Ilya Prigogine (1917-2003)

Abstract:

During a long and productive career, Belgian physical chemist Ilya Prigogine (1917-2003) pursued a coherent research program in thermodynamics, statistical mechanics, and related scientific areas. In many publications for general audiences, he maintained that his scientific work was relevant to deep questions of wide philosophic importance.

In the course of his study of far-from-equilibrium chemical systems, Prigogine identified “dissipative structures” — coherences of dynamic processes that maintain integrity while exchanging material with their surroundings. These units operate far from thermodynamic equilibrium and generate entropy at high rates. Consideration of this type of structure has clarified the relationship between basic thermodynamics and evolutionary processes. In every spontaneous change, the entropy of the universe increases: as evolution proceeds, stable coherences of dynamic processes (dissipative structures) arise and increase the rate of entropy generation. This research has been a fertile source of models and metaphors that are useful in other areas of the physical and social sciences.

Prigogine aimed to establish that the origin of irreversibility (“the arrow of time”) as local (residing in the details of specific interactions) rather than as global (solely dependent on details of the “big bang”), or as the result of human ignorance. “Resonances” (transient interactions) are ubiquitous in “large Poincaré systems” (LPS) — those that contain large numbers of more or less independent units. (Systems studied by physical chemists generally are LPS.) Those resonances prevent integration of the differential equations that describe system dynamics, so that probability distributions, rather than trajectories, specify the temporal evolution of such systems. Prigogine believed that the most recent stages of his research program had achieved his long-term goal and had established that the arrow of time has its main origin in the details of dynamic interactions.

End of Abstract

Belgian chemist and physicist Ilya Prigogine (1917-2003) made substantial advances in the science of non-equilibrium thermodynamics. The Nobel Prize for Chemistry for 1977 recognized those achievements. He also published books and articles for general audiences, maintaining that his scientific work was relevant to deep questions of wide philosophical and cultural importance.

Prigogine’s family had fled Russia (where his father was a chemical engineer and factory owner) in 1921 and eventually settled in Belgium in 1929. Ilya's brother Alexander (four years older) studied chemistry at the Université Libre de Bruxelles (ULB, the Free University of Brussels). Influenced by the unstable politics of Europe in the 1930s, the younger Prigogine followed his brother into the ULB chemistry curriculum rather than pursuing his interests in history, archaeology, or music (he was an outstanding pianist). Throughout his career, he maintained a lively interest in aspects of culture other than science.

The importance of formal philosophy to his intellectual development is evident from a short autobiography that he prepared in connection with his Nobel Prize.

> Since my adolescence, I have read many philosophical texts. I still remember the spell *L'évolution créatrice* cast on me. More specifically, I felt that some essential message was embedded, still to be made explicit, in Bergson's remark: "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." (Prigogine 1977)

French philosopher Henri Bergson (1859-1941) received the Nobel Prize for Literature for 1929. His influence was strong in French-speaking Belgium when Ilya Prigogine (recently arrived from Germany) was in school there. Bergson held that classical science had excessively "spatialized" time, to the neglect of duration and "lived time." A consuming interest in time — and especially its relationship to the emergence of new types of organization — was a salient characteristic of Prigogine’s work, both in his science and in his publications aimed at general audiences.

German physicist Ludwig Boltzmann (1844-1906), who also held a chair of natural philosophy (Fasol-Boltzman 1990), was another of the young Prigogine's favorite authors. Boltzmann had a high regard for Charles Darwin’s contributions, and made heroic efforts to develop a theoretical framework that would unify evolutionary theory, thermodynamics, and physical mechanics.

> Since the time of my first graduation in science, I have been an enthusiastic reader of Boltzmann, whose dynamical vision of physical becoming was for me a model of intuition and penetration. Nonetheless, I could not but notice some unsatisfying aspects. It was clear to me that Boltzmann introduced hypotheses foreign to dynamics; under such assumptions, to talk about a dynamical justification of thermodynamics seemed to me an excessive conclusion, to say the least. In my opinion, the identification of entropy with molecular disorder could contain only one part of the truth if, as I persisted in thinking, irreversible processes were endowed with the constructive role that I never cease to attribute to them. (Prigogine 1977)

Prigogine’s mentor Théophile De Donder (1873-1957) had earned his Ph.D. in physics while teaching secondary school and then taught theoretical thermodynamics for engineers at ULB. Prigogine’s autobiography continues:

