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The 1983 Nobel Prizes. Part 1. Physics and Chemistry Awards Go to Chandrasekhar, Fowler & Taube

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We have examined each group of annual Nobel Prize winners since 1979. Beginning with the 1982 awards,[1] we included data from the research fronts we identify each year for *Science Citation Index®* (*SCI®*). Briefly, a research front is a group of current papers that cite a cluster of "core" papers identified by co-citation clustering. These procedures have been described previously.[2]

By systematically reviewing our research front data from year to year, one may be able to forecast fields that may eventually be acknowledged with a Nobel Prize. However, it is careless and fallacious to claim that citation analysis or any other method can *predict* the choice of the prize-awarding committees. Citation analysis, however, *will* identify individuals who are *of Nobel class*.[3] From these groups, one might forecast winners for their fields once the prize-awarding committees choose to recognize those areas.

This part of the essay will discuss the 1983 Nobel Prize in physics—awarded to Subrahmanyan Chandrasekhar, University of Chicago, Illinois, and William A. Fowler, California Institute of Technology (CalTech), Pasadena—and the chemistry prize, awarded to Henry Taube, Stanford University, California. Part two will discuss the prizes in physiology or medicine, economics, and literature.

Since we began work on this essay, the 1984 Nobel Prizes have been announced. Carlo Rubbia, Harvard University, Cambridge, Massachusetts, and the Center for European Nuclear Research (CERN), Geneva, and Simon van der Meer, also of CERN, won the physics prize. Their work led to the discovery of the W and Z particles, the communicators of weak nuclear interactions.[4] The 1984 prize in chemistry went to R. Bruce Merrifield, Rockefeller University, New York, for his revolutionary method of protein synthesis. It created completely new possibilities in the fields of peptide and protein chemistry.[5] A future essay will discuss the work of each of these scholars.

Physics

The 1983 Nobel Prize in physics was shared by Subrahmanyan Chandrasekhar and William A. Fowler for their work on the evolution of stars.[6] Fowler's work demonstrated the process by which reactions in the nuclei of stars form sequentially heavier elements. Chandrasekhar's theoretical work deals with a large number of features in stellar evolution relating to equilibrium and stability criteria of stellar configurations. Both astrophysicists are so well known in their field that it comes as no surprise that their works repeatedly appear on our lists of highly cited publications.

Fowler's work on nucleosynthesis—the formation of sequentially heavier elements in the heart of a star—began in 1954 during a Fulbright professorship at Cambridge University, England, where he formed a collaboration with Sir Fred Hoyle. Astrophysicists Geoffrey R. and E. Margaret Burbidge also worked with Fowler and Hoyle at Cambridge, and later at CalTech. Together, the four produced a comprehensive theory of the nucleosynthesis of all the elements and their isotopes. An isotope of an element has the same atomic number and number of protons, as well as similar chemical properties, but a different atomic weight because it contains a larger number of neutrons.

In 1956, the group, then working in Fowler's lab at CalTech, wrote a preliminary paper for *Science* that briefly described the mechanisms of nucleosynthesis in stars.[7] This brief article was published mainly to establish the priority of their work.[8] It was followed in 1957 by a more detailed description in *Reviews of Modern Physics*.[9] This paper is commonly referred to as B^2FH—taken from the initials of the four investigators. It describes in detail the stellar synthesis of all naturally occurring chemical elements. These elements are formed by a series of processes that occur in successive generations of stars. Since there is little mixing of material inside most stars, the hot core quickly consumes its hydrogen supply. When this happens, the star becomes a red giant—a bloated, cool star of high luminosity. At the red giant stage, new nuclear reactions occur. As a result, new and heavier elements are made. The most important is the formation of carbon from three helium nuclei. Successive bombardment of carbon nuclei by helium creates other heavier elements, such as iron. The iron group nuclei are then seeds for further synthesis. As stars evolve, some of the matter is returned to interstellar space, either gradually or by supernova. A supernova is a stellar explosion during which a star greatly increases in luminosity while vast quantities of star matter are expelled into space.

