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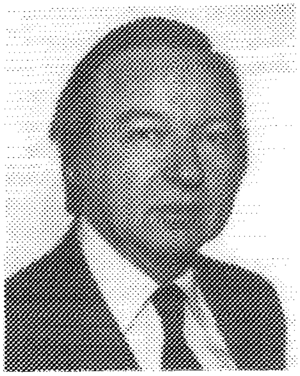
The Most-Cited Physical-Sciences Publications in the 1945-1954 *Science Citation Index*



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This essay examines the 52 most highly cited papers and books in the physical sciences, 1945-1954, based on the *Science Citation Index®* cumulation for that decade. It discusses some of the major trends, achievements, and researchers in the physical sciences in the period including World War II. Comparisons are made between citation frequency and other measures of importance, such as Nobel Prizes and judgments by historians of science. Virtually all of the 52 most-cited physical-sciences publications presented in the Bibliography at the end of this essay are in physics or chemistry. Smaller fields with lower citation frequencies, such as mathematics, geosciences, and astronomy/astrophysics, are not well represented. In Part 2, we will identify and discuss high-impact works from these fields.

Introduction: The Top Five *Citation Classics* of 1945-1954

A few years ago, when I was trying to encourage chemists to take an interest in the history of their discipline,[1] I asked them a simple question: Who do you think is the most important chemist of the twentieth century? Who should be presented to the public as the hero of modern chemistry, corresponding to Albert Einstein, who has been extensively promoted as the hero of modern physics? Having read a lot about how chemistry is a science in which experiments are more valuable than theories, and having seen how much chemists dislike being told that chemistry can be reduced to physics, I was unprepared for the answer.

Every member of this small and unsystematically selected sample, after expressing some puzzlement that anyone should ask such a strange question, finally came up with the same answer: Linus Pauling. Yet Pauling is best known for his development of the *theory* of molecular structure—a theory based directly on physics!

After that experience it was no surprise to learn that Pauling's book, *The Nature of the Chemical Bond and the Structure of Molecules and Crystals: An Introduction to Modern Structural Chemistry*, was the most highly cited publication in the physical sciences during the decade 1945-1954. The total number of citations for the 1939 and 1940 editions was 571 during this period. Citations to all editions of this book number more than 16,000, according to an analysis by Zelek S. Herman, Linus Pauling Institute of Science and Medicine, Palo Alto, California.[2] There were more than 600 citations to all editions of the book in the 1989 *Science Citation Index®* (*SCI®*).

Publications in chemistry were also the second, third, and fourth most cited during that period, which can be seen in the Bibliography at the end of this essay. A 1938 paper by Stephen Brunauer and Paul H. Emmett, then at the Bureau of Chemistry and Soils, Washington, DC, and Edward Teller (widely acknowledged to be the inventor of the hydrogen bomb), George Washington University, Washington, DC, on "Adsorption of gases in multimolecular layers" received 450 citations. It, too, is a contribution to theoretical chemistry using concepts borrowed from physics—although, as in Pauling's monograph, comparisons with experimental data play an important part.

The monograph on the *Theory of Rate Processes* (1941) by Samuel Glasstone, Keith J. Laidler, and Henry Eyring, Princeton University, New Jersey, cited 418 times, was written in part (according to its preface) to show how much progress had been made in calculating absolute reaction rates by using quantum mechanics and statistical mechanics. *The Ultracentrifuge* (1940) by Teodor Svedberg, Kal O. Pedersen, and Johannes H. Bauer, University of Uppsala, Sweden, received 381 citations; it describes a physical method of great utility to chemists. Not until we reach the fifth most-cited item, "Table of isotopes" (1948), cited 259 times, by Glenn T. Seaborg and I. Perlman, Department of Chemistry and Radiation Laboratory, University of California, Berkeley, do we find a publication on physics itself rather than on its application to chemistry.

While chemistry dominates the five most highly cited papers, the physical sciences as a whole account for only 11 percent of the top 250 most-cited papers in the 1945-1954 *SCI* cumulation. ISI® therefore decided to publish two separate articles: one by Bernard Dixon, former editor of *New Scientist* and currently contributing editor to *Bio/Technology*, surveying the 102 most-cited articles in the life sciences,[3] and this one, devoted only to the physical sciences.

