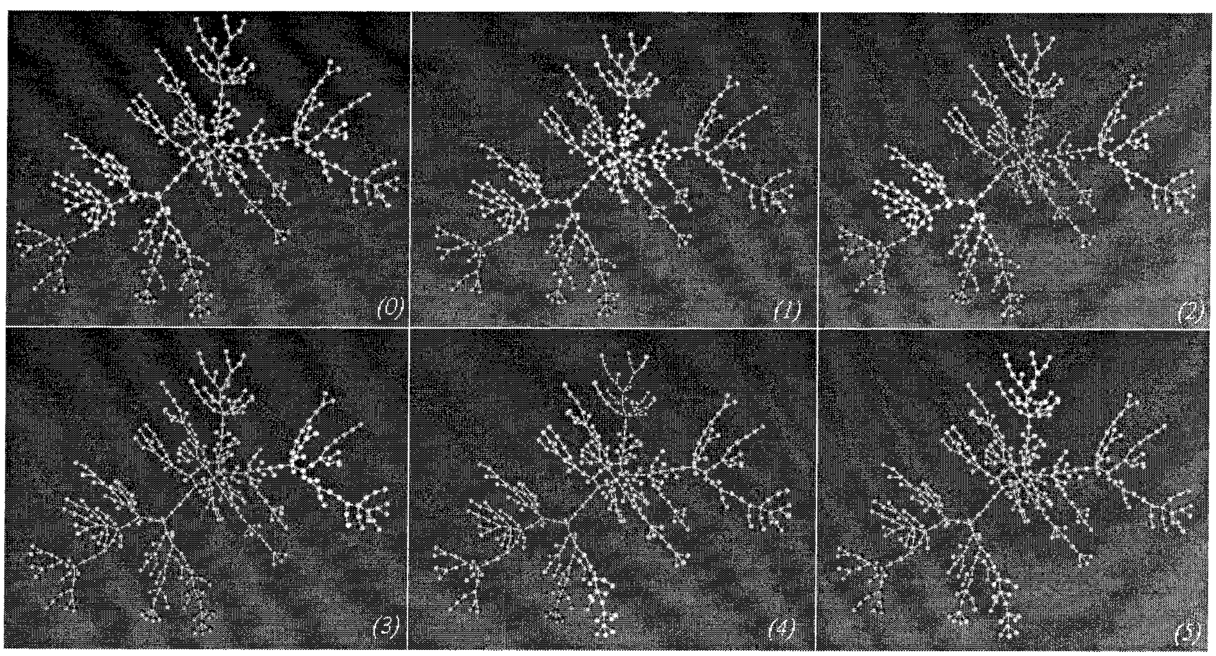

FIG. 7. A sequence of animation frames reveals the high-dimensional structure of the domain.

