activation of molecular hydrogen by rhodium complexes. The discovery that $(Ph_3P)_3RhCl$ (now called Wilkinson's catalyst) was a versatile homogeneous catalyst for the hydrogenation of olefins and acetylenes at 25°C and 1 atmosphere pressure was followed by active and successful pursuit of other transition metal–based homogeneous catalyst systems effective in promoting olefin isomerization, hydroformylation, hydrogenation, and hydrosilylation reactions.

However, with all the intense activity in transition metal–organic chemistry during the last two decades, the view that the simple σ-bonded alkyl derivatives of type R_nM (R, alkyl; M, metal) were inherently unstable still persisted. In 1972 Wilkinson proved this belief fallacious by his isolating and characterizing hexamethyltungsten as a stable molecule, and other simple transition metal alkyls with β-branched alkyl substituents were found to be quite stable.

Wilkinson's name is well known throughout the world to chemistry students in inorganic courses as the coauthor (with his former student, F. A. Cotton) of *Advanced Inorganic Chemistry*. This book has influenced greatly the content and teaching of inorganic chemistry courses.

Professor Wilkinson has received many awards honoring his distinguished research accomplishments. He was elected a Fellow of the Royal Society (1965) and a foreign member of the Royal Danish Academy of Sciences (1968) and of the American Academy of Arts and Sciences (1970). The American Chemical Society Award in Inorganic Chemistry (1965), the Lavoisier Medal of the French Chemical Society (1968), and the Chemical Society Award in Transition Metal Chemistry (1971) are among the awards that he has received. He has held many invited lectureships in Europe and in the United States.

All who know Geoffrey Wilkinson have been impressed by his warmth, quick wit, and optimistic enthusiasm, as well as by his creative, intuitive approach to chemistry. It is these qualities, together with the confidence he has instilled into his students, which have made his research group an exciting and enjoyable one to be associated with.

Most chemists will applaud this recognition of creative basic research in synthetic chemistry: research that does not necessarily have direct applications in terms of products useful to society, but which stimulates the efforts of many other chemists in new directions and by doing so inevitably leads to useful and practical results. This has been an award to two "chemist's chemists" whose originality and creativity have over the past 22 years repeatedly resulted in major and important "quantum jumps" in organometallic, inorganic, and organic chemistry.

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The 1973 Nobel Prize for Physics

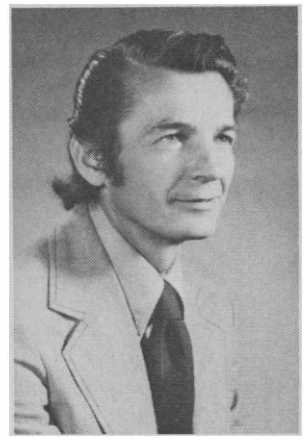
The 1973 Nobel Prize for Physics has been awarded to Brian D. Josephson of the Cavendish Laboratory, University of Cambridge, Ivar Giaever of the General Electric Research and Development Center, and Leo Esaki of IBM's Thomas J. Watson Research Center. Josephson, a theorist, will receive half the prize money, and Giaever and Esaki, both experimentalists, will share the other half. The three discoveries for which they have been honored were made independently in Japan, the United States, and England between 1958 and 1962, but all are linked to a single quantum mechanical phenomenon called tunneling. All three have had a profound influence on the development of physics during the last decade, and all three have important technological consequences in being and in prospect.