Citation Data Vary by Field

This decision reflects the view that the absolute citation count for a publication is less significant than its citation count relative to other works in the same field. Some fields simply have a bigger literature than others—more authors, more papers, more citations. Thus, as Eugene Garfield has pointed out, any list of most-cited papers for all of science must make allowances for field or disciplinary differences: "The most-cited works in fields like botany, radioastronomy, mathematics, and so on, would not turn up on this undifferentiated list."[4]

Indeed, the list of 250 most-cited works from the 1955-1964 *SCI* omits astronomy, mathematics, the earth sciences, and other relatively small fields.[4] And the list of the 52 most-cited books and articles in 1945-1954 presented here is composed almost entirely of publications in chemistry (25) and physics (25); there are only 2 in mathematics, and none in astronomy or the earth sciences. Rather than omit mathematics, astronomy, and the earth sciences, ISI is compiling additional lists for those fields, which will be presented and discussed in the second part of this essay.

With the exception of a small-scale citation study of 16 physics journals of the 1920s,[5] the new 1945-1954 *SCI* cumulation represents the earliest period for which citation data are now available.[6] This compilation thus offers an exceptional opportunity to look back at a historic period of science and see what articles were *Citation Classics*® during this time.

Of the 52 publications most cited from 1945 to 1954, 5 were published before 1935 and 3 appeared after 1949 (a detailed chronological breakdown for all the physical-sciences publications is given in Table 1). I will concentrate on the 15-year period (1935-1949) in which the other 44 publications appeared.

Major Developments and Trends: Physics

The most important advance in twentieth-century physical science was the development of quantum theory by Max Planck, Albert Einstein, Niels Bohr, Louis de Broglie, Werner Heisenberg, and Erwin Schrödinger in the period 1900-1926.[7-9] By 1935 the basic principles of quantum mechanics and their application to the simplest systems had been firmly established. This may be seen from the fact that the 1930 ar-

Table 1: Chronological distribution of publication dates for the physical-sciences papers and books most cited in the *SCI*® cumulation, 1945-1954.

Publication Year	Number of Papers
1920-1924	1
1925-1929	0
1930-1934	4
1935-1939	8
1940-1944	17
1945-1949	19
1950-1954	3

ticle on quantum treatment of "Atomic shielding constants" by John C. Slater, Harvard University and the Massachusetts Institute of Technology, Cambridge, Massachusetts, needed no significant revision and was still highly cited in the 1955-1964 decade (336 citations)[4] as well as in 1945-1954 (176 citations).

Physicists were not satisfied that quantum theory could give an adequate account of the interaction between subatomic particles and radiation consistent with relativity theory, but this problem was set aside for a dozen years. In 1947 Willis E. Lamb and Robert C. Retherford, Columbia University, New York, showed that the energy difference between two excited states of the hydrogen atom, a difference theoretically due to the electron-radiation interaction, could be measured by experiment.[10] This result prompted theorists to work out detailed calculations, leading to the establishment of "quantum electrodynamics," a theory that achieved remarkable quantitative agreement with the experimental results.

Richard P. Feynman, California Institute of Technology (Caltech), Pasadena, and Julian Schwinger, Harvard University, in the US, and Sin-itiro Tomonaga, University of Education, Tokyo, Japan, independently developed this theory, for which they won the 1965 Nobel Prize in physics. Tomonaga's work was not widely known in Europe and America until after 1947 and is not represented in the Bibliography. But both Feynman and Schwinger published two papers on quantum electrodynamics that became *Citation Classics* in the 1945-1954 *SCI*. The Bibliography also lists two papers by another American (originally British) physicist, Freeman J. Dyson, Institute for Advanced Study, Princeton, which explained and extended the Feynman-Schwinger-Tomonaga theories.