> …since the fundamental work by Clausius, the second principle of thermodynamics has been formulated as an inequality: entropy production is positive. … Given my interest in the concept of time, it was only natural that my attention was focused on the second principle, as I felt from the start that it would introduce a new, unexpected element into the description of the evolution of the physical world. … A huge part of my scientific career would then be devoted to the elucidation of macroscopic as well as microscopic aspects of the second principle, in order to extend its validity to new situations…(Prigogine 1977)

The fundamental laws of both classical mechanics and quantum mechanics have time-reversal symmetry — it is not possible to decide whether a video of a collision of billiard balls (or of an interaction involving a single atom and a photon) is running forwards or backwards. It is not obvious how to understand the irreversibility of events we observe in ordinary life — such as the loss of heat from hot liquid. Boltzmann had recognized that spontaneous changes (such as cooling of coffee) involve transitions from less probable (more highly organized, lower entropy) arrangements to situations that are more probable (less highly organized, higher entropy). On this basis, Boltzmann inferred that the early stages of the universe must have been highly organized indeed (very low entropy).

Some have interpreted the time-reversal symmetry of basic physical laws to suggest that time is not fully “real” — that it depends on the perceptions of human observers. Albert Einstein wrote: “For us believing physicists, the distinction between past, present and future is only an illusion, however persistent.” Prigogine regarded this point of view as both wrong and pernicious — since it implies radical separation between human concerns and fundamental physical reality. Prigogine (as Bergson had done) considered time to be objective, real, and creative — rather than a result of human inadequacy, or of some peculiarity of the early universe. He held the opinion that much current science and philosophy did not take proper account of the reality and significance of time. He claimed that this gave rise significant errors both in science and in philosophy — an excessive focus on equilibrium states and insufficient attention to the importance of combinations of contingent events in determining outcomes.

Calculation of the microscopic state of systems not at equilibrium is not possible without approximations. Usually, one computes average values of thermodynamic quantities for many small but still macroscopic volumes, and then combines those results to yield corresponding values for the whole system. Such "coarse graining" does produce irreversibility, but that result may be an artifact of the approximation used. Prigogine did not agree that irreversibility of the processes that chemists and engineers encounter derives only (or mainly) from human ignorance. He held that the ubiquitous irreversibility of nature has its principal source in the details of the dynamics of specific interactions involved in natural processes, rather than in the choice of the variables used in their description, or in the initial singularity. Throughout his long and active scientific career, Prigogine sought to establish conclusively that the main origin of irreversibility was local rather than global.

Boltzmann’s inference that the initial state of the universe must have been a low-entropy state is widely endorsed (Albert 2000) but some (Winsberg 2004) claim that such conclusions are based on philosophic presuppositions rather than on other arguments. Roger Penrose (1989) discussed the entropy of cosmological singularities (black holes and "the big bang") in terms of two tensors RICCI and WEYL. WEYL corresponds to a tidal distortion of an initially spherical object, changing symmetry but preserving volume; RICCI refers to a symmetry-preserving contraction that reduces the volume of the sphere. Penrose reports:

> We generally find that [in spatiotemporal singularities] WEYL is much larger than RICCI…. Such behaviour is associated with a singularity of *high entropy*. However, the situation with respect to the big bang seems to be quite different… As we approach the initial singularity, we find that it is RICCI that becomes infinite rather than WEYL… This provides us with a singularity of *low entropy*. (Penrose 1989)

Steven Hawking (1985: 2490.) comments on Penrose's approach: "[i]n effect, one is putting in the thermodynamic arrow by hand." (Hawking has alternative suggestions for the cosmological origin of the arrow of time. These, too, are subject to objections. (Price 1996)) Penrose concedes that the main argument for considering that RICCI much larger than WEYL for the big bang is the apparent thermodynamic requirement. The extent to which the arrow of time derives from the initial singularity remains more an open question than is generally supposed.