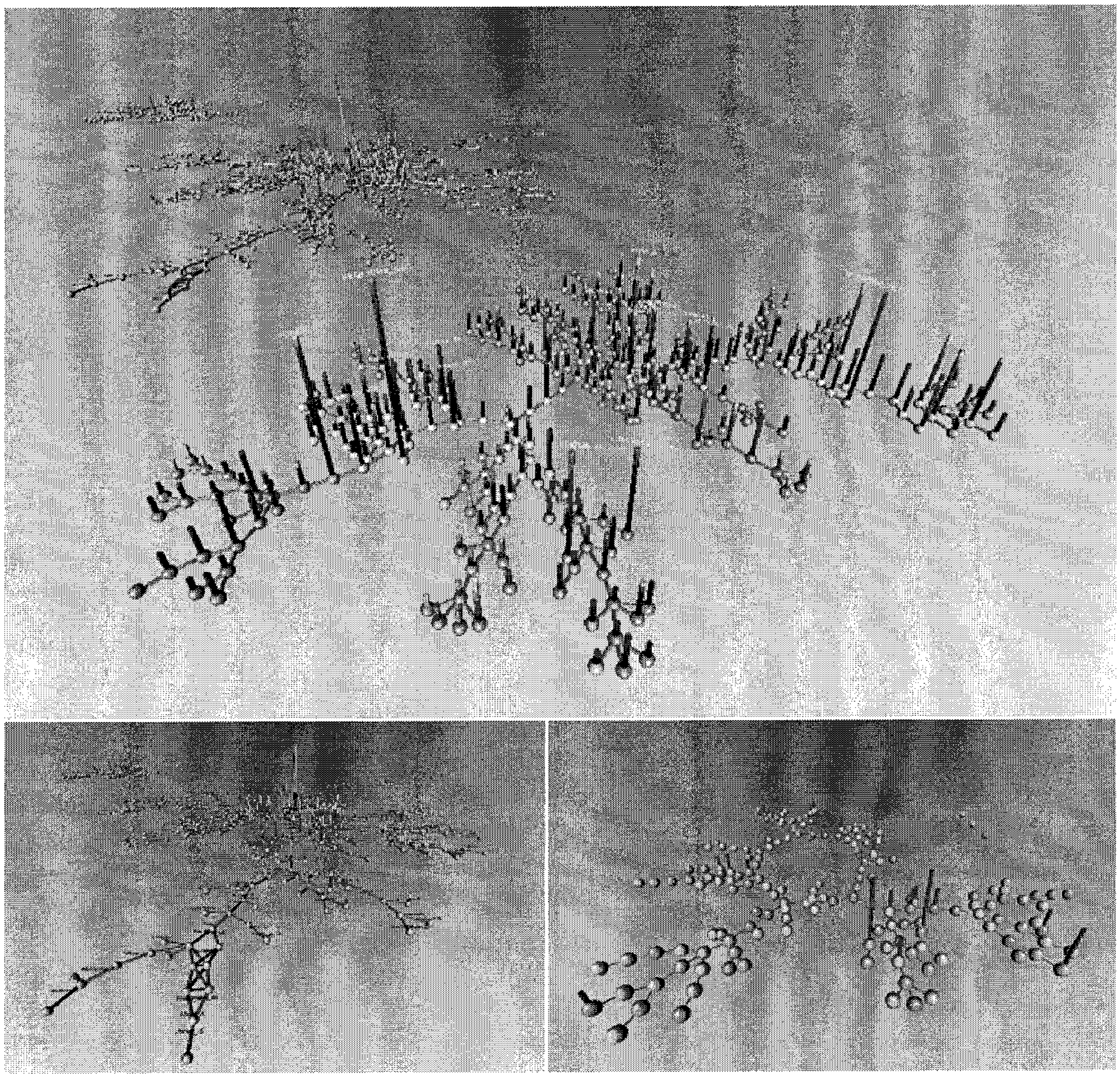

FIG. 8. A domain landscape of *IEEE CG&A* (1982–1999).

nection between our work and that of ResearchIndex, which has played a substantial role in helping us to assess the details and nature of various citations. A closer integration of these techniques will considerably advance our ability to track the growth of knowledge and map scientific disciplines. The practical use of the approach has implications on a variety of research fields, including information visualization, citation analysis, digital libraries, and domain analysis.

IEEE CG&A as a prestigious journal reflects significant aspects of computer graphics. Of course, it is not the only journal in the field. There are a vast amount of publications in the literature on this subject. To gain a comprehensive picture of the subject domain, one must consider other influential sources, such as journals and conference proceedings. As these relationships within a discipline become clearer, one can expect that mapping scientific disciplines will result in useful roadmaps to

TABLE 12. Crossreference between review articles and factors identified.

Reviews	Subfields reviewed	Matching factor	Factor name
(Watt, 1996)	Rendering techniques	1	Rendering and Ray Tracing
(House, 1996)	Three-dimensional computer graphics	1, 3	Rendering and Ray Tracing Geometric Modeling and Computer-Aided Design
(Ebert, 1996)	Modeling techniques	Indirect	Geometric Modeling and Computer-Aided Design
(Kaufman, 1996)	Volume visualization	4	Image Processing
(Thalmann & Thalmann, 1996)	Computer animation	5	Modeling the Nature

guide researchers to locate expertise as well as individual publications.

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Mackinlay, J.D., Rao, R., & Card, S.K. (1995). An organic user interface for searching citation links. Paper presented at the ACM CHI'95 conference on human factors in computing systems.

Noyons, E.C.M., Moed, H.F., & Luwel, M. (1999). Combining mapping and citation analysis for evaluative bibliometric purposes: A bibliometric study. Journal of the American Society for Information Science, 50(2), 115–131.

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