Feynman subsequently became much better known to the public when he served on the commission appointed to investigate the *Challenger* disaster. By dropping an O-ring into a glass of ice water, he vividly demonstrated the dangers of launching a shuttle in cold weather. His two-volume autobiography (the second volume was published just after his death in 1988) is a fascinating account of the human side of science.[11,12]

The reason the development of quantum electrodynamics was postponed until the late 1940s was of course that physicists were preoccupied with the atomic nucleus. In 1938 Otto Hahn and Fritz Strassmann, Kaiser Wilhelm Institute for Chemistry, Berlin-Dahlem, Germany, performed the experiment that their colleague Lise Meitner, Academy of Sciences, Stockholm, Sweden, recognized as the discovery of fission.[13] The theory of this ominous phenomenon was explained in 1939 by Bohr and John A. Wheeler, Princeton University. Meitner's crucial role in the discovery was ignored when Hahn alone received the 1944 Nobel Prize in chemistry and has only recently come to be recognized.[14,15]

Of these only the Bohr-Wheeler paper appears in the Bibliography. Its 149 citations greatly underestimate the impact of knowledge about how fission works because scientists soon realized that this knowledge was too dangerous to be published in a world on the brink of war. For the next six years, most of the citations to the revolutionary papers on nuclear fission were confined to the secret reports of weapons laboratories, not included in the *SCI* database. This may also be true of the *Citation Classic* book by Sydney Chapman and T.G. Cowling, Imperial College of Science and Technology, London, since it was the authoritative source on the theory of the diffusion processes used to separate uranium isotopes for the Manhattan Project.

After Hiroshima and Nagasaki, nuclear physics was largely declassified and occupied a significant part of the journal literature for the next several years. This research activity is reflected by several highly cited works on isotopes, energy levels, and magnetic moments of nuclei—F. Ajzenberg and T. Lauritsen, Kellogg Radiation Laboratory, Caltech; F. Bloch, Stanford University, California; N. Bloembergen *et al.*, Harvard University; Melvin Calvin *et al.*, University of California, Berkeley; Eugene Feenberg and Kenyon C. Hammack, Washington University, St. Louis, Missouri; M. Goldhaber and A.W. Sunyar, Brookhaven National Laboratory, Upton, New York; Emil J. Konopinski, Indiana University, Bloomington; Maria G. Mayer, Argonne National Laboratory, Illinois; and Seaborg and Perlman.

Scientists were extensively involved in the public debates about nuclear weapons during the postwar period. The two most-cited publications carry the names of scientists who were on opposite sides of those debates. Pauling won his second Nobel Prize—the 1962 Peace Prize—for his leadership in the movement to ban nuclear tests. Teller, on the other hand, was an outspoken advocate for the development and testing of new weapons.

Missing from the list of *Citation Classics* is a subfield of physics that had already become prominent by 1949 and that was to attract an increasing share of intellectual and financial resources in the following decades: elementary particles. Hideki Yukawa's 1935 proposal that nuclear forces are carried by a particle with a mass of about 200 times that of the electron, and the discovery of the pi-meson by Cecil F. Powell and G.P.S. Occhialini in 1947, were recognized by the award of Nobel Prizes in 1949 and 1950. But the two review articles on cosmic rays (one by Bruno Rossi and Kenneth Greisen, Cornell University, Ithaca, New York, and the other by Rossi alone) are the only ones in the Bibliography directly related to this subfield, although the publications on quantum electrodynamics mentioned above were to have some influence on theories of elementary particles.[16]

The widening impact of quantum mechanics during the period 1935-1949 can be seen in several areas outside of atomic physics. *The Modern Theory of Solids* (1940), a *Citation Classic* by Frederick Seitz, then at the Carnegie Institute of Technology, Pittsburgh, Pennsylvania, is an obvious example, as is his review article on a special topic within this field, "Color centers in alkali halide crystals" (1946). The theory of the superfluidity of helium (1941) by L.D. Landau, Kharkov University, USSR, applied quantum mechanical ideas to fluids in a novel fashion that first mystified but ultimately enlightened the physics community.[17]

Chemistry

As noted at the beginning of this essay, Pauling used quantum mechanics to explain the chemical bond and molecular structure. A 1945 book on infrared and Raman spectra by Gerhard Herzberg, National Research Council of Canada, Ottawa, Ontario, and a 1941 paper on molecular vibrations by E. Bright Wilson at Harvard, along with the 1941 book by Glasstone, Laidler, and Eyring on rate processes, also taught many chemists how to use quantum mechanics to deduce by experiment quantitative information about molecular properties.

