The 1982 Nobel Prize in Physics

The past decade has been a good one in which to be a theoretical physicist, not least because of the contributions of Kenneth Geddes Wilson, which have sparked an era of highly fruitful cross-fertilization between condensed matter, elementary particle, and even cosmological theorists. The ideas of scaling and the renormalization group are as familiar in the grand unified theories, which predict such anomalies as proton decay, and in calculations of the hadron spectrum in strong interaction theory, as in the theory of phase transitions, where they had their first major successes. There are by now numerous new applications in condensed matter theory, such as the theory of localization and of mixed-valent metals, and even in classical dynamics. The Nobel Prize in Physics was awarded to Wilson specifically for the phase transition work, but seldom in recent years has the award been more justified in terms of total influence on the world of theoretical and experimental physics and chemistry.

The Problem of Critical Points

The problem that was solved by the award-winning work has been implicit since Gibbs first considered phase equilibria and was formulated explicitly by Ehrenfest, in response to the discovery (in the 1920's) of the λ-point of liquid helium, as the existence of "higher-order phase transitions." There is a bewildering variety of phases or states of matter—not just gas, liquid, and solid, but also ferromagnetic, superfluid, antiferromagnetic, superconducting, ferroelectric, nematic, smectic, and so on. With changes in temperature, pressure, composition, and other control variables such as magnetic fields any given substance can undergo several phase transitions from one to another state; for example, helium will first liquefy at 4.2 K and then become superfluid at 2.1 K. Ehrenfest classified transitions into first-order ones, such as solidification, which are relatively simple and involve merely the coexistence of two phases (like liquid and solid ice at 0°C) each separately in equilibrium, and higher-order or continuous ones, such as the ferromagnetic Curie point or the λ-point of helium, which are without latent heat or other signs of discontinuity of properties and in which the phases slide imperceptibly into each other but do not coexist.

Landau in the 1940's (and independently Tisza) developed a phenomenology of such transitions, emphasizing that they invariably involved the appearance of a new physical parameter or "order parameter" such as the magnetization or superfluid density. This brilliant insight was tremendously fruitful, but the accompanying quantitative theory was almost immediately demonstrated to be wrong by the famous explicit solution, by Lars Onsager in 1944 (verifying work on similar lines by Kramers and Wannier in the 1930's), of the two-dimensional Ising model for ferromagnetism and order-disorder transformations (or, via Yang's "lattice gas" ideas, the gas-liquid critical point). This solution exhibited strange mathematical singularities (logs and ⅛ powers) at the phase transition point that were totally unexpected from Landau's theory. Landau, just before his death, nominated this as the most important as yet unsolved problem in theoretical physics, and many of us agreed with him. In particular, since Landau's theory contained virtually no assumptions but conventional Gibbs fluctuation theory plus the idea of order parameters, the solution had to involve something fundamental.

Kenneth G. Wilson

Experimental observations of singular behavior at critical points (such as deviations of critical fluctuations or "critical opalescence" from the naïve Ornstein-Zernicke form predicted in the 1930's) multiplied as the years went on, and computational estimates, by such workers as Domb of King's College and his student Michael Fisher, focused on the idea of exponents. For instance, it had been observed that the magnetization of ferromagnets and antiferromagnets appeared to vanish roughly as $(T_c - T)^{1/3}$ near the Curie point, and that the λ-point had a roughly logarithmic specific heat [$(T - T_c)^0$ nominally; it is now known to be $(T - T_c)^{-0.02}$].

This activity culminated in 1965 with two very important papers by Ben Widom of Cornell and Leo Kadanoff, who was then at Brown. Widom postulated, on somewhat phenomenological grounds based on a concept of scaling, a general mathematical form for the singular part of the free energy near critical points (which was exactly the form later to be derived by Wilson). This led to a certain new identity between the three independent critical exponents for specific heat, order parameter, and critical fluctuation scale length. (This identity had been conjectured by Rushbrooke.) Kadanoff independently (with a reference to Widom added in proof) derived this identity on the basis of a physical picture in which, for the first time, the concept of a "cell theory" or "block variables" was introduced; that is, at each value of $\epsilon = (T - T_c)/T_c$ there is a dominant scale on which the fluctuations are important, so that shorter-range fluctuations may be averaged out with impunity and one may deal with block variables or cell variables averaged over the relevant scale. The crucial identity seemed to be empirically correct, and hence the conceptual structure of some kind of scaling was clearly a part of the final solution that remained to be found.

Wilson's Solution

Wilson came to the problem from a background in quantum field theory, which was in no sense as irrelevant as it seems. He did very important early work on the asymptotic behavior of quantum field theory evinced in deep inelastic

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scattering studies, which was very closely related to his later applications of his techniques to particle theory. Having become interested in the phase transition problem, partly under the stimulus of his colleagues Michael Fisher and Ben Widom, he presented in two classic papers published by *Physical Review B* in 1971 what is now accepted as the full solution in principle of the behavior at critical points and other continuous phase transitions.

