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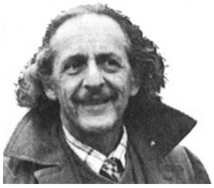


The 1982 Nobel Prize in Physics

Number 50 December 12, 1983

The Nobel prize is a universal symbol of recognized excellence in science and literature. And although many other prestigious prizes are awarded in the sciences and the humanities each year,[1] the Nobel awards are unique because they are so well known to the general public. For several years, we have commented on each new crop of Nobel prizewinners.[2-4] These essays included an analysis of each recipient's most significant work. We performed these analyses to determine whether any of our earlier citation studies had anticipated or somehow confirmed the decisions of the Nobel committee. If not, we wanted to understand why.

Trying to follow our own injunctions to perform individual evaluations in great depth,[5] we have incorporated ISI®'s research front data into our annual study of the Nobel prizes. To report on this requires more space. So this year we will cover the awards in several separate essays. The work of Kenneth G. Wilson, the 1982 laureate in physics, is discussed here. Future essays will cover the prizes in chemistry, physiology or medicine, economics, and literature. Incidentally, the 1983 Nobel prize in physics was shared equally by Subrahmanyan Chandrasekhar, University of Chicago, Illinois, and William A. Fowler, California Institute of Technology, Pasadena, for their work on what happens as stars age, consume their fuel, form new elements, and finally collapse.[6] Both men have appeared in a number of our citation studies, and their work will be the subject of a future essay.

Our Nobel studies, as well as certain earlier papers,[7] may have led to the widespread idea that one can *predict* Nobel prizewinners. This kind of game appeals more to the popular science press[8] than it does to serious scholars. The truth is that such "predictions" are, in an important sense, impossible, unless one is privy to confidential information. But long before the first nominations are in, one can forecast the *fields* of research that are likely to be recognized one day. On that subject we are entitled to speak with some authority.

Indeed, if you name a particular field, citation analysis can help identify those individuals *of Nobel class* who are members of a much larger "invisible college" or specialty. The term "of Nobel class" was coined during the course of a conversation I had some years ago with Robert K. Merton and Harriet Zuckerman,[2] Columbia University, New York, to characterize those individuals whom Zuckerman has described as "peers of prizewinners in every sense except that of having [won] the award."[9] (p. 42)

A significant reason why one can use citation analysis to discuss Nobel-class work with greater confidence than less eminent achievement is the statistical reliability involved. High impact work is less likely to be subject to the vagaries of citation practices or behavior. The number of citations is usually so large that neither self-citation nor typographical errors of one kind or another can seriously affect the *impression* one obtains from the use of *Science Citation Index®* (*SCI®*). The scientist *of Nobel class* is generally a prolific producer of high-quality papers, which is reflected in an even greater and consistently high citation impact over long periods.[7]

But even in a discussion of eminent achievers, as mentioned in my recent essays on faculty evaluations, it is essential to make comparisons *within* a given field.[5] In the case of radio astronomy, for example, we partitioned *SCI* so that we could identify and compare the key people in that discipline. In the same way, knowing who has received the Nobel prize and the field it recognizes, we can use *SCI* to provide support for a decision made by an extensive peer-reviewing system. For this we use ISI's co-citation clustering techniques. These methods allow us to identify the emerging research fronts of science.[10] The microstructure of the maps we create consists of the individuals and the institutions actually doing the research. We have been creating maps of science at ISI since the inception of *SCI*, in part due to the urging of Derek J. de Solla Price. Later, it was the work of Henry G. Small which produced our first co-citation clustering experiments.[11,12] Since 1970, we have identified more than 20,000 research fronts. And we have created thousands more for such disciplinary files as *ISI/GeoSciTech™*, and for numerous specialized, privately sponsored studies.

The 1982 Nobel prize in physics was awarded to Kenneth G. Wilson, age 46, Cornell University, Ithaca, New York, for his work on the theory of phase transitions in physical systems at their critical point. "Phase," the form or nature of a substance, refers not only to the familiar solid, liquid, and gaseous states of matter, but also to such characteristics as ferromagnetism, ferroelectricity, superfluidity, and superconductivity.[13] A substance is said to have reached its "critical point" when ambient temperatures and pressure or other conditions have combined to force it to undergo a "phase transition," or a profound change in its structure.