An alternative to Pauling's "valence bond" method was the "molecular orbital" approach popularized by Robert S. Mulliken, University of Chicago, Illinois. The highly cited 1941 paper on "Hyperconjugation" by Mulliken and University of Chicago colleagues Carol A. Rieke and Weldon G. Brown illustrates this approach. Another paper by Mulliken (1952) on the molecular orbital method was a "late bloomer"—that is, it was more highly cited from 1955 to 1964 than in the previous decade covered in this study, 1945-1954. Table 2 lists this and nine other "late-bloomer" publications, including another molecular orbital theory paper by C.C.J. Roothaan, University of Chicago.

Curiously, historians and philosophers of science have largely neglected these major

Table 2: "Late bloomers"—10 physical-sciences items published before 1954 that were among the 250 most cited in the 1955-1964 *SCI*® cumulation but not in the 52 physical-sciences items most cited in the *SCI* cumulation for 1945-1954. An asterisk (*) indicates that the item was the subject of a *Citation Classic*® commentary. The issue, year, and edition of the commentary follow the bibliographic reference. A=total number of 1945-1954 citations. B=total number of 1955-1964 citations.

A	B		Bibliographic Data
97	475		**Blatt J M & Weisskopf V F.** *Theoretical nuclear physics.* New York: Wiley, 1952. 864 p.
122	356	*	**Chandrasekhar S.** Stochastic problems in physics and astronomy. *Rev. Mod. Phys.* 15:1-89, 1943. (47/89/ET&AS; 47/89/PC&ES)
79	404		**Cruickshank D W J.** The accuracy of electron-density maps in X-ray analysis with special reference to dibenzyl. *Acta Crystallogr.* 2:65-82, 1949.
73	357	*	**Herzberg G.** *Molecular spectra and molecular structure. I. Spectra of diatomic molecules.* New York: Van Nostrand, 1950. 658 p. (13/83/PC&ES)
23	325	*	**McWeeny R.** X-ray scattering by aggregates of bonded atoms. 1. Analytical approximations in single-atom scattering. *Acta Crystallogr.* 4:513-9, 1951. (17/81/PC&ES)
79	403		**Mulliken R S.** Molecular compounds and their spectra. II. *J. Amer. Chem. Soc.* 74:811-24, 1952.
135	459		**Racah G.** Theory of complex spectra. II. *Phys. Rev.* 62:438-62, 1942.
47	352		**Roothaan C C J.** New developments in molecular orbital theory. *Rev. Mod. Phys.* 23:69-89, 1951.
20	355		**Shockley W & Read W T.** Statistics of the recombination of holes and electrons. *Phys. Rev.* 87:835-42, 1952.
115	438	*	**Van Vleck J H.** The dipolar broadening of magnetic resonance lines in crystals. *Phys. Rev.* 74:1168-83, 1948. (31/79/PC&ES)

contributions to the foundations of chemistry while giving perhaps excessive attention to the foundations of physics.[1] Thus the *Isis Cumulative Bibliography 1976-1985*, which lists nearly all publications on the history of science published during this period, has only 5 items on Pauling and 3 on Mulliken, compared to 234 on Einstein, 33 on Bohr, 26 on Heisenberg, 16 on Planck, 15 on Ernest Rutherford, 13 on de Broglie, and 12 on Robert Andrew Millikan, Caltech.[18] Since one of the articles on Pauling also deals with Mulliken, the total for both authors is only seven. Other works by Pauling are listed in the *Critical Bibliography of the History of Science and Its Cultural Influences*, published annually in *Isis*. In this case the citation data are especially valuable in calling attention to influential contributions in a large body of technical literature that few nonspecialists can understand.

While the largest number of chemistry *Citation Classics* (6 out of 25) involve the application of quantum mechanics, almost as many (4) deal with polymers. As Paul J. Flory, then at Esso Laboratories, Standard Oil Development Co., Linden, New Jersey, author of two of these papers, recalled in his Nobel lecture, Hermann Staudinger had established by about 1930 that polymers are covalently linked molecules, rather than aggregates of smaller molecules.[19] The first attempt at a mathematical description of their spatial configurations was published in 1934 by Werner Kuhn, University of Basel, Switzerland. The subject was further discussed in a 1943 paper by Kuhn and Hans Kuhn, also at the University of Basel. Both papers are listed in the Bibliography.

