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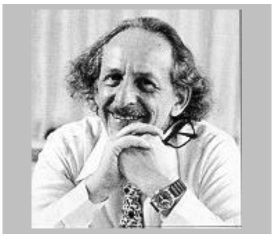

Current Comments®

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The Uses and Limitations of Citation Data as Science Indicators: An Overview for Students and Nonspecialists

Number 49 December 7, 1992

Introduction

Many *Current Contents*® (*CC*®) essays have described how citation data are increasingly being used by science analysts and policymakers as quantitative indicators to measure research performance. The subject was discussed earlier this year in an essay on ISI®'s contract research services for governmental, academic, and industrial clients.[1] We also touched on it in essays on *Science Watch*®, ISI's monthly newsletter reporting on citation-based trends in science and technology.[2,3]

In these and other essays, we have stressed an important point that bears repeating. That is, citation data are uniquely useful tools for "scientometric" analyses but their responsible application requires careful and informed interpretation by experts.[4-6] The reprint that follows gives us the opportunity to reiterate this point.

A Primer on S&T Indicators for Students and Nonspecialists

Adam Holbrook, Industry, Science and Technology Canada (ISTC), Ottawa, Ontario, invited us to contribute a paper[7] to a special issue of *Science and Public Policy*, of which he was guest editor. He explained that the issue would focus on the link between science and technology (S&T) indicators and the public policy process. Acknowledging that there were many excellent scholarly works on the subject, he wanted to provide a more general introductory review for nonspecialists and graduate students in public policy.

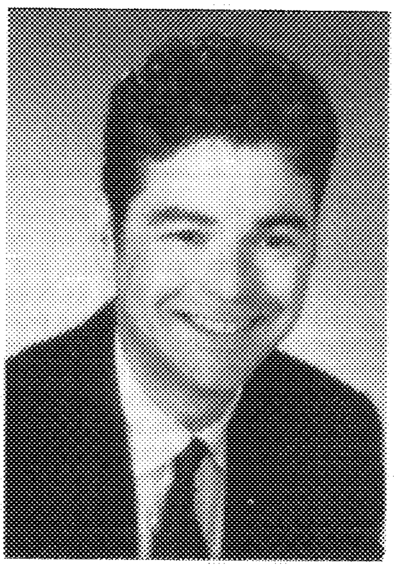
We were happy to accept Adam's invitation. So Al Welljams-Dorof, ISI's director of corporate communications, and I submitted the paper reprinted below. It illustrates the variety of ways that citation data can be used as indicators of scientific performance at levels ranging from individual authors to entire nations.

J.A.D. Holbrook

Science and Public Policy

Science and Public Policy is the bimonthly journal of the International Science Policy Foundation (ISPF), London. My good friend Maurice Goldsmith is director of ISPF, which he founded in 1966. He is also founding editor of *Science and Public Policy*.

In 1992, John de la Mothe, University of Ottawa, was appointed chairman of ISPF. He is also the coeditor of *Science and Public Policy* along with Philip Gum-


John de la Mothe

mett, University of Manchester, England. The journal is a refereed international publication focusing on science and technology policies as well as the implications of science and technology for public policy.

De la Mothe received a PhD in science and technology policy from Concordia University, Montreal, an MSc from the University of Sussex, and MA degrees from both the University of Oxford, England, and Concordia. He has published more than 40 articles and books on science policy.

Holbrook is a licensed professional engineer who started his career at Telesat Canada before moving on to the Treasury Board Secretariat of the Canadian government. In 1986 he joined the Ministry of State for Science and Technology, where he established and manages the S&T Economic Analysis Division of ISTC. He has been guest lecturer at Queen's University, Kingston, Ontario, the University of Ottawa, and Tsinghua University in China. He has written papers on upper atmosphere physics, satellite control problems, and science policy.

Conclusion

Hopefully, the paper reprinted below will discourage the simplistic and invidious interpretations of citation data that sometimes make their way into print, even in well-respected peer reviewed journals. Ironically, readers of these flawed analyses often complain to us, as if the fault somehow lies with ISI's data rather than the original authors' misuse of them. But citation data or any other quantitative indicators are neutral. Their value and usefulness are realized in the appropriate, responsible, and informed interpretation of the data.

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My thanks to Al Welljams-Dorof for his help in the preparation of this essay.