According to John Maddox, editor of *Nature*, B^2FH is a milestone publication for several reasons.[10] First, it provided a coherent explanation of nucleosynthesis. Second, it settled the dispute about the direction of stellar evolution along the Hertzsprung-Russel diagram, which characterizes stars according to brightness and surface temperature. Finally, B^2FH provided the basis for calculating the internal constitutions of stars, as well as for understanding the fate of massive stars in a supernova explosion. In fact, although B^2FH was published in 1957, according to the Swedish Academy of Sciences, the work it represents "is still the basis of our knowledge in this field, and the most recent progress in nuclear physics and space research further confirms its correctness."[11]

After publication of B^2FH, Fowler continued to work out details of stellar nucleosynthesis. Much of Fowler's theoretical work was done in collaboration with Hoyle. More than 25 of Fowler's 200 papers were coauthored by Hoyle. In 1963, Fowler and Hoyle published a theory suggesting that strong radio waves from certain galaxies resulted from cataclysmic events near the centers of those galaxies.[12] Fowler and Hoyle noted that these radio waves could not be the result of the energy of nuclear fusion. They suggested that they were propagated by the energy released in a supernova, as the gravitational collapse of the star's interior blows off the outer shell of stellar material. This work,[12] published in *Nature*, has been cited in over 100 subsequent publications.

With Hoyle back in Cambridge in 1963-1964, Fowler derived the equations for the binding energy of a super-massive star and published them in 1964 in another article in *Reviews of Modern Physics*. This paper has also been explicitly cited about 100 times.[13]

In 1967, in a letter to the editor of *Nature*, Fowler and Hoyle suggested that the indications that quasars are so distant may be misleading.[14] The objects may in fact be much closer to the Earth than formerly thought. However, this idea is not widely accepted throughout the scientific community.

In another 1967 paper coauthored with R.V. Wagoner, Hoyle and Fowler discuss the synthesis of elements at very high temperatures.[15] This publication, cited more than 300 times, appears in our 1974 study of papers from the *Astrophysical Journal*.[16] Fowler's 1973 paper[17] on light elements appears in the list of papers most cited in that year.[18] That same work, done in collaboration with, among others, French scientist J. Audouze, appeared in our study of French scientists.[19]

From 1955 through 1983, Fowler's collective work has been cited approximately 5,900 times. Not surprisingly, B^2FH is the most-cited paper. From its publication in 1957 to date, it has been cited in over 800 publications. In a 1974 interview with Charles Weiner, Center for the History of Physics, New York, directed by Spencer Weart, American Institute of Physics, New York, Fowler commented, "I anticipate that if I am remembered in science it will be as the F in B^2FH."[8]

Some of the more recent *SCI* research fronts in which articles by Fowler are core documents appear in Table 1. In the 1981 research front, "Grand unification theories, proton decay, neutrino masses, flavor dynamics, and Higgs boson in the SO(10) model," the 1967 paper by Wagoner, Fowler, and Hoyle[15] discussed above is one of 63 core papers. Of the 682 citing documents in this research front, all were published in 1981. This research front carried through to several

Table 1: *SCI®* research fronts in which articles by William A. Fowler occur as core documents. A = number. B = name. C = number of core papers. D = number of citing papers.

A	B	C	D
81-0312	Grand unification theories, proton decay, neutrino masses, flavor dynamics, and Higgs boson in the SO(10) model	63	682
81-1062	Isotopic anomalies in meteorites in relation to solar system formation	9	140
82-0034	Primordial nucleosynthesis and cosmology	5	68
82-1691	Stellar evolution	2	52
83-0768	Nucleosynthesis and elemental abundances in stellar evolution	10	133

research fronts in 1982. One, "Weak neutral bosons in gauge models and grand unified theories," has 10 core documents. Four of these also are core to the 1981 research front. Another, "Grand unified theories," has six core documents. Five of these also are in the core of the 1981 research front. And "Proton decay" has six core documents, three of which also are core to the 1981 research front. The paper by Wagoner, Fowler, and Hoyle is also among the five that form the core of the 1982 research front, "Primordial nucleosynthesis and cosmology." Figure 1 provides a multidimensional scaling map of these papers. The lengths of the connecting lines are inversely proportional to the co-citation strength.[2]

