The Footnotes of Science

...in acknowledging the work of others, authors tell a lot about science itself.

Also see Introduction:Has citation analysis "arrived"? or, a footnote to "The footnotes of science"p.285, Essays, Vol:2

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Reprinted from:
Mosaic 6(2):22-27, March/April 1975.

In October 1971 an assistant professor of biochemistry was informed that her employment soon would be terminated. It was a routine matter for the university, but she didn't respond in a routine manner. She remembered that the university's Faculty Handbook listed as the criteria for promotion, "effectiveness as a teacher; research and scholarship; professional stature; and other contributions"—and she considered herself a competent teacher and a contributing scientist. She believed that the university had discriminated against her because she is a woman, since tenure had been granted to two comparable male assistant professors in the same department. She sought and was granted a court injunction under the Civil Rights Acts of 1964 (as amended in 1972), prohibiting the university from firing her pending trial.

In her case, which has not been resolved as of this writing, one question is paramount: How can scientific performance be accurately, objectively measured? A growing number of scientists believe that citation analysis of a researcher's published papers is the best measure of the scientist's competence and stature.

Evaluation of an individual scientist's performance in this way is a complex process in which sophisticated statistical methods are used. Basically, it makes use of an information mechanism which is built into the structure of every scientific paper: the citations by which the authors of papers acknowledge prior work upon which their papers are based. These acknowledgements are brought together each year in the *Science Citation Index* (SCI), published by the Institute for Scientific Information in Philadelphia, which allows them to be counted and handled mathematically.

Citation indexing is practiced by a new breed of sociometrician—the scientist of science, who is concerned with understanding the behavior of scientists and who bases his observations on the scientific journal literature. By examining the interconnecting links in networks of citations, these sociometricians can observe historical and sociological processes at work.

Counting citations

One way to measure a scientist's relative performance would be to take a raw citation count; simply count up all his citations and compare them with those of another

The raw data. In the annual *Science Citation Index*, a source index (left over-leaf) lists all journal items processed in a given year -- each item published by an author, including the co-authors, full titles, and other bibliographic data. The citation index (right over-leaf) shows which papers by the author have been subsequently cited by others.

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51 J CHEM SOC 257

MANZOORI M	Z NATURFO C		C 29	209	74

51 J CHEM SOC 278

VYSTRCIL A	COLL CZECH		39	1382	74

51 J CHEM SOC 1042

TEE OS	J AM CHEM S		96	3141	74

51 J CHEM SOC 1444

MILLIET A	TETRAHEDR L		1974	1939	74
WILLUHN G	PLANTA MED		25	115	74

51 J CHEM SOC 2988

52 J CHEM SOC 2210

MAZHARUL	J CHEM S P2		1974	228	74

53 CHEM IND 644

MINALE L	TETRAHEDRON		30	1341	74

53 J CHEM SOC 1027

DIMMOCK JR	CAN J PH SC		9	33	74
ROBB MA	MAGY KEM LA		29	121	74
RUZ M	AN AS QUIM		62	25	74

scientist. But what if the citations are self-citations (cited by the author himself)? What if a paper is cited because it is sloppy or in error? What if a paper is cited solely because a co-author happens to be an eminent, prestigious scientist? Should a citation to a paper by a single author count the same as a citation to a paper which lists five authors? Should a paper published in an obscure journal count equally with one published in a journal recognized for its high quality? What about the rare papers, often unusually highly cited, that introduce techniques?

Robert E. Davies, John S. deCani, and Nancy Goeller, all of the University of Pennsylvania, have developed statistical routines to deal with these "built-in" hazards of citation analysis. For example, derogatory and self-citations are identified; multiple authorships are dealt with by dividing the number of citations by the total number of authors; the stature of the journal in which a citation appears is scored; and unusual techniques papers are allowed for. Also, Davies, deCani, and Goeller have developed procedures for predicting the lifetime citation rate of scientists, allowing comparisons between junior and more established scientists.

