uniqueness theorems for positivistic systems, but also for normative formulations of how a system should optimally function.

I shall briefly refer to Arrow's work in the area of risk and decision theory, as summarized in his collected papers on the subject. In 1952, he stated for the first time the necessity for optimal allocation of risk-bearing of so-called Arrow-Debreu contingent-securities (which pay different returns depending on which one of all possible contingent states of the world materialize).

I conclude with an indication of what is involved in his celebrated Impossibility Theorem, which is to mathematical politics something like what Gödel's 1931 impossibility theorem is to mathematical logic.

Imagine 3 (or more) states: for example, Taft is elected President in 1912, Wilson is elected, Roosevelt is elected. Imagine 3 (or more) individuals, each of whom has a preference ordering of these states. Thus, $(WRT)_1$ means man 1 prefers Wilson to Roosevelt or Taft, and Roosevelt to Taft.

Arrow asks: Given *any* 3 of the $(3!)^3$ choices for $(\ )_1$, $(\ )_2$, $(\ )_3$, how can we define a social preference ordering, call it $(\ )_0$, that obeys a few appealing axioms? (Thus, each man's vote is sometime to count. If Roosevelt dies or lives, *that* should not affect choice between Taft and Wilson. And so forth.)

He then proves by elegant reasoning that it would involve a self-contradiction for there to be a solution satisfying all of these appealing axioms.

Aristotle must be turning over in his grave. The theory of democracy can never be the same (actually, it never was!) since Arrow.

The Scientists' Way

Scholars make their primary contribution through their writings. We judge them as men by their influence on students and co-workers. Both Hicks and Arrow have been blessed in this regard, and have shed blessing.

For sociologists of science, like R. K. Merton, Hicks and Arrow each demonstrate that one need not be at the outstanding university of the moment to make one's scientific mark. Hicks, at LSE and Manchester, helped elevate those places to distinction in economics. Stanford gave Arrow his chance before he was famous. He rewarded it by creating the Stanford school of economic theorists. It says something for academic life that both men were recognized as being deserving of the most prestigious academic posts, and were able to exercise choice among numerous opportunities.

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Notes

1. Sir Roy Allen is said to have told the story of how, when Hicks asked him about determinants—no doubt matrices were still too esoteric—he lent Hicks Netto's little book on the subject, and in three weeks Hicks had worked out the essence of *Value and Capital*, his magnum opus. Even if the anecdote is not literally exact, it is well told.
2. A Hicks bibliography, complete through 1968, appears in J. N. Wolfe, Ed., *Papers in Honor of Sir John Hicks, Value, Capital and Growth* (Edinburgh University Press, Edinburgh, 1968), pp. 531–537. Important items are *Theory of Wages* (1932, 1963), *Value and Capital* (1939, 1946), *The Social Framework: An Introduction to Economics* (1942, 1952, 1960), *A Contribution to the Theory of the Trade Cycle* (1950), *A Revision of Demand Theory* (1956), *Capital and Growth* (1965), *A Theory of Economic History* (1969), and various collections of articles, such as *Essays in World Economics* (1959), and *Critical Essays in Monetary Theory* (1967).
3. A selected bibliography for Arrow would include *Social Choice and Individual Values* (1951, 1963), *Essays in the Theory of Risk Bearing* (1971), *Studies in Linear and Non-Linear Programming* (1958, with co-authors L. Hurwicz and H. Uzawa), *Studies in Mathematical Theory of Inventory and Production* (1958, with co-authors S. Karlin and H. Scarf), *Public Investment, The Rate of Return, and Optimal Fiscal Policy* (1970, with co-author M. Kurz), and *General Competitive Analysis* (1971, with co-author F. H. Hahn).