The Kuhn theory was based on a simplified model, the molecule being represented by the "random walk" of a point particle. Flory made a significant improvement by taking account of the "excluded volume effect"—the fact that two segments of the molecule (unlike the path of a moving point particle) cannot occupy the same space. Flory's work led to major advances in understanding the properties of polymers, substances that also have considerable technological importance.[19] He identifies his own key contribution to the subject as a paper published in 1949 and does not mention the earlier papers listed here.

Nobel Laureates

For physics and chemistry, the obvious question about any list of highly cited works is: How many were authored by Nobel laureates? And how many Nobel Prize-winning papers *don't* appear on the "most-cited" list?

There are 78 authors for the 52 most-cited publications (some of them being authors of more than one item). If one omits the two mathematicians (Stefan Banach, University of Lvov, USSR, and Harald Cramér, University of Stockholm, Sweden), there are 18 Nobel laureates among the 76 physicists and chemists. They are listed in Table 3, which also shows the year in which they were awarded the prize.

Eleven items in this study list at least one Nobel physicist author. Since 1 of the 25 physics publications was coauthored by a Nobel chemist (Seaborg), one could also say that 48 percent of the most-cited physics publications were written by Nobel laureates. And there are 11 items with at least one Nobel chemist author. Of the 25 chemistry items, 10 (including two editions of Pauling's book) or 40 percent were authored by a chemistry Nobel laureate.

This is not to say that the publications identified here are necessarily the Nobel laureates' prizewinning works. As pointed out by Garfield, the most-cited publications by Nobel laureates are sometimes *not* the ones for which they won the prize.[20] In some cases the prize is given for a body of work rather than a single publication. Moreover, it is still possible for a scientist to win the Nobel Prize in the future for work done during this period. For example, the 1989 prize in physics went to Norman Ramsey, Harvard University, for his research on molecular beams in the late 1940s.[21]

Another reason many *Citation Classics* don't win Nobel Prizes is that they do not report original research discoveries. Instead, they describe useful new experimental instruments or methods, or they review progress in a field or compile data. I estimate that only about 40 percent of the items in the Bibliography are first reports of original research.

Of the Nobel laureates in this study, Bohr, Lars Onsager, and Svedberg won it for work done before they published the *Citation Classics* listed here. Calvin, Herzberg, Nevill F. Mott, and Pauling were honored for research originally published in journals; their *Citation Classics* are monographs covering the same and related subjects. Similarly, Seaborg's and Mayer's highly cited papers are compilations of data relevant to their research. Bloembergen, Feynman, Flory, Landau, Mulliken, Purcell, Schwinger, and Karl Ziegler won the Nobel Prize for research that does include papers on the most-cited list.

Onsager is the only Nobel laureate on the list whose highly cited paper is on a subject clearly different from the research for which he received the prize. He received the prize for a 1931 work on reciprocal relations in irreversible processes.[22,23] But I consider his solution of the two-dimensional Ising problem[24] more significant than that work or his paper on electric moments in liquids[17] included in the list.

Table 3: Nobel laureates listed as authors of the most-cited physical-sciences papers and books in the 1945-1954 *SCI*®, showing the field and year of their awards.

Nobelist	Field	Year
Bloch F	Physics	1952
Bloembergen N	Physics	1981
Bohr N	Physics	1922
Calvin M	Chemistry	1961
Feynman R P	Physics	1965
Flory P J	Chemistry	1974
Herzberg G	Chemistry	1971
Landau L D	Physics	1962
Mayer M G	Physics	1963
Mott N F	Physics	1977
Mulliken R S	Chemistry	1966
Onsager L	Chemistry	1968
Pauling L	Chemistry	1954
	Peace	1962
Purcell E M	Physics	1952
Schwinger J	Physics	1965
Seaborg G T	Chemistry	1951
Svedberg T	Chemistry	1926
Ziegler K	Chemistry	1963

Mathematics

The books by Banach (1932) and Cramér (1945), the only mathematics publications in the Bibliography, are *Citation Classics* for rather different reasons. Cramér's com-

Table 4: The 1988 *SCI®* research fronts that include at least one of the 1945-1954 most-cited physical-sciences items as core documents. The names of first authors from the Bibliography appear in parentheses. A=number of Bibliography items that are core to each research front. B=total number of core documents. C=total number of 1988 citing papers.