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Citation data: their use as quantitative indicators for science and technology evaluation and policy-making

Eugene Garfield and Alfred Welljams-Dorof

Publication and citation data offer the potential to develop new quantitative, objective indicators of S&T performance. The limitations of these indicators is discussed. The conclusion is that they provide a valuable and revealing addition to conventional methods of S&T evaluation.

Few would dispute the claim that a nation's science and technology (S&T) base is a critical element of its economic strength, political stature, and cultural vitality. In recent years, efforts to evaluate and assess research activity have increased. Government policymakers, corporate research managers, and university administrators need valid and reliable S&T indicators for a variety of purposes: for example, to measure the effectiveness of research expenditures, identify areas of strength and excellence, set priorities for strategic planning, monitor performance relative to peers and competitors, target emerging specialties and new technologies for accelerated development, and so on.

One of the many quantitative indicators available for S&T evaluation and assessment is the published research literature—that is, primary research journal articles. Publication counts have traditionally been used as indicators of the "productivity" of nations, corporations and institutions, departments, and individuals. However, judgment of the *influence*, *significance*, or *importance* of research publications requires the qualitative analysis by experts in the field, an often time-consuming and expensive process.

Eugene Garfield is Founder and Chairman and Alfred Welljams-Dorof is Director of Corporate Communications at the Institute for Scientific Information, 3501 Market Street, Philadelphia, PA 19104, USA.

But the advent of citation databases—which track how often papers are referenced in subsequent publications, and by whom—has created new tools for indicating the impact of primary research papers. By aggregating citation data, it is then possible to indicate the relative impact of individuals, journals, departments, institutions, and nations. In addition, citation data can be used to identify emerging specialties, new technologies, and even the structure of various research disciplines, fields, and science as a whole.

This is *not* to say that citation data *replace* or *obviate* the need for qualitative analysis by experts in the field. Rather, they *supplement* expert judgments by providing a unique perspective on the S&T enterprise. Indeed, citation data themselves require careful and balanced interpretation to contribute most effectively to S&T evaluation and assessment.

Citation databases of ISI®

The Institute for Scientific Information®'s (ISI) *Science Citation Index*® (*SCI*®) was developed primarily for the purpose of information retrieval. However, its quantitative citation databases are especially well-suited for application as S&T indicators for a number of reasons. For example, they are *multidisciplinary*, representing virtually all fields of science and the social sciences. Thus, ISI's databases can accommodate S&T analyses whose scope ranges from the narrowest focus on a particular subspecialty to the broadest perspective on science as a whole.

Also, ISI's databases are *comprehensive*, indexing all types of items that a journal publishes. These include not only original research papers, review articles, and technical notes but also letters, corrections and retractions, editorials, news features, and so on. ISI studies have shown that these items are significant means of scholarly communication.[1] Thus, the S&T analyst has great flexibility in choosing which types of items to include in an evaluation.

In addition, ISI *fully indexes* these items—including all authors' names, institutional affiliations and addresses, article titles, journal, volume, issue, year, and pages. This enables S&T analyses of individual researchers, institutions and departments, cities or states or nations, journals, established and emerging specialties, and so on.

As noted earlier, ISI indexes not only all journal source items but also all the references they cite. This provides the basis for developing a variety of quantitative S&T indicators—not just output or productivity (number of papers) but also "impact" (average number of citations per paper, journal, author, institution, and so on), "citedness" (percent of total publication output that was later cited), and so on.

At present, ISI's databases include about 15,000,000 papers published since 1945 and more than 200,000,000 references they cited. This offers the potential for extended time-series analyses of S&T trends to policymakers, administrators, and managers as well as historians, sociologists, and information scientists.

The following sections illustrate the variety of analyses at different levels of specificity—from individual authors to entire nations—that are possible using citation data. The examples are taken from *Science Watch*®, a monthly ISI newsletter reporting on citation-based trends and developments.[2]

Most-cited authors

Over the years, ISI has published several studies identifying the most-cited authors

Table 1. Most-cited authors of the 1980s, ranked by citations to papers indexed in the 1981-1990 *Science Citation Index* (*SCI*).