Using these procedures and their particular expertise in citation studies, they have examined in "exquisite detail" the citation history of all the scientific papers of the female scientist being denied tenure—as well as those of every full, associate, and assistant professor in her department, including the two men who, unlike her, acquired tenure. They report that her work is, in Davies' words, "of full professorial stature, and in many ways of better quality than that of the chairman of the department. It is clearly equal to that of all the full professors in the department."

They maintain that citation analysis is objective because it "is based on written information that anyone can check. It is the aggregate of the subjective decisions of all publishing scientists. Everyone publishing a paper, when he comes to decide which papers to refer to, makes subjective decisions. He says, 'Of the millions of published papers, of the thousands relevant to my work, I will pick these 20 or so papers to cite.' Personal biases tend to get washed out."

Forecasting success

A dramatic demonstration of the sociometric power of citation indexing was made in 1968, when Eugene Garfield of ISI "forecast" the winners of future Nobel prizes by preparing a list of the 50 most cited authors for 1967. Six of them have since won the Nobel prize; six others had won it previously. Since there are about one million scientists in the world, a list of 50 that contains the names of 12 Nobel prize winners is an impressive achievement, especially since the method used was purely objective and did not require a personality appraisal or a reading of the scientists' works.

Garfield also showed that Nobel laureates–who can be assumed to have made outstanding contributions to science–are, as would be expected, among the most highly cited of scientists. Scientists who won the Nobel prize in physics between 1955 and 1965 averaged 58 citations each in the 1961 *SCI*; only one percent of the quarter-million scientists who appeared in that index received as many.

Additional evidence supporting the use of citation counts was presented in 1957 by psychologist Kenneth F. Clark, who asked a panel of experts to list the psychologists who had made the most significant contributions in their field. He then investigated the correlation between the panel's choices and various other measures of scientific output. The measure which correlated most highly with that of the panel was the number of journal citations to the scientist's work, leading Clark to conclude that citation counts are the best available

RANK	AUTHOR	TOTAL TIMES CITED
1	LOWRY OH	2921
2	CHANCE B	1374
3	*LANDAU LD*	1174
4	BROWN HC	1150
5	*PAULING L*	1063
6	**GELLMANN M**	942
7	COTTON FA	940
8	POPLE JA	933
9	BELLAMY LJ	906
10	SNEDECOR GW	904
11	BOYER PD	893
12	BAKER BR	876
13	KOLTHOFF IM	853
14	**HERZBERG G**	842
15	FISCHER F	826
16	SEITZ F	822
17	DJERASSI C	801
18	BERGMEYER HU	754
19	WEBER G	750
20	REYNOLDS ES	748
21	MOTT NF	741
22	*ECCLES JC*	737
23	FEIGL F	729
24	FREUD S	727
25	PEARSE AGE	726
26	ELIEL EL	721
27	STREITWIESER A	717
28	*MULLIKEN RS*	712
29	*JACOB F*	711
30	*BORN M*	710
31	BRACHET J	706
32	WINSTEIN S	702
33	ALBERT A	687
34	LUFT JH	674
35	**DEDUVE C**	673
36	**VONEULER US**	668
37	FIESER LF	666
38	HUISGEN R	661
39	NOVIKOFF AB	655
40	GOODWIN TW	643
41	**BARTON DHR**	632
42	FISHER RA	631
43	BATES DR	627
44	**FLORY PJ**	626
45	STAHL E	626
46	DEWAR MJS	619
47	GILMAN H	618
48	FOLCH J	618
49	DISCHE Z	614
50	GLICK D	609

** Received Nobel prize after this list was compiled in 1967.

* Had already received Nobel prize when this list was compiled.

Forecasting. An example of the use of citation indexing to identify individuals who may make a major impact on science. A simple list compiled in 1967 of the 50 most-cited authors for that year contained six who had won the Nobel prize already, and another six, at least, who won it subsequently.

indicator of the "worth" of psychological research.