Number	Name	A	B	C
88-0046	Polymer mixtures, binary blend void systems, statistical thermodynamics, and Monte-Carlo simulations of lattice models (Flory)	1	11	136
88-0082	Superdeformed states of rotating nuclei, complex fragment emission, gamma-ray spectroscopy, high angular momentum, and intermediate energies (Bohr)	1	37	338
88-0141	Superfluid He-4, interatomic potentials, deep inelastic neutron-scattering, collision induced spectroscopies, and long-range 3-body interactions (Landau)	1	38	329
88-0465	Symmetrical hydrogen-bonded ice, continuum model proton transfer, dynamics of solitons, amorphous SiO_2, high-pressure phases, and bonding defects (Bernal)	1	33	306
88-1474	Nuclear-spin relaxation, nematic phase, thermotropic liquid crystals, proton NMR, and spectral densities for isotropic intermolecular interactions (Bloembergen)	1	12	147
88-3298	Sodium tetrahydroborate, efficient reduction of acyl chlorides, and living cationic polymerization (Nystrom)	1	3	21
88-3360	Adsorption of water, anomalous synthetic tobermorites, and surface characteristics (Brunauer)	1	2	118
88-4626	Electrical-resistivity in $YBa_2Cu_3O_{7-\delta}$, ferromagnetic Ni-base alloys, and thin antiferromagnetic films (Mott)	1	4	35
88-4982	Symmetry group transfomation operators in the interaction picture and quantum fluid at nonzero temperature (Dyson, Feynman)	2	2	17
88-5199	Unified photon dosimetry approach, pencil beam kernels, and arbitrary dose distributions (Rossi)	1	5	27
88-8156	Molecular vibrations, infrared spectroscopic data, and ethyl bromoacetate (Wilson)	1	2	13

prehensive treatise was useful to many scientists because it presented modern mathematical models that could be conveniently learned and applied to problems requiring statistical analysis. Banach's monograph stimulated further research by mathematicians working in harmonic analysis, partial differential equations, algebra, and topological vector spaces. Although Cramér's book was more directly applicable to empirical research in the physical sciences, Banach's had a closer intellectual relation to the theoretical approach that dominated physics and chemistry in the second quarter of the twentieth century.

Banach (1892-1945) seems to have had no interest in quantum mechanics and it would be difficult to show that it had any influence on his ideas. Nevertheless, his work on linear operators and the invention of "Banach space" fall squarely within the tradition that provided the mathematical foundation for the versions of quantum mechanics developed by Schrödinger, Paul Dirac, John von Neumann, and Feynman.[25,26] The key idea in this tradition is to generalize the idea of a "space," originally defined in terms of a few variables (x,y,z), whose values are numbers, to spaces of *functions*; these can be regarded as spaces with an infinite number of dimensions. In quantum mechanics the state of a system is represented by a wave function that may be treated as belonging to a "Hilbert space," a special case of the more general space studied by Banach. The "linear operators" in the title of Banach's *Citation Classic* monograph correspond in quantum mechanics to physical entities like energy and momentum, whose values can be found by letting the operators operate on the wave function.

Research Fronts, Chronological and National Distributions, and Journals of the Top 52 Physical-Sciences *Citation Classics*

Table 4 lists current 1988 research areas that frequently cite one or more of the items in the Bibliography. The cited items are considered part of the "core" for the "research fronts," as determined by an algorithm developed at ISI.[27-29] Items in a core must be

Table 5: The number of authors per paper for the 36 physical-sciences papers most cited in the *SCI®* cumulation, 1945-1954.

Number of Authors per Paper	Number of Papers
5	1
4	1
3	4
2	11
1	19

Table 7: The journals that published the 36 papers listed in the Bibliography. The numbers in parentheses are the 1988 impact factors for the journals. (The 1988 impact factor equals the number of 1988 citations received by the 1986-1987 articles in a journal divided by the number of articles published by the journal during the same period.) Data were taken from the 1988 *JCR®*. The figures at the right indicate how many papers from each journal appear in the Bibliography.