According to the Royal Swedish Academy of Sciences, Wilson's Nobel prizewinning work involved the application of his novel "renormalization group theory" to the study of critical phenomena,[14] or the events that occur in a system during a phase transition. Wilson reported the invention of his new mathematical language and techniques in two revolutionary articles published back-to-back in a single issue of *Physical Review B—Condensed Matter* in November 1971. They amounted to a whole new way of looking at and thinking about physical relationships, and turned out to be particularly applicable to the study of critical phenomena.

Wilson's theory was born of his unique background in physics. His doctoral dissertation had been in quantum field theory, and his early work in particle physics. Still, he took an interest in critical phenomena, and was tutored in the problems of that field by Cornell colleagues Michael E. Fisher and Ben Widom, who, together with Leo P. Kadanoff, University of Chicago, had done much to define the mechanics of phase transitions. But Wilson's eclectic training enabled him to bring a unique perspective to bear on problems in critical phenomena. He was among the first to recognize, through mathematical analogies, that particle physics and critical phenomena—two apparently unrelated fields—were in fact intimately linked. In his two key 1971 articles, Wilson provided the underlying theory that explained the universal character of diverse physical systems. "The house was already there, but he provided the foundation," said Fisher, commenting on Wilson's work.[15]

Wilson's new techniques allow physicists to successively replace variables representing the physical relationship between different structural levels of matter at the critical point with larger and larger blocks of average values. Thus, they afford an understanding of systems of matter and energy from the simplest interactions of their microscopic components up to the most complex macroscopic effects.[16] Wilson's renormalization methods may therefore find application in numerous engineering problems, such as the effects of frost heaving, oil flow in underground reservoirs, crack propagation in building materials, and turbulence in fluids.[14] And they have already "sparked an era of highly fruitful cross-fertilization between condensed matter, elementary particle, and even cosmological theorists," according to 1977 physics Nobel laureate Philip W. Anderson, Princeton University and Bell Laboratories, New Jersey.[13]

Wilson's most-cited papers are listed in Table 1. Both parts of the article reporting the revolutionary work on renormalization that won him the Nobel prize are among the papers in this table. His most-cited paper, "The renormalization group and the epsilon expansion," was written in collaboration with J. Kogut, Institute for Advanced Study, Princeton. Besides being an exposition of his theory, it reviews the applications of his renormalization techniques to problems in critical phenomena and quantum field theory.

These applications were made possible, however, only after Wilson and Fisher, in their paper, "Critical exponents in 3.99 dimensions," obtained values for certain crucial parameters called "critical exponents," which are as important in renormalization equations as the constant pi is in geometry. Wilson's paper, "Feynman-graph expansion for critical exponents," shows how those parameters could be calculated systematically to a higher level of accuracy. It was these two papers on critical exponents which "unlocked access"[15] to Wilson's 1971 *Physical Review* articles. Put simply, the revolutionary ideas the two earlier articles contained were not understood or appreciated until the two later papers on critical exponents were published.

Incidentally, speaking of Feynman graphs, it is worth noting that Richard Feynman, California Institute of Technology, who won the Nobel prize in physics in 1965, has been quite vocal on

Table 1: Wilson's most-cited papers for the period 1961-1982. Data are from *SCI*®. The papers are arranged in descending order, according to number of citations. A = number of citations received. B = bibliographic data.

A	B
886	**Wilson K G & Kogut J.** The renormalization group and the ε expansion. *Phys. Rep.—Rev. Sect. Phys. Lett.* 12:75-199, 1974.
774	**Wilson K G.** Confinement of quarks. *Phys. Rev. D—Part. Fields* 10:2445-59, 1974.
766	**Wilson K G.** Non-Lagrangian models of current algebra. *Phys. Rev.* 179:1499-512, 1969.
434	**Wilson K G.** Renormalization group and critical phenomena. I. Renormalization group and the Kadanoff scaling picture. II. Phase-space cell analysis of critical behavior. *Phys. Rev. B—Condensed Matter* 4:3174-205, 1971.
392	**Wilson K G.** Feynman-graph expansion for critical exponents. *Phys. Rev. Lett.* 28:548-51, 1972.
385	**Wilson K G & Fisher M E.** Critical exponents in 3.99 dimensions. *Phys. Rev. Lett.* 28:240-3, 1972.
296	**Wilson K G.** The renormalization group: critical phenomena and the Kondo problem. *Rev. Mod. Phys.* 47:773-840, 1975.
151	**Wilson K G.** Renormalization group and strong interactions. *Phys. Rev. D—Part. Fields* 3:1818-46, 1971.
108	**Wilson K G.** Operator-product expansions and anomalous dimensions in the Thirring model. *Phys. Rev. D—Part. Fields* 2:1473-93, 1970.
78	**Wilson K G.** Quantum field-theory models in less than 4 dimensions. *Phys. Rev. D—Part. Fields* 7:2911-26, 1973.

