

Obituaries: Ilya Prigogine

Ilya Prigogine, the Belgian scientist who received the 1977 Nobel Prize in Chemistry for his work on nonequilibrium thermodynamics, died on May 28 in Brussels. He was 86.

He was born in Moscow, on January 25, 1917—a few months before the revolution. Difficulties with the new regime led his family to leave Russia in 1921. They spent a year in Lithuania before moving to Berlin, and then eventually to Belgium in 1929. Ilya became a Belgian citizen in 1949.

He obtained both his undergraduate and graduate degrees at the Université Libre de Bruxelles—Licencié en Sciences Chimiques and also en Sciences Physiques in 1939, Docteur en Sciences Chimiques in 1941, and Agrégé de l'Enseignement Supérieur en Chimie Physique in 1945. He became a professor at ULB in 1947 and an honorary professor in 1987. In 1959 he was named director of the International Solvay Institutes for Physics and Chemistry in Brussels. In 1967 he joined the faculty of the University of Texas at Austin as a professor of physics and chemical engineering; the same year, he founded the Center for Studies in Statistical Mechanics and Thermodynamics (renamed the Ilya Prigogine Center for Studies in Statistical Mechanics and Complex Systems in 1977) at the university. In 1977 he was appointed Regental Professor. From 1967 on, he divided his time between Brussels and Austin.

Ilya Prigogine was the second son of Roman Prigogine, a factory owner and chemical engineer, and Julia Wichman Prigogine, who had been a student at the Conservatory of Music in Moscow. Ilya studied chemistry at ULB, although on entering the university was interested more in history, archaeology, and music, especially piano. According to his mother, he was able to read musical scores before the printed word; he once won a prestigious piano competition. From his adolescence, he read widely. A lasting influence was Henri Bergson, especially the philosopher's remark on time: "The more deeply we study the nature of time, the better we understand that duration means invention, creation of forms, continuous elaboration of the absolutely new."

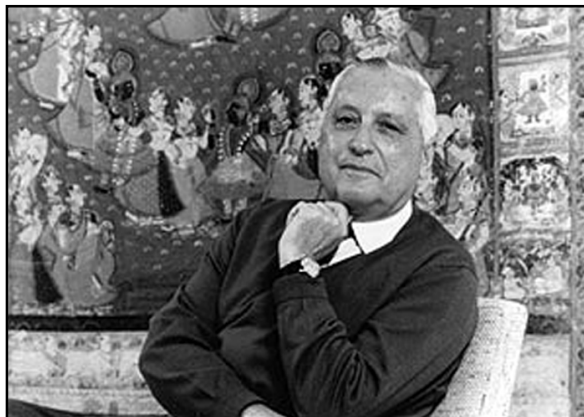
His interest in chemistry developed in a rather unusual way. He and his parents had agreed that he would pursue a legal career, and he decided that the best way to begin would be to understand the mind of the criminal. While looking for books on criminal psychology, he discovered a volume on the chemical composition of the brain. His plans to study law soon gave way to a passionate interest in chemistry.

At the university Prigogine was strongly influenced by two professors: Théophile De Donder and Jean Timmermans. It was De Donder who inaugurated the course in thermodynamics for engineers that would lead to the birth of the Brussels thermodynamics school. To understand the originality of De Donder's approach, Prigogine believed, it was necessary to recall the fundamental work of Clausius, and his formulation of the second law of thermodynamics as an inequality: "Uncompensated heat"—or, in more modern terms, entropy production—is positive. The inequality refers, of course, to phenomena that are *irreversible*, as is any natural process. Until the middle of the 20th century, the latter were poorly understood. They appeared to engineers and physical chemists as "parasitic" phenomena, which could only hinder something—here the productivity of a process, there the regular growth of a crystal—without being of any intrinsic interest themselves. The usual approach, then, was to limit the study of thermodynamics to an understanding of equilibrium laws, for which entropy production is zero.