Jonathan R. Cole of Columbia University and Stephen Cole of the State University of New York at Stony Brook have also found citation counts to be highly correlated with various other measures of eminence. In one study, they found the quality of work of 120 university physicists—as indicated by citation counts—to be correlated with each scientist's visibility to his colleagues and with the number of awards he had received.

However, Cole and Cole have also pointed to possible sources of error in evaluations based on citation counts. Revolutionary new ideas which lead to basic changes in scientific paradigms have sometimes been resisted or ignored by the scientific establishment. If, for example, citation indexing had been in existence in the 19th century, it would have failed to reveal the importance of Mendel's work in genetics, which was unappreciated by his contemporaries but greatly honored by later scientists. Also, using citation counts as indicators of quality assumes that authors cite articles which they have found useful in their research. But citation frequency is a function of many variables besides scientific merit: an author's reputation, controversiality of subject matter, circulation of the journal, availability and extent of library holdings, reprint dissemination, coverage by secondary indexing and abstracting services, and allocation of research funds. Many of these variables defy quantification.

While cautioning that small differences in citation rates may not be significant, Cole and Cole assert that, even with its problems, "The data available indicate that straight citation counts are highly correlated with virtually every refined measure of quality. . . . There can be little doubt that large differences in the number of citations received by scientists do adequately reflect differences in the quality of the work."

Little science, big science

Besides evaluating individual scientists, citation analysis has proved itself a valuable tool for the study of science at its largest and most complex: in the area of national science policy.

"We are getting to the point where there must arise a fairly hard, respectable, and useful academic discipline that will do for science what economics does for the economic life of nations," says Derek J. de Solla Price of Yale University, a physicist and science historian. "Since the 1920's and 1930's, when this sort of 'Science of Science' came into being, it has been evident that the essential difficulty was in devising some reasonable measure of scientific effort or output."

Price has been using citation indexing for nearly a dozen years as the basis for measuring the quality of scientific research. In his book, *Little Science, Big Science* (Columbia University Press, 1963), for example, Price develops a perspective which takes in the structure of the worldwide science community throughout history. He points out that 90 percent of all the scientists who have ever lived are alive right now—and this statement has held true for the past two centuries, as science has continued to grow exponentially. He asserts that "the average productivity of scientists—the number of scientists who write one paper, two papers, three, etc., in a given interval of time—does not vary from country to country very much, and hardly at all from century to century, since the invention in the 17th century of the scientific paper right up to the present day."

Bringing his observations more up to date, Price points out that for most of the world's countries the *per capita* activity in science correlates well with the *per capita* wealth. For example, "The United States publishes about one-third of the world's physics and chemistry, one-third of the astrophysics, and gets about one-third of the big prizes and discoveries—and has also about one-third part of the world's weath. Its share is not anything near to six percent, which is its share of the world's population. . . ."

Relating the wealth of nations to their activity in science yields some interesting results. Price has designed an ingenious chart that relates the economic size of most of the world's countries, expressed in gross national product, to the country's scientific size, expressed in number of first authors listed in *SCI*. The visual result is striking: Almost all the countries fall within a narrow band or "main sequence," and it is apparent that the United States has the largest scientific size by far. But Israel appears far above the main sequence, indicating that its scientific size is much larger than would be expected from its wealth. Also above the main sequence, though to a lesser extent, are the United Kingdom, Switzerland, and Hungary. Conversely, China and the U.S.S.R. fall well below the norm.

Price explains that "the game of basic science is played according to the same rules by almost all participating nations. Rather than nationalistic goals, or even practical considerations, the extent and direction of basic research seems directly tied to overall economic wealth. . . . There is a universal admission price to the scientific arena. In this phase of the world's development, a ticket costs about 0.7 percent of gross national product, and the price will double in the next ten years."

Boxes within boxes

Many people think of the structure of science in terms of disciplines: physics, chemistry, biology, etc. But Belver C. Griffith of Drexel University and Henry Small of ISI have found that the primary structure in science is the small specialty group. They have reached this conclusion largely through their efforts to create maps of science using the *SCI* data base.