Journal	Number of Papers
[1] Phys. Rev. (N/A)	13
J. Amer. Chem. Soc. (4.57)	8
Rev. Mod. Phys. (15.13)	6
J. Chem. Phys. (3.59)	3
[2] Ber. Deut. Chem. Ges. B (N/A)	1
Helv. Chim. Acta (1.97)	1
[3] Ind. Eng. Chem. Anal. Ed. (N/A)	1
[4] J. Phys. SSSR (N/A)	1
[5] Just. Liebigs Ann. Chem. (N/A)	1
[6] Kolloid Z. Z. Polym. (N/A)	1

[1] Divided in 1970 into Phys. Rev. A—Gen. Phys. (2.32), Phys. Rev. B—Solid State (changed in 1978 to Phys. Rev. B—Condensed Matter [3.82]), Phys. Rev. C—Nucl. Phys. (2.01), and Phys. Rev. D—Part. Fields (2.33)
[2] Merged with Ber. Deut. Chem. Ges. A in 1947 to form Chem. Ber. (1.53)
[3] Changed to Anal. Chem. (3.98) in 1947
[4] Published 1939-1947
[5] Changed to Liebigs Ann. Chem. (1.10) in 1979
[6] Changed to Colloid Polym. Sci. (0.95) in 1974

related to each other by co-citations, and must also satisfy a minimum "citation strength" criterion that weights each citation relative to the total number of citations in the reference list of the citing paper. This procedure should to some extent mitigate the bias against fields such as mathematics in which articles have shorter reference lists.

It is interesting to note that both of the core papers in research front #88-4982, "Symmetry group transformation operators in the interaction picture and quantum fluid at nonzero temperature," are *Citation Classics* included in this study— Dyson's 1949 paper on the Tomonaga-Schwinger-Feynman radiation theories and Feynman's 1949 paper on the space-time approach to quantum electrodynamics. That these and other works of comparable age are still co-cited in current research fronts indicates that they have not been "obliterated by incorporation." This phenomenon, described by sociologist Robert K. Merton,[30] Columbia University, and discussed by Garfield,[31] refers to important discoveries that have become so completely integrated into scientific knowledge that authors no longer feel a need to cite the original publication.

Other statistical characteristics for the 36 articles in this study are given in Tables 5-7: the number of authors per paper, nationality based on authors' institutional affiliations, and journal of publication, respectively (except for the table showing nationalities, these three tables exclude this study's 16 books).

Table 6: National locations of the institutional affiliations listed by authors in the Bibliography, according to total appearances (column A). B = number of items coauthored with researchers affiliated with institutions in other countries. C = national locations of institutions listed by coauthors.

Country	A	B	C
US	37	2	Canada, Denmark
UK	6		
Canada	2	1	US
Germany	2		
Sweden	2		
Switzerland	2		
Denmark	1	1	US
Poland	1		
USSR	1		

Conclusions

In this essay I have tried to sketch a few of the scientific developments of the 1930s and 1940s and to contrast the visibility of those developments at mid-century, as measured by citation frequency, with their im-

portance as perceived in subsequent decades.

Since some science departments now use citation counts in evaluating faculty for promotion and tenure, it should be emphasized that most of the papers that are later judged to contain outstanding discoveries were *not* highly cited by contemporaries. Thus one cannot dismiss publications as insignificant merely because they are not frequently cited (even relative to other papers in the same journals).[32]

For historians and others interested in understanding the science of a particular period, citations (to say nothing of the more sophisticated kinds of citation analysis now used in the discipline of scientometrics) can be quite revealing. The fact that a publication was highly cited shows that it was visible to the scientific community for *some* reason; one must then look at the citing articles to find out *why* it was cited. In some cases (e.g., the article by Brunauer *et al.* on adsorption) one learns about important original research that may have been neglected by historians of science. The list of articles that cited a publication is also extremely helpful in studying how and why a theory or discovery was accepted or rejected by the scientific community, which I demonstrated in a historical study of theories of the origin of the solar system.[33]

As those who have participated in the scientific enterprise have learned (sometimes by bitter experience), it is not sufficient merely to publish your ideas and results; you must also persuade other scientists to accept them. The *SCI* offers a valuable tool for investigating the dynamics as well as the structure of science.

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