the subject of awards. In a television interview on the Public Broadcasting Service program *NOVA*,[17] he voiced his objection to awards of any kind. His unconventional views on this subject are clearly not shared by most other awardees! I'm sure that Feynman is not alone in feeling that all awards should be abolished. Their proliferation *is* sometimes exhausting.[1] But I suspect that people who agree with Feynman would not be good managers. And the "managers" of the worldwide scientific enterprise may have good reason to believe in awards.[18] Scientists, like all other human beings, need periodic recognition of their accomplishments.

Later, Wilson began to apply his renormalization techniques to problems other than those pertaining to critical phenomena. In his paper, "The renormalization group: critical phenomena and the Kondo problem," Wilson reviews the basic renormalization group ideas in the context of critical phenomena, then explains their use in the solution of the Kondo problem, or the description of a single magnetic impurity in a nonmagnetic metal. Wilson's paper, "Renormalization group and strong interactions," published in early 1971, applied the renormalization procedures developed by Murray Gell-Mann and Francis Low to field theories of strong interactions, the force which holds atomic nuclei together. It must be noted that the techniques developed by Gell-Mann and Low were very different from the ones Wilson later developed. They share the same name because it was the Gell-Mann/Low techniques that inspired Wilson to originate his own theory.

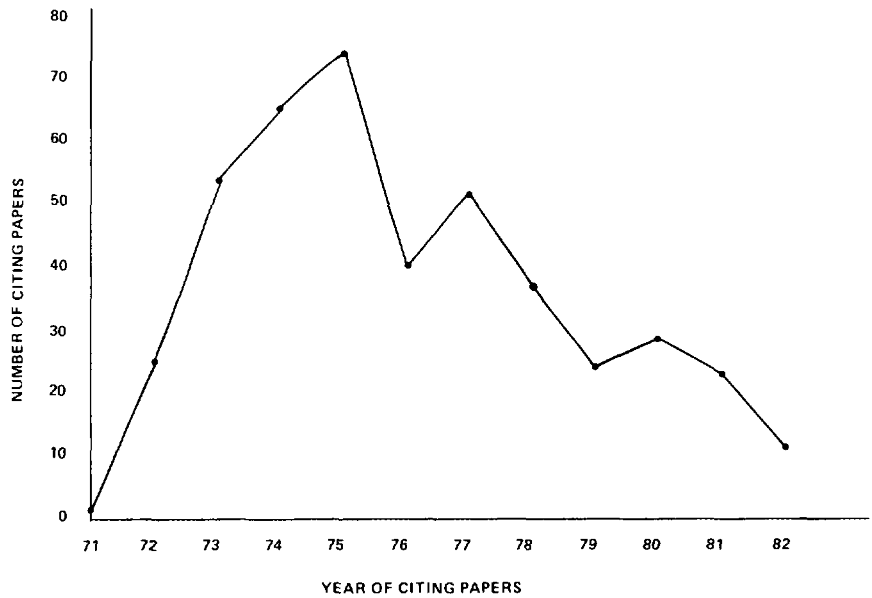
Since Wilson's background is in quantum field theory, it is not surprising to find that some of his early work had little to do with problems of critical phenomena *per se*. One of Wilson's most influential early papers, "Non-Lagrangian models of current algebra," published in 1969, proposes an alternative to certain specific algebraic systems. And his highly cited paper, "Operator-product expansions and anomalous dimensions in the Thirring model," provides a model field theory of the short-distance behavior of strong interactions. In "Confinement of quarks," Wilson proposes a new mechanism for binding or isolating quarks—subatomic particles whose theoretical existence has yet to be justified by actual observations.

Like all the 1982 Nobel prizewinners in science, Wilson is highly cited. From 1961 through 1982, his papers have received over 5,200 citations. Not surprisingly, Wilson was among the 1,000 contemporary authors most cited for work published from 1965 through 1978.[19] Both of his papers on critical exponents, listed in Table 1, appeared in our study of the 25 articles published in 1972 that were most cited during that same year.[20] And as expected, these same articles showed up again when we analyzed 1972 papers cited in the period 1972-1975.[21]

It is especially interesting to explore in depth the citation history and clustering patterns of Wilson's two-part 1971 breakthrough paper. In 1971, both parts were cited in only a few papers. But following the publication of the two papers on critical exponents in 1972, the number of citations to the earlier *Physical Review* articles jumped to 25 in 1972, and 55 in 1973. Figure 1 shows their citation history from the date of their publication through 1982. The steeply rising curve following the publication of the papers on critical exponents illustrates the impact of Wilson's ideas. The graph of their citation frequency may also aid in understanding whether and why a research front can emerge.