"The structure of science is like a series of boxes within boxes," Small explains. "The smallest possible box represents the single scientist or document. The next box is the specialty or cluster of documents. Next is clusters of specialties, or disciplines. The outermost box is all of science."

"Basically," Small says, "the problem is that the *SCI* is like a telephone directory. How do you get a handle on it? What is its structure?" Small assumes that it *does* have a structure and that its structure *does* reflect the structure of science. "We feel that the coverage is the best you are going to get anywhere with any data base. So if science has a structure it ought to be evident in this data base, and what we have done is to show that the primary structure is the specialty."

Griffith and Small define a specialty by a few critically important and highly cited papers which appear early in the specialty's history. For instance, this pattern was closely followed by the development of nuclear physics in the 1920's.

Relationships between papers—which indicate activity—may occur in various ways. Direct citation is the citing of an earlier paper by a later paper. Co-citation is when two papers are cited together by a third author (the strength of co-citation is a measure of proximity which can be used in mapping). Bibliographic coupling is when two papers cite one or more papers in common; again, it is useful in mapping.

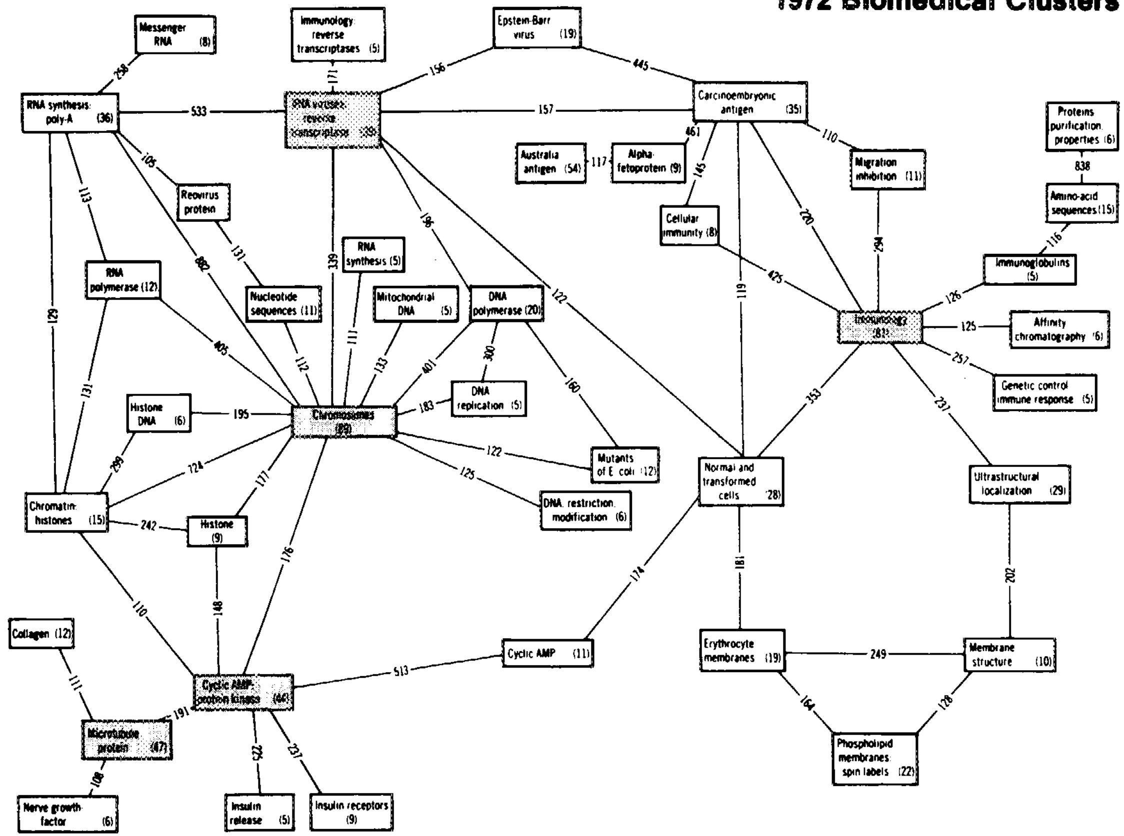
Griffith and Small have developed computer procedures for measuring the associations between papers, and thus the level of activity in a specialty. One procedure, for example, extracts pairs of highly cited documents linked by co-citation. The documents may be clustered according to the strength of the co-citation links. The clusters represent specialties which currently exhibit high levels of activity. By applying a technique known as "multidimensional scaling," which generates a spatial configuration of objects that have a specified relationship to one another, the result is a visual display—a map formed in two, three, or even four dimensions. For most purposes, however, the two-dimensional display is adequate.