The principle of the solution is the successive elimination of microscopic, short-wavelength degrees of freedom to replace them by averages over larger and larger blocks. At each stage, the Hamiltonian H (the effective energy as a function of the remaining variables) is artificially rescaled to refer to exactly the same size of system, so that we can think of the process as a series of transformations in the "Hamiltonian space" of the system: $H(S_i,T, \ldots) \rightarrow H'(S_i,T, \ldots)$.† At this point Wilson borrowed from mathematicians the key ideas of the theory of mapping of a space onto itself, namely, the ideas of stable and unstable fixed points, attractors, and so on, which have come to have increasing relevance to other problems in physics as well. The central concept is that the transformation will always lead eventually to one or another stable fixed point $H^*(S_i,T)$, and that these stable fixed points are a "universal" representation of the different stable phases of matter. Exactly at a phase transition, however, the scaling will approach an unstable fixed point, or saddle point between two different stable fixed points of the mapping, and the nature of the behavior near these unstable fixed points determines all the exponents of the phase transitions. As the system approaches such a "critical point" most of the parameters of H will tend to vanish (the "irrelevant variables"), while a certain few (recalling the nature of H^* as an unstable fixed point) will grow without limit and hence become increasingly relevant.

These papers immediately clarified the overall structure of the problem and suggested a number of key concepts. The very important concept of universality and of universality class, for instance, exploits the idea that, given the dimensionality of the system and the symmetry of the order parameter, only a small number of fixed points H^* are available, each representing a "universality class" of phase transitions all of which may be mapped onto each other; for example, all gas-liquid critical points have exactly the same exponents, an intuitive result that now received formal explanation. The universality class depends only on dimensionality and the symmetry of the order parameter.

No matter how elegant the formal structure of such a theory, it required a systematic, quantitative expression, if only to carry conviction to the world of physics as a whole. This was provided the next year by Michael Fisher and Wilson, in the form of a perturbation series technique involving the parameter $\epsilon = 4 - d$, where d is the dimensionality. This concept of dimensionality as a continuous variable not only has been the basis of much quantitative work but also has turned out to lead to a number of deep insights. Fisher, especially, has gone on to systematize the entire subject of phase transitions on the basis of the Wilson-Fisher work.

†This transformation has many properties in common with the older renormalization group idea in field theory which Bogoliubov, Goldberger, and Gell-Mann used to solve the infrared problem of quantum electrodynamics; but Wilson's more complex use of the idea and of the mathematics of mapping amounts to a wholly new method, which, however, goes by the same name (and hence is occasionally mistakenly thought not to be original).

Further Work by Wilson

Wilson himself moved on almost immediately from direct concern with the critical point problem. Using a brilliant combination of renormalization group ideas (formerly applied to this problem by this author and by Zawadowski) with numerical techniques of great sophistication, he developed an accurate numerical treatment of the Kondo model of a magnetic impurity to illustrate the method's value in purely quantum field theoretical problems. He then went on to tackle with the same kind of techniques the very serious and difficult question of non-Abelian color gauge theories. He developed methods of working with gauge theories on a lattice and has made important contributions to the problem of quark confinement. The methods pioneered by him have, when exploited by other groups, led to highly promising results for the hadron spectrum of the strongly interacting particles.

Wilson's most recent concern has been to improve the level of scientific computing to the point where this most basic of many-body problems can be treated really accurately; an improvement that he has found involves political and financial problems as well as scientific ones. His hope is to develop a synergy between the scientific user community and the computer industry on the basis of mutual benefit to each side: stimulus and software development and debugging by the scientists, advanced computer designs and financing from the industry. Perhaps the present prize will aid in this effort.

Background

Wilson was born in 1936, the son of E. Bright Wilson, Jr., an eminent and much-loved Harvard chemical physicist who received a number of honors, including the National Medal of Science, and who was one of the pioneers of microwave spectroscopy. His grandfather was Bright Wilson, a well-known lawyer, dollar-a-year man, and Speaker of the Tennessee House. Ken graduated from Harvard in 1956, took his Ph.D. under Murray Gell-Mann at Caltech in 1961, and then became a Junior Fellow at Harvard. Since 1962 he has been on the faculty at Cornell. He has been awarded a number of prizes, including the Dannie Heinemann award of the American Physical Society in mathematical physics in 1973, the Boltzmann Medal, and the Wolf Prize (with Fisher and Kadanoff) in 1980. He is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences.

There can be no question that Wilson's achievements are more than suitable for the sole award of a Nobel Prize. The inappropriateness of sharing a prize for such a giant contribution must have been on the minds of the Nobel Committee. Nonetheless, the contributions to this work of Fisher, especially, and also of Kadanoff and Widom, seem to this author to be of the highest order and to be only barely separable from Wilson's work. Landau's original insight that the solution of this apparently minor problem must be so profound as to deeply affect the whole of physics and much of chemistry—and we do not know what else—turns out to have been almost too modest. Each in his own way, Kadanoff, Fisher, and Widom have gone on to exploit this great breakthrough in many important ways, and one can hope that the Nobel Committee's books are not yet closed on this subject. In particular, it is unfortunate, because it may be seen as somewhat divisive, that the award has gone only to the high-energy theorist in the group.—P. W. ANDERSON

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