Let's recap the procedure for identifying research fronts. Only a very small fraction of the papers cited each year are cited 17 or more times—usually less than one percent. Papers cited at this threshold—or whatever number is estab-

Figure 1: Chronological distribution of articles citing Wilson's two-part 1971 *Physical Review* paper.



lished—are computer-matched to determine which, if any, are cited *together* in current articles. For 99 percent of the possible pairs of highly co-cited papers, most are not co-cited to a significant degree with any other highly cited paper.[10] Those papers whose co-citations *do* form a significant percentage of their total citations, however, are designated "co-citation pairs." The papers that cite one or more co-citation pairs identify a "research front." The "cluster," or group of highly cited papers around which a research front is established, can also be referred to as the front's "core documents." A cluster of highly cited papers is formed by following the path of the strongly co-cited pairs until no new papers are encountered.

One of the more interesting aspects of our clustering techniques, from the standpoint of the historian of science, is their usefulness in creating "cluster strings." A cluster string enables us to track the evolution of a given field backward or forward in time.[22] A string is determined by the continuity a given research front's core literature exhibits from year to year. If any of the core documents of a given research front continue to achieve the required citation and co-citation thresholds for their field in an adjacent year, a cluster string is born. Naturally, as research in a field progresses, some papers that had been cited together often enough to form a co-citation pair in one year do *not* continue to be cited at or above the threshold set for that field in another year. So they would no longer qualify as core documents of the research front, and would drop out of the cluster string. Conversely, new pairs of papers might achieve the citation threshold as the field changes or expands. They would join the core literature of the research front, and would be added to the cluster string. And as research diversifies and branches out, pursuing new lines of thought, the research fronts themselves