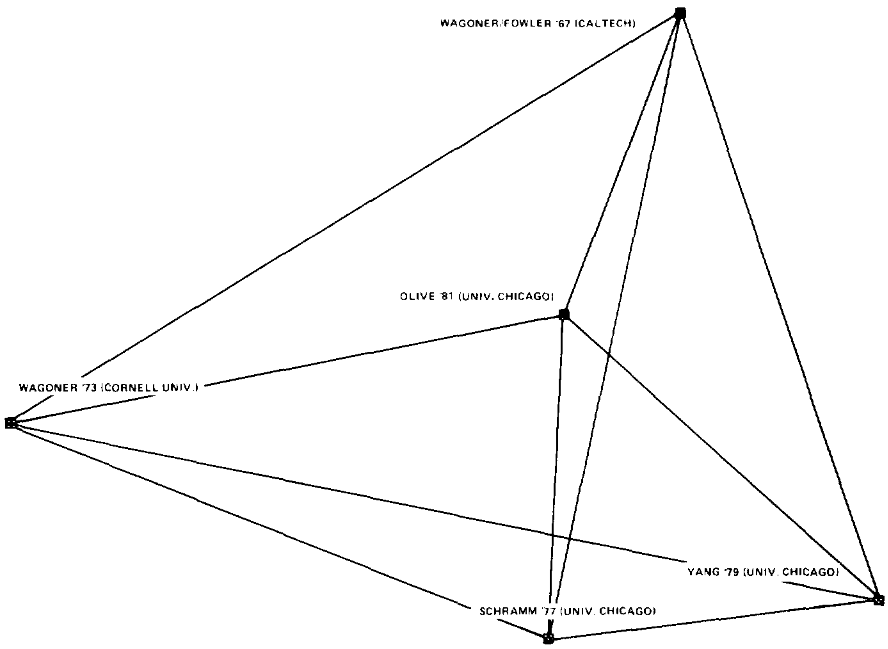
B^2FH is one of the core documents in another 1981 research front, "Isotopic anomalies in meteorites in relation to solar system formation." It is interesting to note that this front split into two research fronts in 1982. One was entitled "Noble gases in meteorites," and the other was named "Petrogenesis and other aspects of inclusions in meteorites and chondrites." B^2FH is also one of 10 core papers in the 1983 front, "Nucleosynthesis and elemental abundances in stellar evolution." So is Fowler's 1975 paper on thermonuclear reaction rates.[20]

While Fowler's work showed how stars during their lifetimes and in their supernova deaths produce all of the chemical elements known today, theoretical physicist Chandrasekhar's work showed that not all stars pass through the white dwarf stage. White dwarfs are very dense stars that have used up their nuclear fuel. They were thought to be the stable end points of stellar evolution for all stars. But Chandrasekhar showed that this was so only if their mass was less than a certain critical value. This maximum, about 1.4 times the mass of the sun, is now called Chandrasekhar's limit. Beyond this limit, stars collapse under their own weight and become black holes.

When Chandrasekhar, at age 24, presented his theory to the Royal Astronomical Society of London in 1935, Sir Arthur Eddington, a preeminent astronomer, denounced the entire theory as absurd.[21] Although some astrophysicists agreed with Chandrasekhar in private, none publicly supported him. Kameshwar C. Wali, Department of Physics, Syracuse University, New York, wrote that Chandrasekhar's work demonstrates the obstacles that affect the acceptance of new scientific theories.[21] Wali noted that contrary to commonly held belief, the human factors such as prestige, personal biases, and authority play as important a role in science as they do in art and literature. It was over 21 years before Chandrasekhar's limit and his theory of stellar evolution were accepted and incorporated into the body of astrophysical knowledge.[21] After publishing his views of stellar evolution in 1939 in *An Introduction to the Study of Stellar Structure*,[22] Chandrasekhar decided that his future in science depended on his going into other areas of research.[23] The book has been cited more than 500 times since 1955, and continues to be cited regularly.