The 1972 Nobel Prize for Physics

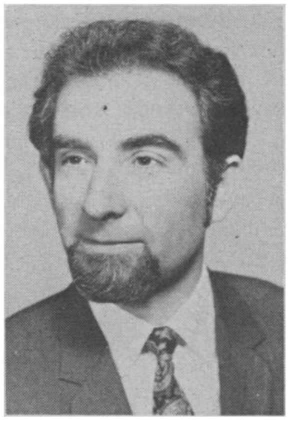
The 1972 Nobel Prize for Physics has been awarded to John Bardeen of the University of Illinois, Leon N. Cooper of Brown University, and John Robert Schrieffer of the University of Pennsylvania for their development of a microscopic theory of superconductivity. Popularly referred to as the BCS theory since it was first put forward in 1957, it has had remarkable success in explaining a wide variety of experimental results, has stimulated new theoretical and experimental studies of superconductivity on an unprecedented scale, and has had an important impact on other fields. The award to Bardeen, who shared the 1956 prize for his role in the invention of the transistor, represents the first time in the history of the Nobel prizes that the same person has received the prize more than once in the same field.

Although the award is frequently shared, the recipients have often worked independently. Such was not the case for Bardeen, Cooper, and Schrieffer, who have frequently emphasized the closeness of their collaborative effort in the Physics Department of the University of Illinois during the years 1955 to 1957.

John Bardeen, the senior member of the group, was 48 at the time of the discovery, and had been awarded the Nobel prize only a few months earlier. Long recognized as one of the world's outstanding solid state theorists, he had come to the University of Illinois from Bell Laboratories in 1951 as a professor of physics and electrical engineering, partly in order to devote more of his time to research on superconductivity. Leon Cooper, 21 years Bardeen's junior, came to Illinois in the fall of 1955 to work as a postdoctoral research associate with Bardeen; his earlier training and experience (as a graduate student at Columbia under Robert Serber and a postdoctoral fellow at the Institute for Advanced Study in Princeton) had been in field theory and nuclear physics. Robert Schrieffer, the junior member of the group, was a third-year graduate student in physics at the University of Illinois and 25 years old in 1957; after his undergraduate degree at the Massachusetts Institute of Technology, he had decided on Illinois for his graduate work in order to have the opportunity to work with Bardeen.

It was this team, a professor, a postdoctoral research associate, and a graduate student, who solved the nearly 50-year-old riddle of the origin of superconductivity. Discovered by Kammerlingh-Onnes in 1911, superconductivity (the ability of the electrons in some metals to exhibit perfect diamagnetism and, once set in motion, to maintain that current-carrying state almost indefinitely) had been the subject of intensive study by many of the theoretical giants of this century, including Bohr, Bloch, Feynman, Heisenberg, Landau, and F. London. This list of outstanding men attests to the importance of the problem. By the same token, its solu-

John Bardeen



Leon N. Cooper

John R. Schrieffer

tion ranks as one of the major achievements in physics of the century.

Developing a successful theory of superconductivity has proved to be such a difficult problem for physicists because the energy associated with the transition is extremely small in comparison with typical energies in the normal state. A completely rigorous derivation of the energy to the required accuracy would involve the solution of many problems of normal metals that are still unsolved. It took a brilliant intuitive leap to produce the Bardeen, Cooper, Schrieffer theory—a theory which is radically different from what one might get from a perturbation theory. The great insight of Bardeen, Cooper, and Schrieffer was to recognize that in a superconductor the correlations between electrons of opposite spin and momentum in the immediate vicinity of the Fermi surface are of decisive importance in determining the behavior of the system. Their basic achievement was to show that when these correlations are properly taken into account in the framework of a many-body theory, they give rise to an energy gap in the elementary excitation spectrum (which is like that of a single particle) and to significant coherence effects in the response of a superconductor to external fields.

The seeds for the development of the BCS theory were planted in 1950, when:

1) Experiments undertaken independently by a group led by B. Serin at Rutgers and by E. Maxwell at the National Bureau of Standards showed that the transition temperature of a superconductor varies inversely with the square root of the isotopic mass.

2) H. Fröhlich (without knowledge of the isotope effect) and J. Bardeen independently attempted to develop theories of superconductivity based on the self-energy of the electrons in the phonon field (the phonon field is the name given to lattice vibrations when treated quantum mechanically).