"The Brussels School of Thermodynamics" (founded by de Donder) focused on thermodynamic treatment of irreversible processes, including chemical reactions. Much of this work concerned rates of entropy production of systems that are close to, but not at, equilibrium. Soon after his appointment to the ULB physical chemistry faculty in 1947, Prigogine demonstrated that non-equilibrium systems that are close to equilibrium approach the equilibrium state in such a way that the rate of entropy production is as low as is possible. This major achievement gave Prigogine a substantial reputation as a thermodynamicist. In the late 1960s, Prigogine shifted the center of his attention away from systems near equilibrium to those that are far from equilibrium. He identified entropy production as the source of novel order for such “high-affinity” systems. This shift in emphasis preceded the development of widespread scientific interest in instabilities and oscillations in chemical systems. The theoretical work of the Prigogine group — particularly investigations connected with the abstract chemical reaction-network model called “the Brusselator” — were centrally important to developing physico-chemical understanding of oscillations, self-organization, and pattern formation in chemical systems, and provided important insights for theoretical biology and social sciences.

In the course of research on chemical instabilities, Prigogine developed the concept of "dissipative structures"—self-restoring coherences of dynamic processes (such as chemical reactions) that persist for more or less extended periods while intimately connected to their surroundings — in chemical cases, through exchange of reactants and products with the environment. The rate of entropy generation of any system at thermodynamic equilibrium is identically zero. As a system moves away from equilibrium, the rate of entropy generation increases. In some cases, the processes comprising a dynamic system may reach a new balance at a condition that is far from equilibrium. This non-equilibrium steady state (NESS) corresponds to a high rate of entropy production. Sometimes such a state may become unstable and transition to another NESS may occur. If the underlying dynamic processes are mutually reinforcing (in ways that we now understand quite well) there may be a shift from one NESS to the other and then the reverse transition — often in such a way that the same sequence of states is reached no matter what the starting conditions may have been. This "limit cycle" corresponds to a more or less long-lived oscillation (of concentrations of reagents, in the chemical case). Stable nonequilibrium steady states and systems on limit cycles are dissipative structures. Insights developed through the study of such coherences have gone a long way to bridging the gap (keenly felt by Boltzmann) between our scientific understandings of the second law of thermodynamics on the one hand and of the historical evolutionary development of the universe on the other hand. In every spontaneous process, the entropy of the universe increases: as evolution proceeds, stable coherences of dynamic processes (dissipative structures) come into existence and increase the rate of entropy generation. Emergence of highly organized dynamic systems is not a violation of the second law but rather an effect of that principle. Adequate integration of this insight into philosophical discussions of evolution and of time is still in progress. Dissipative structures in physics and chemistry connect in interesting ways to "evolutionarily stable structures" of theoretical biology, and to analogous concepts in contemporary mathematics, economics, psychology, and political science.

Investigators in a wide variety of fields in science, social science and humanities have found that Prigogine's writings (e.g., Prigogine 1984) have provided insights and metaphors that are useful and productive in their various fields, often supplementing or replacing models that derive from earlier science. The work of the Prigogine group called long-established scientific and philosophic presuppositions into question. It did engender some opposition (Bricmont 1995).

Some of the tension between Prigogine and his critics may connect to a perennial debate about metaphysical presuppositions (Hein 1980).

Complex sets of differential equations, concerned with many chemical reactions and with diffusion of reagents and products, govern far-from-equilibrium chemical systems. Even though the fundamental laws that describe the underlying physical processes are fully reversible, such systems exhibit irreversible evolution in the direction that increases total entropy — the direction that leads to the future and not to the past. Bram Edens (1991) reviewed the work of Prigogine and his associates at ULB and at the Prigogine Center for Statistical Mechanics of the University of Texas, Austin —"the Brussels–Austin group"(BAG) and identified several phases in the development of that group's understanding of the source of irreversibility. Beginning about 1983, the BAG identified entropy as a selector, ruling out trajectories that led to the past rather than the future —some initial states require infinite information and therefore are impossible. In the 1980s and 1990s, the BAG explored "embedding" — the suggestion (Mackey 1992) that every function in phase space is a *trace* of a function in a space of higher dimensionality. About 1986, the group recognized that eigenfunctions for systems involving persistent interactions lie outside Hilbert space, and have intrinsically broken time symmetry. This required use of "rigged Hibert space." Detailed studies of model systems that involve deterministic chaos have been increasingly significant in this research program. Prigogine and his coworkers considered that their results from these several research initiatives were mutually reinforcing and largely cumulative.