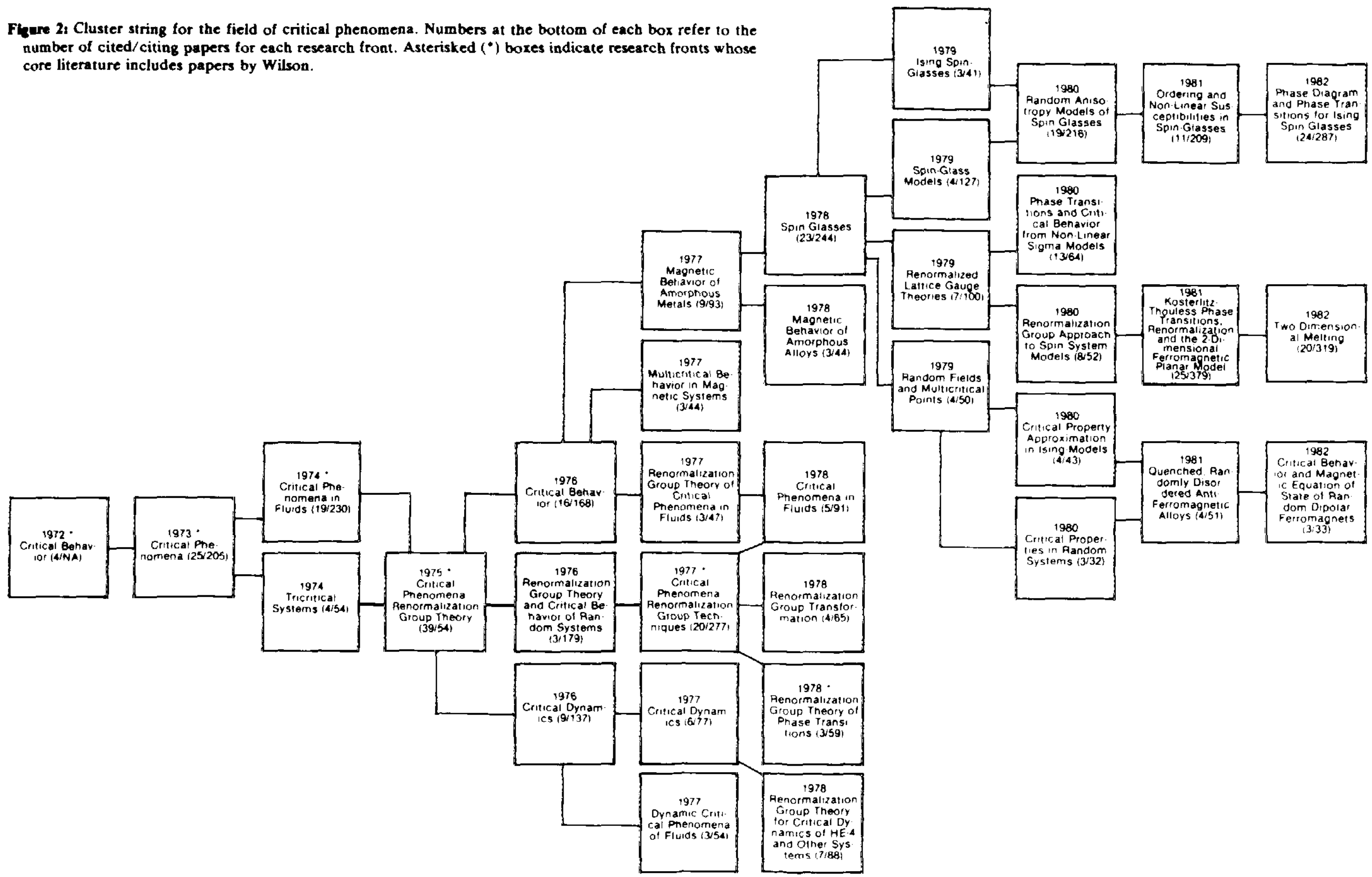
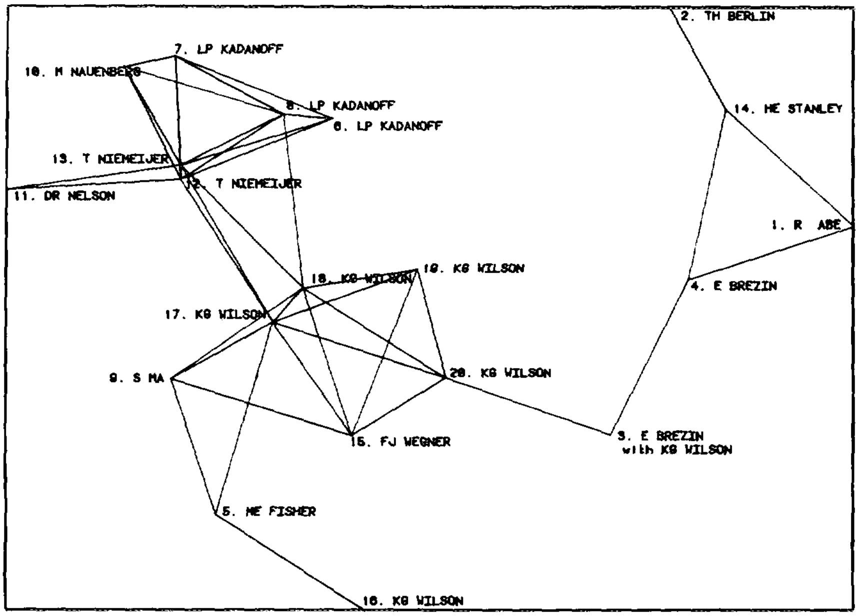


Figure 2: Cluster string for the field of critical phenomena. Numbers at the bottom of each box refer to the number of cited/citing papers for each research front. Asterisked (*) boxes indicate research fronts whose core literature includes papers by Wilson.

Figure 3: Multidimensional scaling map showing links between core papers of research front #77-0010, "Critical phenomena: renormalization group techniques." See accompanying key for bibliographic data and authors' affiliations.



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often acquire new names and divide, almost mitotically, to accommodate new specialties.

The citations that Wilson's two 1971 articles received by 1972 had provided the quantitative clue we needed to realize that an *SCI* research front was emerging. We called it "Critical behavior," based on a statistical sampling of the words used in the titles of the articles in the front. It should be noted, however, that the field was not *founded* by the papers in this front. The key papers establishing the contemporary study of critical phenomena had been published by Fisher and Kadanoff in the mid-1960s—long before we started clustering *SCI*.

The 1972 front entitled "Critical behavior" was followed in subsequent years by other research fronts, in which the articles reporting Wilson's prizewinning work, as well as other important publications, helped us to identify and track the developments of that field. From this information, we were able to construct a microhistory of the field. This is shown in Figure 2, which presents the string of year-to-year *SCI* clusters associated with Wilson's work. Each box represents a research front based on the number of core papers indicated. We have shown the string of clusters associated with Wilson's work up to 1982.