Author	Field	1981-1990 Citations	1981-1990 Papers
Gallo RC	Virology	36,789	591
Schlossman SF	Immunology	21,682	348
Nishizuka Y	Biochemistry	20,143	181
Hood LE	Molecular biology	18,288	324
Messing J	Molecular biology	18,229	35
Fauci AS	Immunology	17,756	563
Bloom SR	Gastroenterology	16,543	1,468
Vale W	Neuroendocrinology	16,422	348
Dinarello CA	Immunology	16,143	482
Berridge MJ	Biochemistry	16,004	93
Rosenberg SA	Surgery/oncology	15,922	430
Rivier J	Endocrinology	15,893	320
Seeburg PH	Neuroendocrinology	14,454	124
Irvine RF	Biochemistry	14,431	108
Chambon P	Molecular biology	14,190	246
Reinherz EL	Immunology	14,067	220
Wong-Staal F	Virology	13,910	254
* Baltimore D	Virology	13,847	222
* Goldstein JL	Genetics	13,120	202
* Brown MS	Biochemistry	13,031	171
Franke WW	Cell biology	12,930	280
Hokfelt T	Neuropharmacology	12,881	381
Strominger JL	Virology	12,817	253
Ullrich A	Biochemistry	12,670	199
* Bishop JM	Virology	12,427	162
* Thomas ED	Oncology	12,306	412
Snyder SH	Pharmacology	12,302	308
Witten E	Physics	12,105	96

Note: *Nobel Prize winner

While rankings of the most-cited authors are fairly straightforward, great care must be taken when using citation data to evaluate the impact of the average individual

in various fields and covering different time periods. It should be noted that authors in larger fields achieve higher citation rates. Thus, undifferentiated citation rankings tend to be dominated by molecular biologists, geneticists, biochemists, and other life scientists while fewer authors in physics and chemistry, for example, are represented.

Table 1 identifies 28 authors who received more than 12,000 citations to papers indexed in the 1981-1990 *SCI*. It is interesting to note that five authors (18%) are Nobel Prize winners. In fact, this and previous most-cited author rankings have been shown to effectively identify groups or sets of authors "of Nobel class."[3] That is, not only are actual Nobelists identified, but authors who later go on to win the prize are also included. It is remarkable that a simple, quantitative, and objective algorithm can consistently anticipate a highly subjective and qualitative selection process. But this is not surprising, because citation data have been shown to correlate highly with other qualitative indicators of "prestige" or "eminence," such as peer ratings, academy memberships, and so on.[4-9]

While rankings of the *most*-cited authors are fairly straightforward, great care must be taken when using citation data to evaluate the impact of the *average* individual. These evaluations can be both revealing and reliable, but only when performed properly—with expert interpretation, peer assessment, and recognition of potential artifacts and limitations.[10]

High impact papers and journals

One of the most obvious uses of citation data is to indicate particular papers that have attracted the highest attention from other peer S&T authors. By varying the time span of citation and/or publication, historical "classics" and currently "hot" papers are readily identified. For example, ISI has published a series of essays on the most-cited papers in the 1945-1988 *SCI* database.[11,12] They provide an interesting perspective on formal research communication for S&T historians, sociologists, authors, editors, publishers, and so on.

Identifying "hot" papers through citation data enables S&T analysts to monitor current breakthroughs at the forefront of research in various specialties. For example, Table 2 lists the ten hottest biology papers at year-end 1991. These and other hot papers in different fields, specialties, and particular research topics are derived from a special ISI database. It is a cumulative three-year file, updated bimonthly, of about 1,000,000 papers that meet two criteria. They were published within the previous 24 months in *SCI*-indexed journals, and they were highly cited in the most-recent two months.

Aggregated at the next level, citation data can also be used to indicate the highest-impact journals in different fields and specialties and over varying time frames. ISI's *Journal Citation Reports*® (*JCR*®) volumes of the *SCI* and *Social Sciences Citation Index*® (*SSCI*®) present a variety of quantitative rankings on thousands of journals annually. From these data, sophisticated time-series comparisons between journals can be made, as shown in Figure 1.

The chart shows the relative rankings by citation impact—average citations per paper—of the five leading clinical medicine journals in the *SCI* database. In this example, impact was calculated for six successive and overlapping five-year periods of publication and citation, from 1981-1985 to 1986-1990. The impact of each journal was then compared relative to the average for all *SCI*-indexed clinical medicine journals.