Henri Poincaré (1854-1912) had found that calculation of trajectories of objects in the solar system were complicated by "resonances" — transient associations of objects that prevented integration of differential equations. Resonances are ubiquitous in "large Poincaré systems" (LPS) — those that involve large numbers of independent units— the class of interest in chemistry and statistical mechanics. Aspects of work of the BAG on LPS did not fit comfortably into the mathematical framework of Hilbert space. A different framework — "rigged Hilbert space" that had been developed earlier for other purposes — turned out to be more appropriate for dealing with dynamic systems of the type of interest to the BAG. The BAG found that calculations using rigged Hilbert space yield descriptions based on probability distributions rather than on trajectories. This led to the conclusion that when resonances are present, probability distributions are basic, and trajectories are derivative and necessarily approximate. From this point of view, thermodynamics then appears as an emergent global phenomenon possessing a temporal direction. (Bishop 2004) Prigogine considered that these investigations had established the local origin of irreversibility.

Shortly before his death, Prigogine wrote:

> As far back as in 1870 Maxwell considered the kinetic equations in chemistry, as well as the kinetic equations in the kinetic theory of gases, as *incomplete* dynamics. From his point of view, kinetic equations for chemistry would be the result of adding “ignorance” to the physical description. This is indeed still the opinion of the majority of physicists today. However, it would be paradoxical if chemistry, which plays a fundamental role in the description of nature, were the result of our own mistakes.
>
> The basic [result] is that the fundamental description of nonintegrable systems is no longer precisely in terms of Hamiltonian equations, but in terms of kinetic equations with broken time symmetry. Once we have the kinetic equation, it is easy to show that we have irreversible processes and entropy production. It seems to me therefore very natural to consider that chemistry is indeed a very important example of nonintegrable Poincaré systems, where the non-integrability is due to resonances. I hope that this new aspect will continue to be explored by future generations of physicists and chemists.” (Prigogine 2003)

Prigogine’s work provides a new approach to long standing scientific problems, and makes contact with complex concerns of engineers, chemists, biologists, social scientists and philosophers in a way that physical science rarely does.

Joseph E. Earley, Sr.
Department of Chemistry
Georgetown University
502 W Broad Street, Suite 501
Falls Church, VA 22046, USA

Bibliography

Albert, D. (2000). *Time and Chance*. Cambridge, MA: Harvard University Press.

Bishop, R. (2004). Non-equilibrium Statistical Mechanics, Brussels-Austin Style. *Studies in the History and Philosophy of Modern Physics* 35, 1-30, 2004.

Edens, B. (1991). *Semigroups and Symmetry: An Investigation of Prigogine's Theories.* Thesis: KUL, Leuven. (http://philsci-archive.pitt.edu/archive/00000436/)

Bricmont, J. (1995). Science of Chaos or Chaos in Science? *Physicalia Magazine*, **17**, 159-208.

Fasol-Boltzmann, L. (1990). *Ludwig Boltzmann, Pricipen der Naturfilosofi: Lectures on Natural Philosophy, 1903-1906*. New York: Springer-Verlag.

Hawking, S. (1985). Arrow of Time in Cosmology. *Physical Review D*, 33, 2489-2495.

Hein, H. (1972). The Endurance of the Mechanism-Vitalism Controversy. *Journal of the History of Biology*, *5*, 159-88.

Mackey, M. (1992). *Time's Arrow: The Origins of Thermodynamic Behavior.* New York: Springer-Verlag.

Penrose, R. (1989). *The Emperor's New Mind.* (Chapter 7, Cosmology and the Arrow of Time.) New York: Oxford University Press.

Price, H. (1996). *Time's Arrow & Archimedes' Point*. New York: Oxford University Press.

Prigogine, I. and I. Stengers (1984). *Order out of Chaos: Man's New Dialogue with Nature*, New York: Bantam.

Prigogine, I. (1977). Autobiography. http://www.nobel.se/chemistry/laureates/1977/prigogine-autobio.html

Prigogine, I. (2003). "Chemical Kinetics and Dynamics" in *Chemical Explanation: Characteristics, Development, Autonomy*. J. Earley, ed. *Annals New York Acad. Science*. *988*, 128-133.

Winsberg, E. (2004). Can Conditioning on the "Past Hypothesis" Militate Against Reversibility Objections? *Philosophy of Science*, *17*, 489-504.