The cluster string in Figure 2 illustrates how rapidly the study of critical phenomena expanded following the publication of Wilson's two seminal articles. In an incredible *tour de force*, the single cluster entitled "Critical behavior," which appeared in 1972, consisted solely of four of Wilson's articles. Among these were the two-part 1971 *Physical Review* article, as well as the two papers on critical exponents. And although the number of core documents contained in the 1973 "Critical phenomena" cluster rose to 25, all four of Wilson's articles easily achieved the citation threshold necessary for inclusion in the later cluster. Indeed, they were joined by yet another paper: "The renormalization group and the epsilon expansion," coauthored with Kogut and not formally published until 1974. In fact, even in unpublished form, this paper was explicitly cited often enough to be included in the 1973, 1974, and 1975 clusters, along with the four original Wilson documents. Indeed, the epsilon expansion paper was the only one by Wilson which attained the co-citation threshold necessary for inclusion as a core paper in the two 1976 fronts entitled "Critical behavior" and "Renormalization group theory and critical behavior of random systems," and the 1977 front, "Magnetic behavior of amorphous metals."

Wilson's 1971 articles appear once more, however, in the core literature of the 1977 research front entitled "Critical phenomena: renormalization group techniques." The 20 core papers for this cluster have been mapped in Figure 3, to show the co-citation strength or distance of their relationship to one another. Wilson's 1971 *Physical Review* articles make their final appearance in the string they helped originate in the 1978 cluster entitled "Renormalization group theory of phase transitions."

Like all good science, Wilson's work was not created in a vacuum. Indeed, Wilson expressed surprise at having alone won the Nobel prize in physics. "One can list 50 to 100 people [in the world who,] at any given moment... would be contenders for [a] Nobel prize," he said. "You never know how it will go."[23]

In fact, Wilson considered himself a likely contender for the prize in physics, as had many knowledgeable physicists. But he fully expected to share it with colleagues Fisher and Kadanoff.[24] The three had shared the prestigious Wolf prize[1] in physics in 1980 for their work on the general theory of the behavior of matter at the critical point.[25] And Fisher—himself one of the 1,000 most-cited authors for 1965-1978[19]—was recently honored with the 1983 National Academy of Sciences Award for Excellence in Scientific Reviewing.[26]

Underscoring the scientists' close working relationship, two of Kadanoff's papers—"Scaling laws for Ising models near T_c"[27] and "Static phenomena near critical points: theory and experiment"[28]—occur together with Wilson's 1971 articles as core documents in the

1982 *SCI*-based *Index to Scientific Reviews*™ (*ISR*™) research front entitled "Thermodynamic anomalies at critical points of fluids, finite-size scaling in Ising systems, and the block-spin method." The former paper by Kadanoff is also a core document in the 1980 *ISI/CompuMath*® research front, "Renormalization group approach to lattice-spin systems," again along with Wilson's 1971 *Physical Review* articles. In fact, both of these papers by Kadanoff played an essential role in the development of the field, and of the ideas on which Wilson later built.

The impact of Fisher's contributions to the study of critical phenomena is emphasized by the fact that his 1967 paper, "The theory of equilibrium critical phenomena,"[29] has been cited explicitly almost 1,100 times—certainly a classic by any definition. Fisher's personal observations concerning this paper were published in *Current Contents*® in 1980.[30] Indeed, this classic paper, together with a 1965 paper, "Correlation functions and the critical region of simple fluids,"[31] and Kadanoff's papers on scaling laws and lattice-spin systems, were the papers mentioned earlier as being instrumental in founding and advancing the contemporary study of critical phenomena.

But although Fisher and Kadanoff were both mentioned in the announcement when the Swedish Academy notified Wilson of his prize, it was Wilson's work alone that was cited as the problem-solving breakthrough that had eluded many others.[23] As noted by Anderson, "The inappropriateness of sharing a prize for such a giant contribution [as Wilson's] must have been on the minds of the Nobel committee."[13] Still, it was the seminal work of Fisher, Kadanoff, and others that set the stage for Wilson's unifying advance. Since the field of critical phenomena and phase transitions has yielded numerous Nobel laureates in the past—among them Johannes van der Waals (1910) and Lev Landau (1962), as well as Anderson—perhaps the Nobel committee's books are not yet closed on this subject.

* * * * *

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