Leading universities and corporations

From the author affiliation and address data on articles indexed and cited in ISI's databases, time-series rankings of leading institutions in different fields and specialties are available for S&T analyses. For example, the highest-impact universities and

Table 2. What's hot in biology

Rank	Paper	Citations This Period (Nov-Dec 91)	Rank Last Period (Sep-Oct 91)
1	T.A. Springer, "Adhesion receptors of the immune system," *Nature*, 346(6283):425-34, 2 August 1990. [Harvard U. Sch. Med., Cambridge, Mass.]	68	3
2	A. Ullrich, J. Schlessinger, "Signal transduction by receptors with tyrosine kinase activity," *Cell*, 61(2):203-12, 20 April 1990. [Max Planck Inst. Biochem., Martinsreid, Germany; New York U. Med. Ctr., N.Y.]	54	2
3	P. Nurse, "Universal control mechanism regulating onset of M-phase," *Nature*, 344(6266):503-8, 5 April 1990. [U. Oxford, U.K.]	36	8
4	D.F. Fiorentino, M.W. Bond, T.R. Mosmann, "Two types of mouse T helper cell. IV. Th2 clones secrete a factor that inhibits cytokine production by Th1 clones," *J. Exp. Med.*, 170(6):2081-95, 1 December 1989. [DNAX, Inc., Palo Alto, Calif.]	34	*
5	J.E. Rothman, "Polypeptide chain binding proteins: Catalysts of protein folding and related processes in cells," *Cell*, 59(4):591-601, 17 November 1989. [Princeton U., N.J.]	31	*
6	P. Sokoloff, B. Giros, M.-P. Martres, M.-L. Bouthenet, J.-C. Schwartz, "Molecular cloning and characterization of a novel dopamine receptor (D_3) as a target for neuroleptics," *Nature*, 347(6289):146-51, 13 September 1990. [INSERM, Paris, France; U. Rene Descartes, Paris]	31	7
7	H.R. Bourne, D.A. Sanders, F. McCormick, "The GTPase superfamily: Conserved structure and molecular mechanism," *Nature*, 349(6305):117-27, 10 January 1991. [U. California, San Francisco; Cetus Corp., San Francisco; Whitehead Inst., Cambridge, Mass.]	31	*
8	J.H. Exton, "Signaling through phosphatidylcholine breakdown," *J. Biol. Chem.*, 265(1):1-4, 5 January 1990. [Howard Hughes Med. Inst., Vanderbilt U., Nashville, Tenn.]	30	*
9	M.E. Hemler, "VLA proteins in the integrin family: Structures, functions, and their role on leukocytes," *Ann. Rev. Immunol.*, 8:365-400, 1990. [Dana-Farber Cancer Inst., Boston, Mass.]	30	*
10	B.J. Bachmann, "Linkage map of Escherichia coli K-12, edition 8," *Microbiol. Rev.*, 54(2):130-97, June 1990. [Yale U., New Haven, Conn.]	28	5

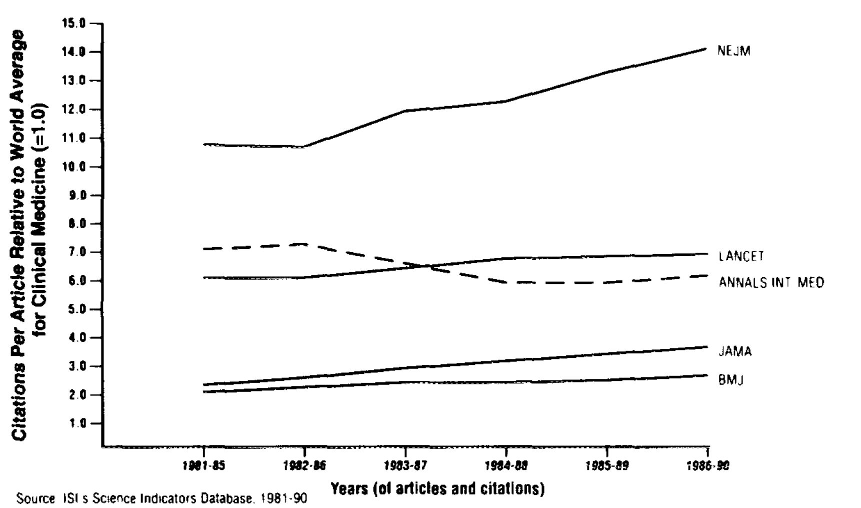
SOURCE: ISI's Hot Papers Database

NB. Only papers published since November 1989 are tracked. An asterisk indicates that the paper was not ranked in the Top Ten during the last period. In the event that two or more papers collected the same number of citations in the most recent bimonthly period, total citations to date determine the rankings.

companies in electrical engineering are shown in Table 3. Figure 2 compares the relative impact of eight biotechnology firms from 1984 through 1990.