One result of their study of co-citations was the finding that nearly all highly cited papers are linked together at the lowest possible level of relationship. This suggests that "the distinct specialties of science are not totally isolated from one another but are somehow connected by weak, although perhaps important, links."

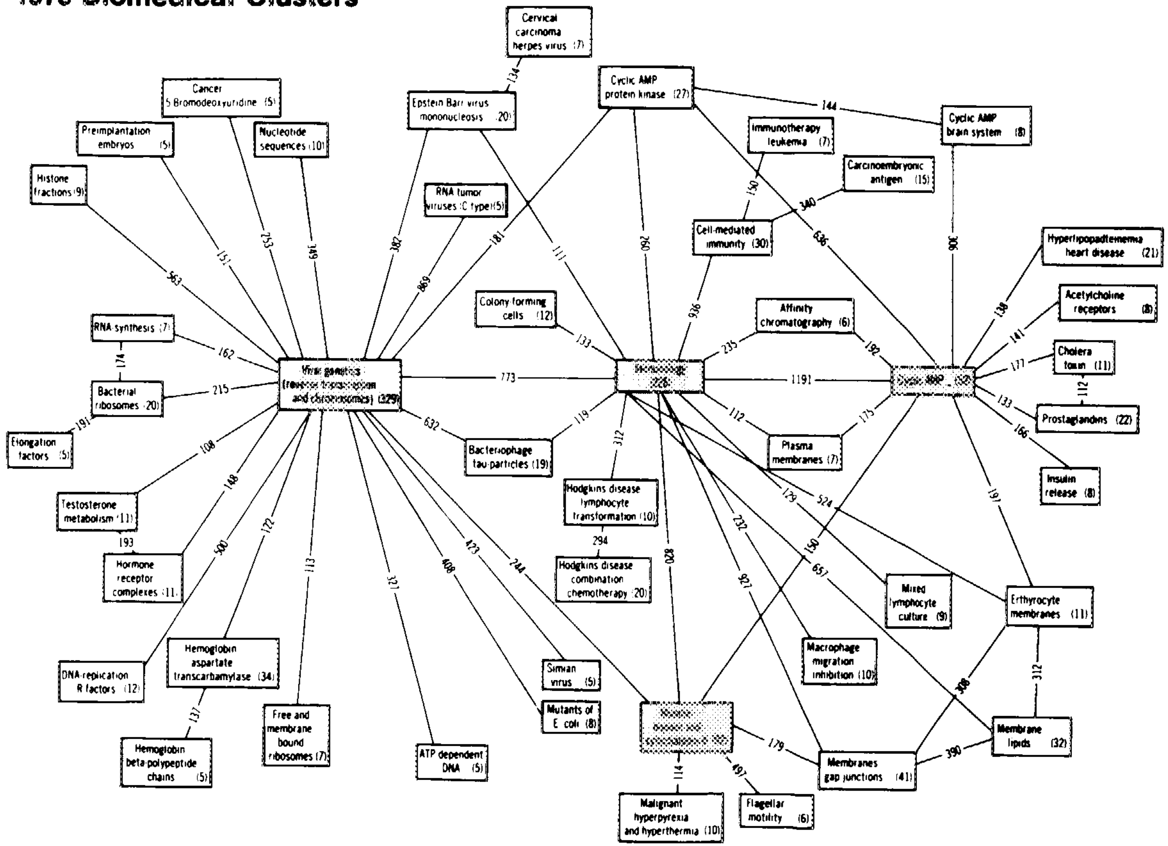
From 1973 citations Griffith and Small observed the appearance of a supercluster on the topic of viral genetics. This was a convergence of many smaller clusters which had appeared in previous years. The supercluster represented an intense level of scientific activity, with an active citation network, heavy citation and co-citation, and citations of