The Bardeen-Frölich theory turned out to be incorrect. However, the challenge to the theorist was clearly posed: to sort out the relative importance of the electron-electron and electron-phonon interactions in metals, in order to pinpoint what aspects of the electron-phonon interaction were relevant to superconductivity.

The electronic properties of normal metals are well described by assuming that each electron moves essentially independently of its fellows, being only weakly perturbed by interaction with the averaged field produced by the other electrons and by the ions. As a consequence of the Pauli exclusion principle, at absolute zero the electrons fill the allowed spin and momentum states in such a way that all the states inside the Fermi surface (most simply, a sphere in momentum space) are occupied while those outside are unoccupied. Excited states of the system are obtained by "exciting" a certain number of particles across the Fermi surface, thereby creating an equal number of particles outside the Fermi surface and holes inside it. Because only an infinitesimal energy is required to accomplish such excitation, one get, on applying a magnetic field, the usual Landau diamagnetism, whereas on applying an electric field, one finds a finite value for the resistivity as a result of the scattering of the electrons against the moving ions, whose excitations are the phonons.

The description of electron interaction was a major concern of theoretical physicists in the 1950's; the resolution of this problem may be described in the following way. Consider two electrons, A and B: First, A sees the Coulomb field of B. plus the polarization cloud of other electrons that surround B and act to screen out this field except at very short distances. The result is a screened short-range repulsive interaction between A and B. Second, it sees the dynamic ionic polarization produced by B; this interaction, customarily called the phonon-induced interaction, is attractive. For electrons in the vicinity of the Fermi surface the attractive phonon-induced interaction is roughly of the same size as the repulsive screened Coulomb interaction, and the possible appearance of superconductivity depends on the delicate balance between these opposing terms.

The period 1950 to 1957 was further marked by a number of important experiments on properties of superconductors; the discovery of an energy gap in the electron excitation spectrum by Goodman (in thermal conductivity measurements) and by Brown, Zemansky, and Boorse (in specific heat measurements), and the discovery by Pippard of nonlocal modifications in the equations describing the penetration of an electromagnetic field deserve special mention. It was likewise a time of rapid development in both physical concepts and mathematical techniques of the theory of many interacting particles—the so-called many-body problem. The origins of the major theoretical and experimental advances that led to the BCS theory were described by Bardeen in his 1962 address upon receiving the third Fritz London Award (*1*) and will not be repeated here. An especially clear indication of the "state of the art" immediately prior to the BCS breakthrough may be found in the proceedings of the Symposium on the Many Body Problem held in 1957 at Stevens Institute of Technology, where Bardeen and Cooper described the progress of their collaborative effort with Schrieffer.

The criterion adopted by Bardeen, Cooper, and Schrieffer for the appearance of superconductivity was that the attractive phonon-induced interaction dominate the repulsive screened Coulomb interaction for electrons near the Fermi surface. They showed that in the presence of an attractive interaction, the near degeneracy of the many low-lying excited states of the normal metal is removed by the formation of a condensate in which there is pairing of electrons of opposite spin and momentum. When there is current flow, the paired states all have exactly the same momentum. There is a one-to-one correspondence between the quasi-particle excitations of the superconducting and normal states, with an energy gap for excitations from the paired condensate of the superconductor. The common momentum of the paired states gives rise to "a kind of solidification or condensation of the average momentum distribution," as earlier suggested by the late Fritz London to account for his insight that a superconductor is "a quantum structure on a macroscopic scale." With a knowledge of the ground state and the spectrum of elementary excitations of superconductors, it was possible to derive many of the thermal and transport properties of superconductors without much more difficulty than for normal metals.

We list below synopses of the most important papers on superconductivity written during the years 1955 to 1957 by Bardeen, Cooper, and Schrieffer:

1) Theoretical indications by Bardeen in 1955 that an energy gap in the spectrum of energy states would lead to the Meissner effect in the form suggested by Pippard (*2*).

2) Derivation in 1955 of the effective electron-electron coupling in a metal, taking into account the Coulomb repulsions and the lattice vibrations (*3*).