The application of these citation-based institutional rankings and trends as S&T indicators is obvious. For example, university administrators and corporate managers can compare their performance with peers and competitors. Government and private funding sources can monitor the return on their S&T investment. And policymakers can identify relative strengths and weaknesses in strategically important S&T sectors.

Figure 1. Citation impact of leading journals of clinical medicine



Source ISI's Science Indicators Database. 1981-90

Like any quantitative indicator, citation data have inherent limitations which are most obvious at the individual level: their importance wanes at higher levels of data aggregation

National comparisons

Of course, citation data can also be aggregated to the national level, enabling comparisons of entire countries on a variety of quantitative indicators for S&T analyses. In Figure 3, the impact of the Group of Seven (G7) nations in engineering, technology, and the applied sciences is charted from 1981 to 1990. The trends provide a new perspective on relative S&T performance and an additional quantitative basis for assessing and evaluating nations.

Analyses of relative performance in "hot" research areas at the forefront of a particular specialty are also possible through ISI's citation databases. For example, Table 4 lists ten research fronts in which Japan and Germany dominate and the USA is underrepresented. They were derived from a 1990 file of more than 8,000 specialty areas identified through co-citation analysis.[13,14]

Basically, each consists of a "core" of papers cited together frequently by authors in 1990, and the current citing papers. The proportion of core papers from Japan and Germany is at least twice the level expected from their average representation in the entire 1990 file. In this example, the research fronts are also ranked by three-year immediacy—the percentage of core papers published in the previous three years. These and other research front rankings enable S&T analysts to compare national performance in various areas of intrinsic interest, commercial potential, or strategic importance.

Potential limitations

As stated earlier, citation data require careful and balanced interpretation to be most effective in S&T analyses.[15,16] Like any quantitative indicator, citation data have inherent limitations. They are most obvious at the individual level—studies of a particular author or journal, for example. But their importance wanes at higher levels of data aggregation and larger sample populations: for example, comparisons of authors, journals, institutions, and nations against appropriate baselines.

Table 3. Highest-impact universities and corporations in electrical engineering, 1986-1990 (at least 50 papers).

	Universities				Industrial Firms			
Rank	Name	Papers 1986-90	Citations 1986-91	Citations Per Paper	Name	Papers 1986-90	Citations 1986-91	Citations Per Paper
1	Stanford University	243	1,283	5.28	AT&T	754	5,366	7.12
2	University of Rochester	51	269	5.27	Fujitsu	151	814	5.39
3	University of Illinois, Urbana	211	1,100	5.21	GTE	71	327	4.61
4	Columbia University	74	343	4.64	Bellcore	223	994	4.46
5	Caltech	69	294	4.26	IBM	316	1,402	4.44
6	University of Southampton	150	631	4.21	Rockwell	61	270	4.43
7	Purdue University	95	366	3.85	Hughes	148	513	3.47
8	Cornell University	97	351	3.62	Plessey	109	363	3.33
9	University of Tokyo	82	293	3.57	British Telecom	469	1,227	2.62
10	Univ. of Southern California	58	195	3.36	Hewlett Packard	253	650	2.57
11	Univ. of Calif., Santa Barbara	66	210	3.18	GEC	140	356	2.54
12	MIT	175	548	3.13	NTT	882	2,183	2.48
13	Georgia Inst. Tech	86	269	3.13	GE	188	462	2.46
14	University of Calif., Berkeley	211	658	3.12	Hitachi	313	753	2.41
15	University of Arizona	64	193	3.02	Honeywell	86	205	2.38
16	University of Wisconsin, Madison	52	157	3.02	Toshiba	212	492	2.32
17	Univ. of Florida, Gainesville	102	296	2.90	Matsushita Electric	135	302	2.24
18	University of Sheffield	92	265	2.88	TRW	83	183	2.20
19	Univ. of Calif., Los Angeles	109	308	2.83	Sony	69	151	2.19
20	Pennsylvania State University	70	193	2.76	RCA	80	164	2.05
21	Univ. of Minnesota, Minneapolis	85	233	2.74	Texas Instruments	229	445	1.94
22	University of Surrey	77	210	2.73	Mitsubishi Electric	133	257	1.93
23	Univ. London, Imperial College	88	231	2.63	Intel	89	164	1.84
24	Univ. of Michigan, Ann Arbor	136	356	2.62	Philips	249	366	1.47
25	Arizona State University	61	152	2.49	NEC	512	733	1.43

SOURCE: ISI's Science Indicators Database, 1986-1991.