The phenomenon of tunneling is a direct consequence of the wave nature of material particles and was recognized very early in the development of quantum or wave mechanics. It is at once familiar and bizarre. In the field of optics it has long been known (under the name "frustrated internal reflection") that under certain circumstances a light beam propagating in a transparent medium like glass will be totally reflected at a glass-air boundary, but if a second piece of glass is brought into close proximity to the first, part of the beam will pass through the gap between the two. With quantum mechanics came the realization that a particle can be expected to display similar behavior. That is, a particle can pass into a region which classically would be forbidden to it and, if the region is not infinitely thick, can pass (tunnel) through it. A macroscopic example would be a baseball which, when thrown at a concrete wall, does not bounce back, but appears on the other side of the wall without making a hole and continues on its way. The probability of this occurring, while not identically zero, is so astronomically small that it is not surprising that the official rules of baseball do not recognize the possibility. The probability of an analogous event in the microscopic world, involving an electron or other fundamental particle and a wall formed by an atomic or nuclear potential barrier of some sort, is still small (1 in 10^9 is not unusual) but nevertheless large enough to lead to important and readily observable effects. Tunneling was first invoked to explain such effects as early as 1928, when J. R. Oppenheimer developed a theory of field ionization of atoms and R. H. Fowler and L. Nordheim produced a theory of electric field induced emission of electrons from metals. In the same year, G. Gamow and R. W. Gurney and E. U. Condon applied similar ideas to the radioactive decay of nuclei with emission of alpha particles.

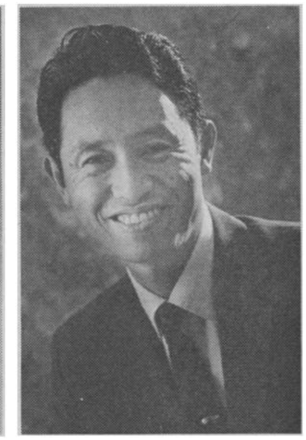
The invention of the transistor in 1948 led to an explosive increase in research on semiconductors and particularly on the properties of *p-n* junctions in semiconductors. If one portion of a semiconductor crystal (for example, silicon) is doped with impurities in such a way that the majority carriers of electric current are negatively charged electrons (*n*-type) and the remainder is doped to create positively charged carriers (holes, *p*-type), the interface between the two regions is a *p-n* junction. The functioning of most transistors and other semiconductor devices depends on one or more such junctions. If a sufficiently large voltage is applied across a *p-n* junction, it will "break down"—that is, the current will rise very rapidly, sometimes catastrophically. Because of the practical importance of junction devices, a great deal of attention was focused on the various mechanisms which might cause this. One possible mechanism had been suggested by C. Zener in 1934 as an explanation for dielectric breakdown in insulating materials. It involves a sort of internal field emission in which the potential barrier is the energy gap between the conduction and valence bands. In a sufficiently large electric field, electrons can tunnel from the full valence band to the empty conduction band, where they can produce a current. This mechanism has never been shown to be important in dielectric breakdown, but it might be expected to appear in *p-n* junctions, where the junction region can be quite thin (a few hundred angstroms) and modest voltages can create very large fields. For nearly a decade a controversy raged over whether Zener tunneling was important or even observable in *p-n* junctions. Esaki's experiments, reported in 1958, established beyond reasonable doubt the existence of tunneling in junctions and opened the way to a whole new class of semiconductor devices.

Esaki completed his undergraduate studies at the University of Tokyo in 1947. He then joined the Kobe Kogyo Corporation while continuing work toward his Ph.D. at the university. In 1956 he moved to the Sony Corporation as head of an advanced device development group. There he attacked the junction breakdown problem in a way which has become an Esaki hallmark: conceptually simple experiments made possible by successful solutions to difficult and sophisticated technological problems. In this case, the experiments consisted simply of measuring the current-voltage characteristics of *p-n* junctions. The junctions, however, were much thinner (less than 150 Å) than previously studied, and achieving this required the development of a technology for producing high-quality alloy junctions in very heavily doped semiconductors. This did the trick. The tunneling was there, and so were several new phenomena, including a negative resistance region in which the current actually decreased as the voltage increased. In his first report, Esaki was able to account for all of his observations in terms of a simple tunneling model. As often happens, the light shed by Esaki's results enabled other workers to see in hindsight that they had observed similar effects without being able to identify their source and significance.