This could only make of thermodynamics a "thermostatics." In this context, the great merit of De Donder was to extract entropy production out of this "sfumato," relating it in a precise way to the pace of a chemical reaction through the use of a new function that he called "affinity." De Donder went further than his precursors in the field of chemical thermodynamics, giving a new formulation of the second law of thermodynamics based on such concepts as affinity and the degree of evolution of a reaction, considered as a chemical variable.

"It is difficult today to give an account of the hostility that such an approach was to meet," Prigogine wrote in his autobiography [8]. "Towards the end of 1946, at the Brussels IUPAP meeting, after a presentation of the thermodynamics of irreversible processes, a specialist of great repute said to me, in substance: 'I am surprised that you give more attention to irreversible phenomena, which are essentially transitory, than to the final result of their evolution, equilibrium.' Fortunately, some eminent scientists derogated this negative attitude."

The other very influential professor in Prigogine's scientific development, Jean Timmermans, was more an experimentalist, with a special interest in the applications of classical thermodynamics to the solutions of liquids, and in general to complex systems, in accordance with the approach of the great Dutch thermodynamics school of van der Waals. Under the guidance of Timmermans, Prigogine gained experience in the precise application of thermodynamical methods. In the following years, he devoted much time to the theory underlying such problems, which called for the use of the theory of solutions and the theories of corresponding states



Ilya Prigogine, 1917–2003

and of isotopic effects in the condensed phase. Research with V. Mathot, A. Bellemans, and N. Trappeniers led to the prediction of new effects, such as the phase separation of the helium isotopes $\text{He}^3 + \text{He}^4$, in perfect agreement with the results of later experiments [11].

Of all the perspectives opened by thermodynamics, the one that was to hold Prigogine's interest was the study of the irreversible phenomena that make so manifest the "arrow of time." From the very start, he attributed a constructive role to these processes; the standard approach, by contrast, saw in them only degradation and loss of useful work. Prigogine, in fact, viewed living beings as striking examples of highly organized systems in which irreversible phenomena play an essential role.

In science, the arrow of time figures strongly in the second law of thermodynamics. The second law states that a system isolated from the rest of the universe will eventually reach a state of equilibrium in which none of its properties, such as temperature, pressure, or composition, will vary with time, and in which no flows of matter or energy will occur in the system or at its boundaries. Conventional thermodynamics allows us to study the properties of such equilibrium systems.

Linear nonequilibrium thermodynamics, which originated in 1931 with the work of Lars Onsager, provides a framework for the study of the flows of matter and energy that bring a system into an equilibrium state. In 1945 Prigogine worked extensively on linear nonequilibrium thermodynamics, developing the formalism and proving the important theorem of minimum entropy production. This theorem gives a clear explanation of the analogy relating the stability of equilibrium thermodynamical states and the stability of biological systems. In collaboration with J.M. Wiame, Prigogine applied this theorem to the discussion of such important problems in theoretical biology as the energetics of embryological evolution [17].

Despite numerous useful applications of this theorem, Prigogine knew from the beginning that minimum entropy production was valid only for the linear region of irreversible phenomena, the one near equilibrium to which the famous reciprocity relations of Onsager are applicable. Prigogine's next challenge was to extend his idea to states far from equilibrium, for which Onsager relations are not valid but which are still within the scope of macroscopic description.

The problems studied by Prigogine followed a consistent pattern: slow maturation, followed by sudden evolution, in such a way that an exchange of ideas with his colleagues became necessary. Indeed, Prigogine and his colleagues struggled with the problem of far-from-equilibrium states for more than twenty years, from 1947 to 1967, until they finally reached the notion of "dissipative structures." He credited, in particular, the enthusiasm and originality of his colleague Paul Glansdorff in the development of his work. Their collaboration was to give birth to a general evolution criterion that is useful far from equilibrium in the nonlinear region, outside the validity domain of the minimum entropy production theorem. The resulting stability criteria led to the discovery of critical states, with branch shifting and the possible appearance of new structures. This quite unexpected manifestation of "disorder-order" processes, far from equilibrium but conforming to the second law of thermodynamics, eventually led to profound changes in the traditional interpretation of the second law. In addition to classical equilibrium structures, scientists now faced dissipative coherent structures, for sufficient far-from-equilibrium conditions. A complete presentation of these ideas can be found in [1].