Chandrasekhar's approach to research has followed a distinctive pattern; his field of research changes every 5 to 10 years. In each field, he first publishes a series of papers. When he has accumulated a sufficient body of knowledge, he then publishes it in the form of a book, presenting a coherent self-contained picture of the field. After publishing his theory of stellar evolution, Chandrasekhar began looking at stellar dynamics in terms of the gravitational interactions between stars in a star cluster. The study resulted in another classic publication, *Principles of*

Figure 1: Multidimensional scaling map showing co-citation links between core papers for the 1982 *SCI*® research front, "Primordial nucleosynthesis and cosmology."



KEY

Olive K A, Schramm D N, Steigman G, Turner M S & Yang J. Big-bang nucleosynthesis as a probe of cosmology and particle physics. *Astrophys. J.* 246:557-68, 1981.
Schramm D N & Wagoner R V. Element production in the early universe. *Annu. Rev. Nucl. Sci.* 27:37-74, 1977.
Wagoner R V. Big-bang nucleosynthesis revisited. *Astrophys. J.* 179:343-60, 1973.
Wagoner R V, Fowler W A & Hoyle F. On the synthesis of elements at very high temperatures. *Astrophys. J.* 148:3-49, 1967.
Yang J, Schramm D N, Steigman G & Rood R T. Constraints on cosmology and neutrino physics from big-bang nucleosynthesis. *Astrophys. J.* 227:697-704, 1979.

Stellar Dynamics, in 1942.[24] This book has been cited over 400 times since 1955. However, until we have completed *SCI* for the post-war period, we won't know how often the book was cited in the years immediately after publication. Indeed, it is well known that publication and citation counts dip considerably during the post-war period.

During World War II, Chandrasekhar focused on radiation transfer from a star's hot interior to its cooler exterior, and understanding the theory of Brownian movement and its application to stellar encounters. The resulting publication, and Chandrasekhar's second most-cited work, "Stochastic problems in physics and astronomy," was published in 1943 in *Reviews of Modern Physics*.[25] This work has been cited over 2,100 times since 1955. It appeared in our 1977 study of highly cited articles of the 1940s.[26] Not surprisingly, this paper also turned up in our recent study of superstar *Citation Classics*™.[27] Although published 40 years ago, the article was cited explicitly 158 times in 1983. The paper is also among the 100 articles most cited in the *CompuMath Citation Index*® (*CMCI*®) from 1976 through 1980.[28]

Chandrasekhar's further work in radiation transfer resulted in another book, *Radiative Transfer*, which was published in 1960.[29] During an interview with Weart, Chandrasekhar noted that he chose the field of radiation transfer because it was "fresh ground" and he could do something significant with it.[23] His impact is reflected in over 1,900 citing publications since 1955. In 1957, Chandrasekhar received the Rumford Medal for this work.[30]

Chandrasekhar went on to study turbulence and stability problems. His 1961 book, and his most-cited work, *Hydrodynamic and Hydromagnetic Stability*,[31] sold more than 10,000 copies. It was cited over 2,100 times. About 20 years ago, we included this work among the 100 essential books needed by new libraries and graduate schools.[32]

Chandrasekhar's next research endeavor involved the stability of ellipsoidal figures. Ellipsoids are imaginary, tangerine-shaped geometric figures. Chandrasekhar systematically analyzed the forces acting on a rotating ellipsoid and published *Ellipsoidal Figures of Equilibrium* in 1969.[33] Scientists use the theories in this book to understand what holds the ellipsoid-shaped Milky Way Galaxy together as it spins. This book has been cited in "only" 262 publications as yet.

Ten years ago, Chandrasekhar started to study black holes. Of particular interest to him was the explanation of how a rotating black hole reacts to external perturbations such as gravitational and electromagnetic waves. His most recent book is *The Mathematical Theory of Black Holes*,[34] published in 1983.

In addition to his intensive research efforts, Chandrasekhar also served as the editor of the *Astrophysical Journal* for 19 years—from 1952 to 1971. During that time, he helped put the journal on a sound financial footing. Although Chandrasekhar believes a journal is only as good as the papers it attracts, his influence guided the *Astrophysical Journal* through an exciting period of research.