A frequently raised question is *whether citations reflect agreement or disagreement* with the referenced paper. In the hard sciences, citations generally tend to be positive, representing the formal acknowledgment of prior sources that contributed to the citing author's research. Of course, there are occasional exceptions, such as the cold fusion controversy, but these are well known and obvious. In the social sciences, however, critical citations are more common. Thus, raw citation counts may not be indicative of an author's or paper's positive impact in the social sciences, and the *context* and *content* of citations should be examined.

Self-citation is another frequently raised caveat. That an author cites his or her own prior research is a legitimate and expected practice, since science is a cumulative process that builds on past findings. But excessive self-citation may lead to inflated impact rankings of authors or papers. Presumably, excessive self-citation would become apparent, and corrected, in the editorial and peer review process. In any case, self-citations are readily identified and can be subtracted from or otherwise weighted against an author's or paper's total citation count.

Citation circles are related to the phenomenon of self-citation. That is, groups of researchers might theoretically "conspire" to preferentially cite only the work of authors in the group. However, in order for this to unfairly "skew" citation and impact rankings, authors in a purported citation circle must be rather prolific, that is, they must publish a substantial number of papers in order to "inflate" the group's ranking.

While citation circles are much talked about, they are rarely, if ever, documented and identified. The problem is, it would be difficult to distinguish between a citation circle and an invisible college—that is, colleagues who legitimately share common research interests and build on (and cite) one

Figure 2. Citation impact of leading biotechnology companies

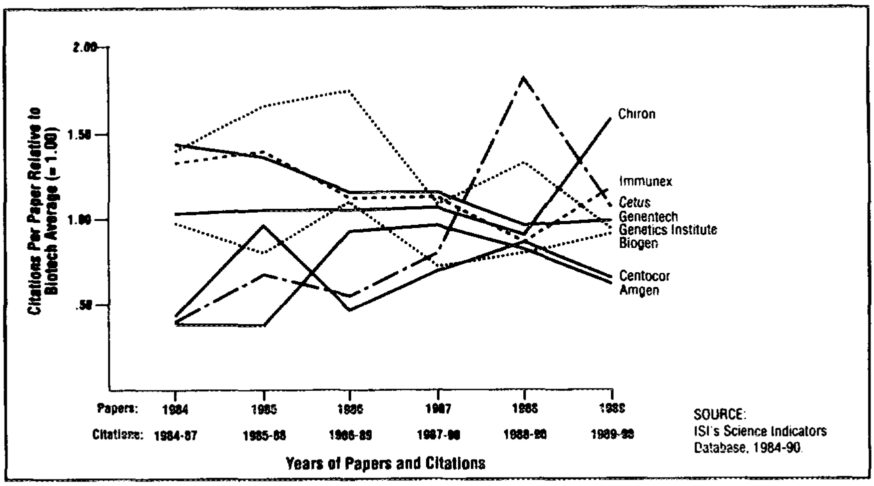
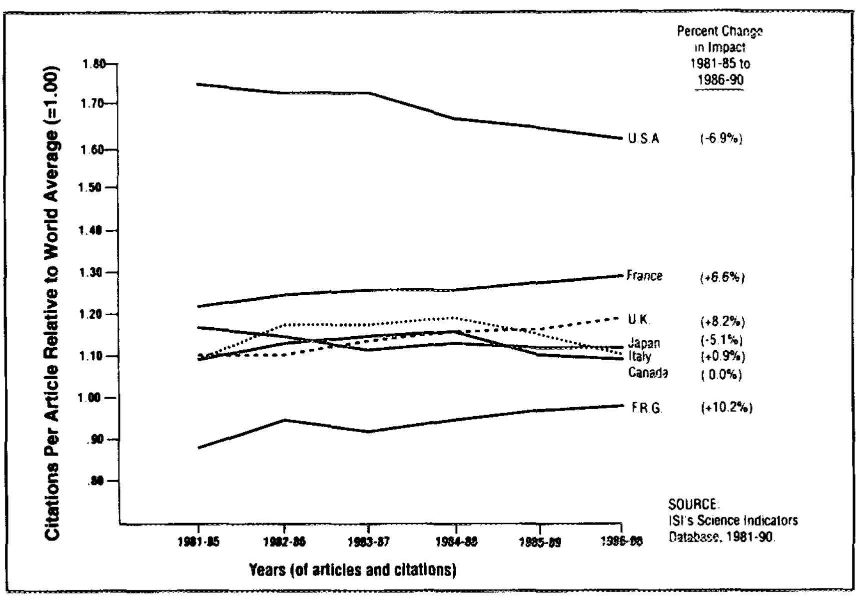


