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Article in *Journal of Biosciences* · December 2003

DOI: 10.1007/BF02708424

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Commentary

Ilya Prigogine (1917–2003)

On 28 May 2003 Ilya Prigogine passed away in Brussels at the age of 86. A major scientific figure of the twentieth century, he pursued his activities for more than six decades and never stopped working on the very same themes that attracted him from the beginning of his career: time, evolution, and irreversibility. His work exerted a profound influence on many fields ranging from Thermodynamics to Statistical Mechanics, and from Physical Chemistry and Physics to Biosciences (the brief choice of selected references given below is restricted to publications pertaining to the latter area).

Ilya Prigogine was born in Moscow in 1917 and came to Brussels at a young age. There he went to school and proceeded to study Physics and Chemistry at the *Université Libre de Bruxelles*, where he began working under the guidance of Théophile De Donder. After 1945, Prigogine developed his work in the Thermodynamics of Irreversible Processes, and later extended it to Nonequilibrium Statistical Mechanics. Thanks to the many books he wrote, and to his enthusiasm and charisma, his group in Brussels rapidly became one of the most active centres in these fields on the world scientific scene.

In the sixties and seventies, Prigogine's interests turned to the physico-chemical bases of nonequilibrium self-organization in chemical, physical and biological systems. Together with his colleague Paul Glansdorff, he clarified the conditions in which dissipative structures can arise beyond a critical point of instability, away from thermodynamic equilibrium (Prigogine 1967, 1969; Glansdorff and Prigogine 1971). The results of these studies stressed the role of fluctuations, which become amplified once a steady state becomes unstable, leading to various patterns of nonequilibrium self-organization



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(Nicolis and Prigogine 1977; Prigogine *et al* 1969). The theoretical developments had a great impact, as they coincided with rapid experimental progress in the study of oscillatory reactions and spatiotemporal dissipative structures in chemical and biological systems. The concomitance of these experimental and theoretical advances triggered the establishment of a whole new field of research. Thus, the Belousov-Zhabotinsky reaction was characterized in the period 1965–1975: this reaction still provides the prototype of temporal and spatiotemporal organization in a chemical system. At the same time glycolytic oscillations were thoroughly studied as an example of a biochemical system oscillating *in vitro*. Besides the contributions of many groups which participated in these studies, it is fitting to recall here the key roles of Arthur Winfree and Benno Hess, who both passed away at the end of 2002. After the years devoted to the study of dissipative structures, Prigogine returned to his quest for the statistical foundations of irreversibility, a topic on which he worked until his last day.

The reason why Prigogine's work was so influential stems from both the originality of his approach, based on Nonequilibrium Thermodynamics, and his radiating personality. Whoever heard him give a talk will never forget the enthusiasm and creativity that emanated from him as soon as he began to speak. After Prigogine received the 1977 Nobel Prize in Chemistry for his work on dissipative structures, there was an incessant flow of journalists who came to Brussels to interview him and his coworkers. After spending hours in the department, one journalist returned home to write a single brief paragraph in which he presented Prigogine as the "Poet of Thermodynamics". To me, this compact definition perfectly encompasses both the scientist and the man, given the broad vision of the world that he had and the poetic sense that he infused in all the topics he addressed.

Life sciences, in particular the origin of life and the progressive increase in biological complexity, attracted Prigogine's interest since the very beginning. One of his early papers was devoted to an application to biological evolution of thermodynamic results obtained in open systems operating in nonequilibrium conditions (Prigogine and Wiame 1946). Another early study, based on a thermodynamic analysis of a chemical analogue of the Lotka-Volterra model, showed that rhythmic phenomena occur only away from equilibrium (Prigogine and Balescu 1956). Reconciling biological order with the laws of Thermodynamics always remained at the forefront of Ilya Prigogine's preoccupations. It is revealing that the article in which he introduced the concept of dissipative structures was entitled "Structure, dissipation and life" (Prigogine 1969).

Studies initiated by Prigogine showed that beyond a critical point of instability of a nonequilibrium steady state, self-organization can take many forms: the system may evolve toward sustained oscillations (temporal organization), a spatially inhomogeneous distribution of chemical species (spatial structure of the type described by Turing), or a spatiotemporal organization in the form of propagating concentration waves, as observed in the Belousov-Zhabotinsky reaction. Moreover, multiple steady states become possible as a result of the nonlinearity of the evolution equations. It becomes increasingly clear that all these types of nonequilibrium self-organization (Nicolis and Prigogine 1977) play major roles in the dynamics of living systems as a result of the nonlinearity introduced by feedback processes, which abound in cellular regulation. Let us only mention the variety of oscillatory phenomena observed in biological systems at the cellular level, from neural and cardiac rhythms to oscillations and waves of cytosolic calcium, and from oscillatory enzyme reactions to pulsatile hormonal signalling and circadian rhythms. Rhythmic phenomena, often accompanied by spatiotemporal organization, and multiple steady-state transitions are being studied by means of a theoretical approach in practically every area of the life sciences. It is a tribute to Prigogine to stress these numerous developments in which the concepts he introduced played such a pioneering role.

In recalling the figure of Ilya Prigogine, his enthusiasm and generosity come first to my mind. Generous he was, with students and coworkers, whom he always encouraged and supported, and also with those unknown to him, who approached him at conferences or for seeking advice. When he received a well-known visitor in his office (for example, his friend the late Aharon Katzir-Katchalsky), he would never fail to gather members of his group, including young Ph.D students, to take part in the discussions. The most characteristic trait of Prigogine, besides his optimism, was his unflinching energy in pursuing the same fundamental questions that occupied him since the very first papers he wrote when he was only 20.

This brief portrait of Ilya Prigogine would be incomplete without mentioning the vast realm of his interests, which went far beyond the scientific domain. He played the piano and was attracted to philo-

sophy. He wrote several books about more philosophical aspects of science. A number of them were with Isabelle Stengers (Prigogine and Stengers 1979), and reached a wide audience. He had also a passion for art, particularly pre-Columbian sculptures and ancient Chinese art. Ilya Prigogine was a modern equivalent of a humanist of the Renaissance period. His aura explains the attraction he exerted on all those who had the privilege of working with him or hearing him lecture. A key for his unique achievements can be found in his attitude towards life: in his last public lecture, given in Brussels in November 2002 on the occasion of a celebration of the 25th anniversary of his Nobel prize, he simply declared: "Astonishment leads to creativity". These words sum up well his relentless, creative questioning of the world.

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