Chandrasekhar was one of the 50 most-cited authors, 1961-1972.[35] More than one-fourth of those authors were Nobel laureates when the list was compiled in 1973. Since then, two more authors on that list have been awarded the Nobel Prize: Chandrasekhar himself, and H.C. Brown, Purdue University, Lafayette, Indiana, who won the 1979 prize for chemistry. If we could ever claim that citation analysis has forecasting potential, surely that simple experiment gave us good reason to speculate along those lines. Chandrasekhar also appeared in the larger study of the 250 most-cited primary authors from 1961 through 1975.[36] This list included 42 Nobel laureates. Between 1961 and 1975, Chandrasekhar's work received an average of 545 citations annually.

The research fronts in which articles by Chandrasekhar are core documents appear in Table 2.

His book *Radiative Transfer*[29] is one of three core publications in the 1983 research front, "Calculations and applications of radiative transfer in a scattering atmosphere." His 1933 article, "Equilibrium of distorted polytropes,"[37] in the *Monthly Notices of the Royal Astronomical Society*, appeared in the 1983 research front, "Models and observations of periodic perturbations in close binary stars." His 1944 article on the negative hydrogen ion, published in the *Astrophysical Journal*,[38] is one of the four core papers that identified the 1983 research front, "Photoluminescence of bound excitons and biexciton binding energies of direct gap semiconductors."

Chemistry

The 1983 Nobel Prize in chemistry was awarded to Henry Taube for three decades of work "in the mechanism of electron-transfer reactions, especially in metal complexes."[39] Electron transfer is the process by which an atom, during a chemical reaction, gains or loses electrons. The number of electrons transferred determines, to a certain extent, the kind of chemical bond formed. Taube's work also was honored in August 1983 with the Robert A. Welch award, which includes an honorarium of $150,000. The award was founded in 1954 as part of the estate of the Houston, Texas multimillionaire.[30]

Taube's electron-transfer work—including a 1970 monograph[40] cited over 200 times through 1983—provides the basis for understanding the dynamic behavior of inorganic compounds. Indeed, his study of the basic mechanisms of inorganic chemical reactions forms not only the framework upon which much of modern inorganic chemistry is built, but also has led to deeper insights into the chemical processes that maintain life.[41]

The Royal Swedish Academy of Sciences described Taube as "one of the most creative contemporary workers in inorganic chemis-

Table 2: *SCI*® research fronts in which books or articles by Subrahmanyan Chandrasekhar occur as core documents. A = number. B = name. C = number of core papers. D = number of citing papers.

A	B	C	D
83-2063	Models and observations of periodic perturbations in close binary stars	4	37
83-3488	Photoluminescence of bound excitons and biexciton binding energies of direct gap semiconductors	4	26
83-3524	Theory of dynamics, diffusion and rate processes	13	299
83-4213	Calculations and applications of radiative transfer in a scattering atmosphere	3	57

try."[42] He was born in Neudorf, Saskatchewan, Canada, on November 30, 1915. He earned a BS degree in 1935 and an MS degree in 1937 from the University of Saskatchewan, Saskatoon, and then after research with William C. Bray at the University of California, Berkeley, received his PhD there in 1940. Taube's first academic appointment was at Cornell University, Ithaca, New York, but it wasn't until he moved to the University of Chicago in 1946 that he became interested in pursuing a systematic approach to coordination chemistry. This started him down the avenue of research that eventually ended with the Nobel.

Taube's work is broad and basic, yet so diffuse that it may be difficult to grasp. In fact, when Taube was asked to write about his work in layman's terms, he said he found himself writing "the lectures for the first year in general chemistry."[41] Thus, to explain the significance of Taube's work, it is necessary to start with some rather elementary definitions.