Brian D. Josephson



Ivar Giaever



Leo Esaki

The invention of what is now known as the Esaki diode or tunnel diode stimulated an enormous variety of developments centered on tunneling in semiconductors. These include the application of tunneling to fundamental studies of lattice vibrations (phonons), electron energy band structure, and impurity states. Tunnel diodes are commonly used in a variety of electronic devices, such as amplifiers, detectors, and oscillators in microwave systems and telemetry systems for satellites and space communications. Esaki has continued to be prominent in these subsequent developments. In 1959, he received his Ph.D. from the University of Tokyo and came to the United States, where he now heads a group studying unusual semiconductor structures at the IBM Thomas J. Watson Research Center at Yorktown Heights, New York. He retains his Japanese citizenship, thus providing two countries an opportunity to take pride in his achievements.

While the waves created by Esaki's discovery were still spreading, events which would lead to another dramatic development based on tunneling in solids were taking place in the General Electric Research and Development Center in Schenectady, New York. Ivar Giaever emigrated from Norway to Canada in 1954, worked briefly as an architect's aide, and then joined the Canadian General Electric Company as a mechanical engineer. In 1956, he went to Schenectady for an advanced engineer's training program and discovered people doing solid state physics, which seemed to him more interesting than engineering. He requested and received a transfer to a physics group and also began taking advanced physics courses at Rensselaer Polytechnic Institute to speed his conversion from engineer to physicist. At Schenectady he began work with J. C. Fisher on electron tunneling between two metals separated by a thin insulating barrier. (Interest in tunneling in such systems in connection with electrical contact problems goes back to 1930.) They succeeded in observing and studying tunnel currents between evaporated films of aluminum separated only by a layer of aluminum oxide several tens of angstroms thick which had been formed by oxidation of one of the films.

Aluminum is a superconductor below 1.2 K, and it appears that the idea of cooling the junctions below this temperature just to see what would happen came up several times in discussions within the group. However, there were plausible reasons for doubting that anything interesting would be observed, so the experiment was not undertaken. Then Giaever came to the subject of superconductivity in one of his courses at Rensselaer and learned for the first time of the energy gap in the electronic excitation spectrum of superconductors and the important role it plays in the Bardeen-Cooper-Schrieffer theory of superconductivity (for which the 1972 Nobel prize was awarded). Recognizing that the gap might have an effect on the tunneling current, he calculated typical gaps in units of electron volts and discovered that they lay in the millivolt range. That was all he needed: he had a reason for doing the experiment and he knew where to look. He set out to measure the current-voltage characteristics of aluminum–aluminum oxide–lead junctions. Lead has a superconducting temperature of 7.2 K, so he could work in the more convenient temperature range around 4 K and still have one of the films superconducting. Giaever found that something interesting did indeed happen: when the lead became superconducting, the tunnel current decreased sharply at voltages below that corresponding to the lead gap parameter, but remained relatively unaffected above.

There followed a veritable explosion of new experimental discoveries in the field of superconductivity. Measurements of the energy gap had previously required complex, sophisticated, and expensive experimental techniques. Giaever had opened up the field to almost anyone who owned a voltmeter and an ammeter. Extensive investigations of the gap and its dependence on a host of parameters in a variety of superconductors were quickly made. It was soon discovered by Giaever and others that the current-voltage characteristics contained fine structure which yielded detailed information on the phonon spectrum of the superconductors. In the hands of J. M. Rowell and W. L. McMillan this has become a powerful solid state spectroscopic technique. The list of other superconducting phenomena that have been studied by using tunnel junctions is far too long to describe in detail here, but the enormous advances in understanding superconductivity that have been made during the past decade have depended on tunneling experiments perhaps more than any other single tool. The technique combines simplicity, directness, and power in a way which we have come to associate with Giaever's style of doing science.