With the concept of dissipative structures, the researchers had opened a new path, and from this time their progress accelerated strikingly. With R. Lefever and G. Nicolis, Prigogine developed a kinetic model that would prove to be simultaneously quite simple and very instructive. The "Brusselator," as it came to be called, manifests the amazing variety of structures generated through diffusion-reaction processes [5].

With the discovery in 1959 and 1964 of experimental oscillating chemical reactions, such as the Belusov-Zhabotinsky reaction, the attention of scientists was drawn to coherent nonequilibrium structures. Since 1967, researchers have produced a huge number of papers on dissipative structures, in sharp contrast with the total absence of interest that prevailed until then. The importance of Prigogine's ideas was now beyond dispute, and scientists were soon applying them across a broad spectrum of disciplines, including cosmology, chemistry, and biology, as well as ecology and the social sciences. An undergraduate-level discussion of his ideas can be found in [3].

Progress in the theory of irreversible phenomena led him also to reconsider their place in classical and quantum dynamics. From the time of his undergraduate degree, he had been an enthusiastic reader of Boltzmann, whose dynamical vision of physical "becoming," or evolution, was for Prigogine a model of intuition and penetration. Nonetheless, he saw in it some unsatisfying aspects. It was clear that Boltzmann had introduced hypotheses foreign to dynamics, and to talk about a dynamical justification of thermodynamics under such assumptions seemed to Prigogine an excessive conclusion.

In his opinion, the identification of entropy with molecular disorder could be only one part of the truth: If irreversible processes were indeed endowed with the constructive role he never ceased to attribute to them, their description could not be reduced to one of supplementary approximations. Moreover, Prigogine's opinion was that in a good theory, a viscosity coefficient would have as much physical meaning as specific heat, and the mean lifetime of a particle as much as its mass. Accordingly, in the early 1950s, with G. Klein, Prigogine took a fresh look at an example already studied by Schrödinger, related to the description of a linear dynamical system consisting of harmonic oscillators. They were surprised that such a simple model made it possible to conclude that systems in this class approach equilibrium [2].

But a decisive step came in 1954, during Léon van Hove's short but fruitful visit with Prigogine's group. Van Hove showed him a way to deduce a "master equation" for nonlinear anharmonic systems from the first principles of dynamics. A unique aspect of van Hove's approach was to impose the statistical assumption only on the level of initial conditions of the solutions of the Liouville-von Neumann equation. As a result, the role of dynamics in the origin of irreversibility can be analyzed precisely, separately from statistical manipulations of initial conditions. In the traditional approach of kinetic theory, based on the so-called BBGKY hierarchy, by contrast, the statistical manipulations are imposed on the level of a set of equations of motion, and not on the level

of the solutions.

This first study by van Hove was restricted to weakly coupled anharmonic systems. Following this new direction, Prigogine achieved a formulation of nonequilibrium statistical mechanics from a purely dynamical point of view with some of his colleagues, mainly R. Balescu, R. Brout, F. Héning and P. Résibois. The method they used, summarized in [10], leads to a “dynamics of correlations,” as the relation between interaction and correlation constitutes the essential component of the description. These methods have led to numerous applications, including work in plasma physics, in the classical kinetic theory of fluids, and in the kinetic theory of car traffic by Prigogine and R. Herman [14]. The latter, in particular, convinced Prigogine that even human behavior, with all its complexity, would eventually be susceptible to mathematical formulation.