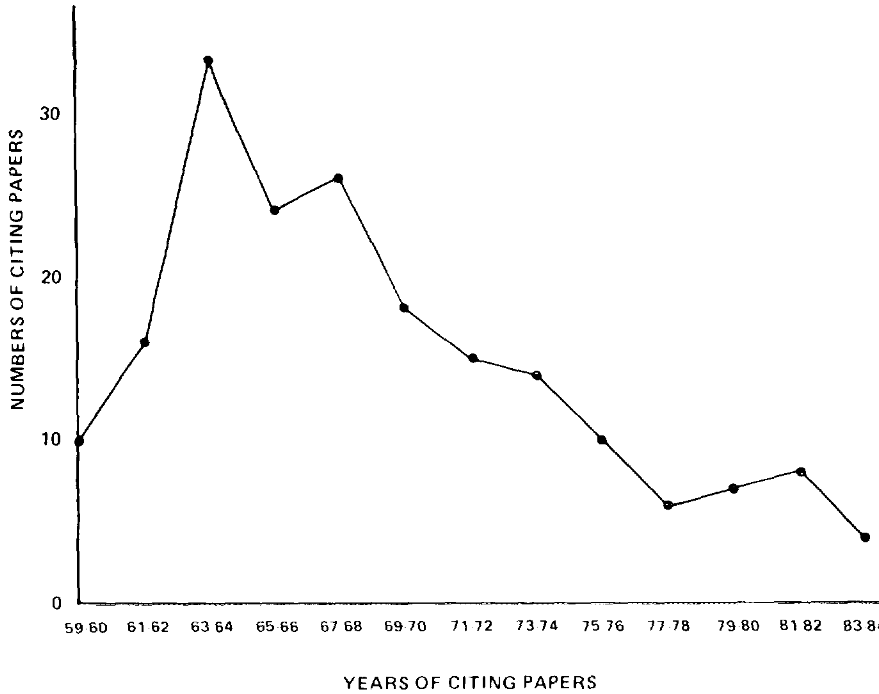
Taube's pioneering studies involved the reactions of transition metals, such as iron, copper, cobalt, and molybdenum.[41] Transition metals are well known for their propensity to form coordination complexes. These complexes are compounds that are composed of a metal ion, or electrically charged atom, bonded to a ligand, which is a non-metallic ion or molecule.[41] Ligands—examples of which include water, ammonia, and chloride ions—can donate at least one pair of electrons to a metal ion. The basic theory of coordination compounds was developed at the turn of the century by Alfred Werner, who won the 1913 Nobel Prize.

Taube's great contribution was the careful experimental work that showed how coordination compounds react with one another. In his most-cited paper, published in *Chemical Reviews* in 1952,[43] Taube described a sweeping correlation between ligand substitution rates and electron configuration for coordination compounds of transition metals. This paper was cited at least 300 times from 1955 through 1983. In fact, this paper still dominates research in the reaction chemistry of coordination compounds.

As the Nobel citation indicates, Taube is best known for his pioneering work on oxidation-reduction reactions, known as redox reactions—especially those involving transition metal ions. A 1959 paper in the first issue of *Advances in Inorganic Chemistry and Radiochemistry*[44] describes the mechanisms of these reactions and has been cited about 200 times to date. Figure 2 shows the citation history of this paper from its publication through 1984. The steeply rising curve from 1960 through 1964 illustrates the immediacy of the article's impact, which is atypical of chemistry classics. In another paper,[45] published in 1954 with H. Myers and cited over 175 times, Taube made use of his earlier correlation of ligand exchange rates to demonstrate the principles of "outer sphere," or electron-transfer, and "inner sphere," or atom-transfer, complexes in redox reactions of transition elements.

Taube's study of electron transfer also led him, together with Carol Creutz, Stanford University, to be the first to systematically prepare and characterize a mixed-valence molecule, now commonly known as the Creutz-Taube ion.[46-48] In mixed-valence substances, two similar metals in different oxidation states are linked by a ligand; electron transfer between the two can occur at various rates. Understanding the structural features that control these rates has been an important theme in Taube's work, and has initiated a large, rapidly growing field of chemistry. Their earliest paper in this area,[46] published in 1969, has been cited about 100 times through 1983. And among the papers to

Figure 2: Chronological distribution of articles citing Henry Taube's 1959 *Advances in Inorganic Chemistry and Radiochemistry* paper.



which this research led, the 1973 work on complexes of ruthenium ammines has been cited about 150 times in 10 years.[48]

By measuring reaction rates and charting the paths of electrons as molecules break apart and recombine, Taube has shown how chemical reactions occur. And although most of his research has had little immediate application, it laid the foundation for understanding the chemical reactions that produce the energy required by living organisms. It also led to the development of processes used in the manufacturing of chemicals.[39] Testifying to the extensive usefulness of Taube's research, his work has been cited explicitly over 8,500 times since 1955. Not surprisingly, Taube was among the 1,000 most-cited contemporary authors we identified several years ago.[49]