At about the same time Josephson, a young undergraduate at the University of Cambridge, was causing a stir by pointing out that an important effect was being overlooked in experiments using the Mössbauer effect to detect the gravitational red shift. By 1962, he was doing graduate work in experimental superconductivity at the Mond Laboratory at Cambridge under the direction of A. B. Pippard. He was also taking a course in solid state theory from P. W. Anderson of Bell Telephone Laboratories, who was then in England on sabbatical leave. In Anderson's words, "This was a disconcerting experience for a lecturer, I can assure you, because everything had to be right or he would come up and explain it to me after class." One day Josephson showed Anderson some calculations he had made of the tunnel current in a junction like Giaever's in which both sides were superconducting. They contained a remarkable result: in addition to the normal electron tunnel current discovered by Giaever, there was a current associated with the tunneling of bound superconducting (Cooper) pairs. This current depended on the relative phase of the superconducting wave functions in the two superconductors. It was possible for a supercurrent to flow in the junction with no voltage drop across it. In the presence of a voltage, the theory predicted a supercurrent oscillating at a frequency simply related to the voltage. A striking dependence of the current on magnetic field was also predicted. This phase-dependent supercurrent seemed so strange that belief in its reality was by no means general among experts in superconductivity. However, Anderson and Rowell quickly found experimental evidence for the zero-voltage supercurrent (the d-c Josephson effect) and S. Shapiro observed the oscillating supercurrent (a-c Josephson effect) soon after. In retrospect, it was clear that many experimentalists working with Giaever junctions had observed the d-c Josephson effect but, lacking any clue to its characteristics and fundamental importance, had ascribed their observations to undesirable and uninteresting "dirt" effects.

Once workers in the field began to comprehend the implications of Josephson's discovery, the effect was electrifying. As someone has put it, the situation was analogous to what might have occurred if the whole beautiful Maxwell theory of electromagnetic waves had been developed before anyone had found a way to do any kind of interference experiment with light. We had an essentially complete theory of the superconducting wave function, but no superconducting interferometer. Josephson had opened the door to superconducting interferometry, to experiments on superconducting devices which are, in effect, enormous atoms to which one can connect macroscopic meters. A flood of experiments arose, some of the most fundamental importance to physics, others with major technological implications. There was a series of beautiful interference experiments by a group including R. Jaklevic, J. Lambe, J. E. Mercereau, and A. H. Silver at the Ford Laboratories which clearly demonstrated the long-range quantum phase coherence of the superconducting wave function. W. H. Parker, B. N. Taylor, and D. N. Langenberg at the University of Pennsylvania used the a-c Josephson effect to determine the fundamental physical constant e/h in experiments which had substantial implications as far afield as quantum electrodynamics and which led to the development of a quantum standard of voltage now used in many national standards laboratories. Many devices based on the Josephson effect have unprecedented sensitivity (10^{-10} oersted, 10^{-15} volt) and have made possible previously impossible experiments in many fields. Computer components that are orders of magnitude superior to the best semiconductor devices are being developed. The list goes on and on—it is fair to say that, in addition to creating a revolution in the field of superconductivity, Josephson initiated a whole new superconducting electronic technology, the implications of which we will be exploring for some time to come.

It should be mentioned that the Josephson effects are not confined to superconducting tunnel diodes. The essential thing is to have two superconductors weakly coupled in some way, and tunneling through an insulating barrier is only one of several ways to accomplish this.

For those interested in the mythology of physics, it might be noted that each of our three new Nobel laureates made his crucial discovery while he was still a graduate student: Esaki at the age of 33, Giaever at 31, and Josephson at 22. This should be an inspiration to today's graduate students. The rest of us will have to take what comfort we can from the fact that none of the three shows any sign of losing the intellectual youth and vigor evident in his trail-blazing early work.

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Notes

1. The initial publications which ultimately led to the 1973 Nobel prize awards are: L. Esaki, *Phys. Rev.* **109**, 603 (195[illegible] I. Giaever, *Phys. Rev. Lett.* **5**, 147 (1960); B. D. Josephson, *Phys. Lett.* **1**, 251 (1962). Each is a model of its kind. Nearly a decade of making a living from the Josephson effects has convinced me that very few of the major developments in the field were not foretold either explicitly or implicitly in the slightly more than two pages of the last reference.
2. Excellent accounts of the circumstances surrounding the Giaever and Josephson discoveries have been given by on-the-spot witnesses. For the former, see R. W. Schmitt, *Phys. Today* (December 1961), p. 38. For the latter, see P. W. Anderson, *ibid.* (November 1970), p. 23.