3) Demonstration in 1956 by Cooper of the possibility of formation of bound electron pairs in a degenerate Fermi gas (*4*).

4) In early 1957 Bardeen, Cooper, and Schrieffer show how to generalize the Cooper pair states to the many-body problem at absolute zero, arriving at a model for a super-conductor at absolute zero with an energy gap for elementary excitations (*5*).

5) Detailed calculations were made by Bardeen, Cooper, and Schrieffer in the spring of 1957 for superconducting properties at temperatures above absolute zero (*6*).

The Bardeen, Cooper, Schrieffer theory accounts for a wide variety of experimental data. There are three parameters in the theory. While it has subsequently proved possible to determine them from first principles, they are customarily evaluated experimentally. Two (the density of states in energy and the velocity of electrons at the Fermi surface) are evaluated from the normal metal. The third, which is related to the strength of the electron-phonon coupling, is evaluated from the measured critical temperature.

The detailed agreement of experiments with theory is nothing short of amazing. The basic idea of electron pairing and the resultant energy gap give rise to dramatic effects which are clearly demonstrated. The success of the theory completely changed the climate in which both experiment and theory are done. The change was already evident in 1959, when David Shoenberg remarked at the Cambridge conference on superconductivity: "Let us see to what extent the experiments fit the theoretical facts."

Impact of the BCS Theory

Sometimes an outstandingly successful theory tends to reduce active research in a given field; quite the contrary has occurred with the BCS theory. It has acted as a powerful stimulus for both theoretical and experimental research in superconductivity (*7*). Two applications of the BCS theory deserve special mention. In 1962 Brian Josephson used the theory to predict the properties of two superconductors separated by a thin normal junction which can transmit phase coherence from one to the other; this is commonly referred to as the Josephson effect. In this work, and the subsequent work of Anderson, the relevance of phase as a variable describing superfluid flow was established. The Josephson effect has made possible the most precise measurements of e/h, and has lead to a number of elegant experiments which show that superconductors exhibit quantum effects on a macroscopic scale and exhibit phase interference effects. Second, the young Soviet theoretical physicist, L. P. Gor'kov, used the theory to derive the Ginzburg-Landau phenomenological theory, previously applied by Abrikosov in describing the so-called Type-II superconductors. This theory, which has been further developed by deGennes and his co-workers, has greatly stimulated research on high-field superconductors and accounts for the properties of the present-day superconducting magnets.

The BCS theory has had a great impact on other fields, as diverse as nuclear structure, astrophysics, and the low-temperature behavior of liquid helium. Following the initial work of Bohr, Mottelson, and Pines in the summer of 1957, nuclear theorists have applied the BCS theory to essentially every aspect of the nuclear many-body problem, from using pair correlations to derive the moment of inertia of a rotating nucleus to calculating the Josephson effect in nuclear transfer reactions. In astrophysics, the Soviet theorists Migdal and Ginzburg suggested that, as a consequence of the attractive interaction between pairs of neutrons, neutron matter in the liquid core of a neutron star might be a BCS superfluid. Following the recent identification of pulsars as rotating neutron stars, this idea has received confirmation in the observation of a macroscopic relaxation time (approximately days to years) in the readjustment of the rotational frequency of the youngest pulsars following sudden speedup. Liquid ^{3}He has long been suspected by the theorists of being a superfluid as a consequence of possible attractive interaction between pairs of ^{3}He atoms in high angular momentum states; quite recently David Lee, R. C. Richardson, and associates at Cornell University have carried out experiments that have been interpreted by Anthony Leggett of the University of Sussex as providing evidence for a possible superfluid transition at temperatures below 3 millidegrees Kelvin. On the day the 1972 Nobel Prize was announced Lee was visiting Illinois and a celebration of the BCS award began with a lunch seminar at which the participants, who included John Bardeen, discussed the new results over a sack lunch accompanied by champagne.

The BCS theory has been broadly recognized as one of the most important contributions to theoretical physics since the development of the quantum theory, and the award of a Nobel prize to its inventors should bring pleasure to the entire community of physicists.

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