Figure 3. Citation impact of journal articles in engineering, technology, and applied sciences for G7 nations, 1981-1990



another's papers. This is especially true in small and emerging subspecialties in which a comparatively small group of authors are active.

Another purported shortcoming of citation analyses is that *methods tend to be identified far more frequently than theoretical papers.* This perception is not necessarily supported by ISI studies of the most-cited papers or authors in various fields—breakthrough theoretical contributions appear in these rankings. This per-

Table 4. Ten fields targeted by both Germany and Japan

Rank	Field	Three-year Immediacy	Percent of Papers from:		
			JAPAN	F.R.G.	U.S.A.
1	Synthesis of alpha-fluoro derivatives	50 %	14.8	40.7	18.5
2	Characterization of chicken anemia agent	50 %	24.0	12.0	16.0
3	Controlled creation of microscopic solids	50 %	23.3	13.3	16.7
4	Immunohistochemical studies of amyloidosis	50 %	30.8	15.4	3.9
5	Iminophosphorane-mediated syntheses	38 %	15.4	14.3	17.6
6	Combination chemotherapy in non-small-cell lung cancer	33 %	23.2	24.6	7.3
7	Adrenoceptor-blocking activity and hemodynamic effects of carvedilol	25 %	44.2	25.6	11.6
8	Endoscopic ultrasonography for clinical staging of esophageal carcinoma	17 %	18.0	13.1	14.8
9	Low-temperature transport in amorphous semiconductors	17 %	23.8	15.9	15.9
10	Performance characteristics of $LaNi_5$ electrodes	15 %	17.2	19.4	16.1

SOURCE: ISI's Research Front Database, 1990.

ception also reflects a curious prejudice of scientists, who seem to value theory more highly than methods.

Practically speaking, new methods and technologies that enable researchers to study phenomena previously inaccessible by conventional techniques or that allow them to conduct research more quickly, efficiently, and cost-effectively are indeed valuable contributions that deserve recognition. In fact, the Nobel Prizes have honored breakthrough methods and technologies—for example, computerized axial tomography, scanning and tunneling electron microscopy, and so on.

The *obliteration phenomenon* must also be taken into account when applying citation data to S&T evaluations. This refers to a well-known process in which breakthrough advances—for example, Einstein's theory of relativity or Watson and Crick's description of DNA's double-helix structure—are paradoxically cited *less* frequently over time.

Such landmark discoveries are quickly incorporated into the generally accepted body of scientific knowledge, and authors no longer feel the need to explicitly cite the original paper. However, citation obliteration tends to occur many years after the paper was published; in the first few years, these papers achieve extraordinary citation frequencies and are thus easily identified as "hot" or breakthrough contributions.

Lastly, publication and citation data are *"lagging indicators"* of research that has already been completed and passed through the peer review and publishing cycle, which can take as long as two years, depending on the field. Of course, especially important papers can appear in print within weeks of submission to a journal, and they become "hot" or very highly cited almost immediately. In any case, citation data still represent the scientific community's current assessment of the impact of earlier research. Thus, citation data retain their value for S&T evaluations since they indicate what is considered important in the opinion of investigators currently active in the field.

Conclusion

In conclusion, publication and citation data offer the potential to develop new quantitative, objective indicators of S&T performance. While they have their limitations as do any quantitative indicators, most, if not all, of these limitations can be statistically weighted, controlled, or otherwise compensated. Properly applied, interpreted, and analyzed, citation data are a valuable and revealing addition to conventional methods—both quantitative and qualitative—used in the S&T evaluation and assessment process.

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