Despite these successes, he was not yet satisfied: The theorem of Boltzmann was as isolated as ever, and the question of the nature of dynamical systems to which thermodynamics applies was still without answer. As is well known, Albert Einstein often asserted that “Time is an illusion.” Indeed, the basic laws of physics, from classical Newtonian dynamics to relativity and quantum physics, do not imply any directionality between past and future. Even today, it is a matter of faith for many physicists that as far as the fundamental description of nature is concerned, there is no arrow of time. On the other hand, we now know that irreversibility leads to a host of novel phenomena, such as vortex formation, chemical oscillations, and laser light, all illustrating the essential constructive role of the arrow of time. Irreversibility is no longer identified with mere appearances that would disappear if we had perfect knowledge. Instead, it leads to coherence, to effects that encompass billions and billions of particles. Without this new coherence resulting from irreversible, nonequilibrium processes, life on earth would be impossible to envision. The claim that the arrow of time is “only phenomenological” is therefore absurd. Prigogine often said that we are the children, and not the progenitors, of the arrow of time, of evolution.

After receiving the Nobel Prize, at the age of 60, he decided to devote himself to the study of irreversibility in statistical mechanics and its relation to the foundation of dynamics. This problem was far wider and more complex than the rather technical work he had considered until that time. It touched on the very nature of dynamical systems, and the limits of Hamiltonian description.

To connect dynamics to irreversibility, he realized the importance of the celebrated theorem of Henri Poincaré on a classification based on integrable and nonintegrable systems. Poincaré had investigated a relation of invariants of motion between noninteracting systems and corresponding perturbed systems through interactions among each degree of freedom. The invariants of motion for the perturbed system have denominators that consist of a linear combination of unperturbed frequencies. Poincaré then proved that for certain classes of Hamiltonian systems, the invariants of motion are destroyed because of vanishing frequency-denominators (hence the name “resonance singularities”). In nonintegrable systems it is impossible to construct a canonical or unitary transformation that generates new invariants of motion by acting on the corresponding unperturbed invariants. In the early stages of his investigation, Prigogine was already aware of the deep relation between this theorem and irreversibility, as explained in his 1962 book on nonequilibrium statistical mechanics [10]. Indeed, broken time-symmetry in the collision term in kinetic equations, such as Boltzmann’s equation in classical mechanics and Pauli’s master equation in quantum mechanics, comes from the contributions at the very points at which the frequency-denominators vanish.

Prigogine worked with many colleagues to develop an extension of transformation theory, first in Brussels (C. George, F. Henin, A. Grecos, F. Mayné, M. de Haan, B. Misra, I. Antoniou, among others), and later in Austin (T. Petrosky, G. Ordonez, H.H. Hasegawa, and D. Driebe). In particular, with Petrosky and Ordonez, Prigogine showed that if a spectrum of frequency is continuous, as is the case for thermodynamic systems with infinite degrees of freedom or for matter–field coupling systems, the resonance singularities can be removed by a suitable analytic continuation of the frequency-denominators into the complex plane; the price, however, is destruction of the canonicity or unitarity of the transformation.

The results are striking. Transformed generators of motion, such as the Liouville–von Neumann operator for distribution functions in classical mechanics, and for density matrices in quantum mechanics, break time-symmetry. Moreover, a product of transformed quantities is no longer a transformation of a product, which is not the case in unitary transformation for integrable systems. In other words, there is an intrinsic fluctuation in the transformed quantities in nonintegrable systems. Probability emerges not from supplementary approximations made because of a lack of knowledge, but rather as a dynamical consequence of resonance singularities in nonintegrable systems. Irreversibility is now formulated in a theory of transformations that expresses in “explicit” terms what the usual formulation of dynamics “hides.” In this perspective, the kinetic equation of Boltzmann corresponds to a formulation of dynamics in a new representation. These results are summarised in [6,7].

Prigogine was also concerned with the broader philosophical issues raised by his work. In the 19th century the discovery of the second law of thermodynamics, with its prediction of a relentless movement of the universe toward a state of maximum entropy, generated a pessimistic attitude about nature and science. Prigogine felt that his discovery of self-organizing systems constituted a more optimistic interpretation of the consequences of thermodynamics. In addition, his work led to a new view of the role of time in the physical sciences.