Changes in biomedical research. As produced by citation data, each box represents a cluster of highly cited documents—specialty area in biomedical research. The number in each box shows how many highly cited documents (cited 15 or more times) comprise the cluster. The lines joining the boxes are primary interspecialty connections; the numbers on the lines indicate the frequency of co-citation between documents in the connected clusters. The major change from 1972 to 1973 was the convergence of several previously separate specialties having to do with chromosomes, reverse transcription, and the genetics of viruses. These merged in 1973 to form a supercluster on viral genetics. In addition, a shift resulted in stronger relations between research on immunology and cyclic AMP, and the emergence of an important new specialty called "Muscle: myosin and cytochalasin-B," a continuation of the 1972 "Microtubule protein" cluster.

1972 Biomedical Clusters



1973 Biomedical Clusters



very recent papers (as opposed to citations of papers five to ten years old). Small explains that the appearance of a supercluster means that "something is happening in this field that deserves special attention. There are many examples of fields that we find are being rejuvenated by discoveries or innovations, but none as big as viral genetics."

Griffith and Small believe that the mapping of specialties is a task of prime importance for understanding the social and intellectual structure of science. Mapping allows comparisons between specialties, as well as comparisons between periods of science. "The perspective this method offers is far broader than can be achieved by any individual scientist. This is the crux of the method: The observed relationships are in substance those which have been established by the collective efforts and perceptions of the community of publishing scientists.

In addition, the mapping of citation networks could have applications for science policy. Griffith and Small "foresee the use of yearly cumulations to map major national scientific achievements.... Governments might examine the clusters to identify which of their laboratories and scientists have international impact, and those fields in which they have such impact."

Evaluating journals

Citation indexing has been nurtured for nearly 20 years by Eugene Garfield, who founded and heads ISI. As overseer of an enterprise that processes every issue of over 5,000 scientific journals, it's not surprising that he has also directed his attention at an analysis of the journals themselves. Simply by analyzing the citations in a sample of scientific journals, he found in a recent study "that only 25 journals (the equivalent of little more than one percent of *SCI* coverage) are cited in 24 percent of all references; that only 152 journals are cited in 50 percent of all references; that only 565 journals are cited in 75 percent of all references; and that only 2,000 or so journals are cited in 85 percent of all references." Garfield also found that "many journals now being published seem to play only a marginal role, if any, in the effective transfer of scientific information."

Of special interest to librarians is Garfield's finding that a multidisciplinary core collection of scientific journals may comprise only 1,000 journals and still effectively cover all of science. As few as 500 journals may suffice for the libraries of developing countries.

Garfield has also been active in the field of historio-bibliography. The idea is that bibliographic citations contain chronological information which permit them to be easily arranged, resulting in a crude history of the development of a subject. Computerizing the operation and arranging the citation network in diagrams raises interesting possibilities. Garfield predicts that, "In the near future, the compilation of bibliographies will be inseparable from writing the history of that field. A scholar will be able to sit before his computer console and he will specify some starting point—a person, a word, a citation, a place. Given a particular word or document, he will then ask the computer to display a list of pertinent papers. Then the computer will draw or display for him an historical roadmap which will show him not merely the list of papers and books, but also a graphical approximation or detailed history of that subject."

The scientists of science are now involved in basic research. Their goal is to understand the social forces at work in the intensely human activity of science, and they largely claim disinterest in the practical applications of their work. However, the present use of citations in basic research could lead scientists to a better understanding of science—and ultimately to a more efficient science. ●