Table 3 lists the research fronts in which articles by Taube, among others, are core documents. In the 1981 research front, "Electron transfer in chemical and biological systems," the Creutz-Taube ion[48] paper is one of three core papers. The other two are papers by M.B. Robin, Bell Telephone Laboratories, Murray Hill, New Jersey, in *Advances in Inorganic Chemistry and Radiochemistry*,[50] and N.S. Hush, University of Bristol, England, in *Progress in Inorganic Chemistry*.[51] The Creutz-Taube ion paper is also among the 10 publications that later formed the core of the 1983 front, "Electron transfer and properties of mixed-valence iron, ruthenium, and related binuclear transition metal complexes studied by Mossbauer and electrochemical methods."

In addition, the paper on "Electron transfer through organic structural units,"[52] coauthored in 1964 with Stanford colleague Edwin S. Gould and cited about 175 times through 1983, is among the three core papers of the 1983 research front, "Kinetics and mechanism of electron transfer in hexaaquochromium (III) and other transition metal complexes with carboxylate ligands." The other

Table 3: *SCI*® research fronts in which articles by Henry Taube occur as core documents. A = number. B = name. C = number of core papers. D = number of citing papers.

A	B	C	D
81-1323	Electron transfer in chemical and biological systems	3	72
83-0499	Electron transfer and properties of mixed-valence iron, ruthenium, and related binuclear transition metal complexes studied by Mossbauer and electrochemical methods	10	110
83-6736	Kinetics and mechanism of electron transfer in hexaaquochromium (III) and other transition metal complexes with carboxylate ligands	3	20

two papers are by R.E. Hamm,[53] University of Utah, Salt Lake City, and M. Krumpolc,[54] University of Illinois, Chicago, both in the *Journal of the American Chemical Society* (*JACS*). Both papers deal with chromium chemistry.

Quite recently, ISI® has created a *Chemistry Citation Index* (*CCI*) in conjunction with *Index Chemicus Online*™. We'll have more to report on this file shortly. Not surprisingly, Taube's papers help form the core of several *CCI* research fronts. His 1973 paper[55] is among the six core papers of the 1981 research front, "Synthesis, structure and mechanistic studies of ruthenium, nickel and related transition metal and mixed valence macrocyclic complexes." Taube wrote three of the papers among the 32 core documents for the 1983 research front, "Synthesis, characterization and electron-transfer and other reactions of mixed-valence binuclear complexes containing ruthenium, iron, and other transition metals." Two were coauthored with Creutz.[46,48] The other paper is on experimental approaches to electronic coupling in metal-ion redox systems.[56] The 1964 *JACS* paper coauthored with Gould[52] is also identified as a core paper in the *CCI* front, "Mechanism of inner sphere electron transfer of cobalt (III) complexes," along with Taube's 1969 review paper on the mechanisms of oxidation-reduction reactions.[57]

According to an article in *Science* by Taube's colleagues Harry B. Gray, Division of Chemistry and Chemical Engineering, CalTech, and James P. Collman, Stanford University, Taube is "a rare figure among internationally acclaimed scientists. He does little or no horn-tooting. Instead, he spends a great deal of time encouraging others, especially young people, to pursue research."[58] Taube's support of students and rising young colleagues is fitting, however, since his groundbreaking work was based on ideas he developed while preparing a series of lectures on coordination chemistry at the University of Chicago: "I knew little about coordination chemistry, and what I knew bored me silly," he said in an interview with C. Norman of *Science*.[59] "I thought I should learn something about it and in preparing my course, I became interested.... My early work in Chicago was really based on what I learned in that course."

In reviewing the 1983 Nobel Prizes in physics and chemistry, we have emphasized not only the pioneering significance of the scientific work involved, but we have demonstrated the three well-established characteristics of most Nobel class work: high productivity, high and long-lasting impact, and work that is not only core to the research fronts that the prize winners helped establish, but work that has led to the proliferation of new and exciting areas of knowledge. I hope readers will understand my delight that all of the winners have been writers of review articles of the highest quality and thus prove once again that the library, personal or otherwise, is the extension of one's laboratory.

* * * * *

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