Seeking to open a dialog with the lay public about the intellectual consequences of his research, he wrote two popular expositions with Isabelle Stengers [15,16], not only explaining his and his colleagues’ scientific discoveries in nontechnical language, but also attempting to place them in a broad historical and philosophical context. His 1980 book [9] is a bit technical but still oriented to a general audience.

Prigogine’s legacy includes more than 1000 papers and 20 monographs. Among his many awards are more than 50 honorary degrees, and numerous medals and prizes, including the Golden Medal of the Swante Arrhenius of the Swedish Academy; the Rumford Gold Medal of the Royal Society of London; the French Descartes Medal and Médaille d’Or; the Russian International Scientific Award; and the Japanese Gold and Silver medals of the Imperial Order of the Rising Sun. He was a commander of the

French Legion of Honor and, in 1989, was awarded hereditary nobility and the personal title of Viscount by Baudouin, King of Belgium.

Prigogine and his first wife, Helene Jofé, a poet, had a son, Yves, who was born in 1945. On February 25, 1961, two days after their first meeting, he decided to marry Marina Prokopowicz, a Polish chemical engineer; their son, Pascal, was born in 1970.

Prigogine's devotion to science was extraordinary. I was astonished at his comments, at age 82, that he would become tired after six hours of continuous work. A remarkable man, a remarkable career, a remarkable life.

References

- [1] P. Glansdorff and I. Prigogine, *Thermodynamic Theory of Structure Stability and Fluctuations*, John Wiley & Sons, New York, 1971.
 - [2] G. Klein and I. Prigogine, *Physica*, 19 (1953), 1053.
 - [3] D. Kondepudi and I. Prigogine, *Modern Thermodynamics, From Heat Engines to Dissipative Structures*, John Wiley & Sons, Chichester, 1998.
 - [4] J. Kovac, "Ilya Prigogine, 1977 Nobel Laureate," *Nobel Laureates in Chemistry 1901–1992*, Laylin K. James, ed., American Chemical Society and Chemical Heritage Foundation, Washington, DC, and Philadelphia.
 - [5] G. Nicolis and I. Prigogine, *Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuations*, Wiley Interscience, New York, 1977.
 - [6] T. Petrosky, G. Ordonez, and I. Prigogine, *Phys. Rev. A*, 2003, to appear.
 - [7] T. Petrosky and I. Prigogine, *The Liouville space extension of quantum mechanics*, in *Advances in Chemical Physics*, eds., I. Prigogine and S. Rice, 99, John Wiley & Sons, 1997.
 - [8] I. Prigogine, *Autobiographie*, Florilège des Sciences en Belgique II, 1980.
 - [9] I. Prigogine, *From Being to Becoming*, W.H. Freeman, San Francisco, 1980.
 - [10] I. Prigogine, *Non-Equilibrium Statistical Mechanics*, Wiley Interscience, New York, 1962.
 - [11] I. Prigogine, A. Bellemans, and V. Mathot, *The Molecular Theory of Solutions*, North-Holland, Amsterdam, 1957.
 - [13] I. Prigogine, Cl. George, F. Henin, and L. Rosenfeld, *Chemica Scripta*, 4 (1973), 5–32.
 - [14] I. Prigogine and R. Herman, *Kinetic Theory of Vehicular Traffic*, Elsevier, New York, 1971.
 - [15] I. Prigogine and I. Stengers, *La Nouvelle Alliance*, Gallimard, Paris, 1979, 1981, 1986, and in English as *Order Out of Chaos*, Bantam, New York, 1984.
 - [16] I. Prigogine and I. Stengers, *The End of Certainty—Time, Chaos, and the New Laws of Nature*, The Free Press, New York, 1997.
 - [17] I. Prigogine and J.M. Wiame, *Experientia*, 2 (1946), 451.
- Tomio Petrosky, *Ilya Prigogine Center for Studies in Statistical Mechanics and Complex Systems, University of Texas at Austin, and International Solvay Institutes for Physics and Chemistry, Brussels, Belgium.*