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Ilya Prigogine was a Belgian physical chemist who won the Nobel prize for investigating the irreversibility of processes in complex physical systems that are far from equilibrium conditions.

The physics equations describing classical dynamical motions are time reversible. One can replace the time variable *t* by negative time -*t* in the equations (reversing the time) and they remain equally valid. For example, if time were reversed, the earth would revolve around the sun in the opposite direction, but that seems quite acceptable.

However, many everyday processes cannot be reversed. If time were reversed, the steam (visible as water vapor) coming out of a kettle boiling water on the stove would instead go back into the kettle. It would look like a film played backwards. With time reversed, a glass shattering on the floor would miraculously reassemble its shards flying in all directions and rise back up onto the table. No such processes are ever seen in nature.

Prigogine's main research was to study the irreversibility of these processes.

> It is now generally recognized that in many important fields of research a state of true thermodynamic equilibrium is only attained

> in exceptional conditions. Experiments with radioactive tracers, for example, have shown that the nucleic acids contained in living cells continuously exchange matter with their surroundings. It is also well known that the steady flow of energy which originates in the sun and the stars prevents the atmosphere of the earth or stars from reaching a state of thermodynamic equilibrium.
> Obviously then, the majority of the phenomena studied in biology, meteorology, astrophysics and other subjects are irreversible processes which take place outside the equilibrium state.
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> These few examples may serve to illustrate the urgent need for an extension of the methods of thermodynamics so as to include irreversible processes.

Prigogine was unhappy with the work of Ludwig Boltzmann which showed how macroscopic irreversibility could arise from microscopic reversibility as a result of statistical considerations. To be sure, Joseph Loschmidt's reversibility paradox and Ernst Zermelo's recurrence paradox prevented Boltzmann's irreversibility from being anything but statistical.

He was also unhappy with classical dynamics, because Newton's equations are "time-reversible." He maintained that Erwin Schrödinger's deterministic wave function implied that even quantum mechanics is time reversible, which it is not. Quantum events lead to the "collapse of the wave function" which is irreversible.

Prigogine was awarded the Nobel Prize in 1977 for his contributions to non-equilibrium thermodynamics, particularly the theory of what he called "dissipative structures." These are physical or chemical systems in far from equilibrium" conditions that appear to develop "order out of chaos" and look to be "self-organizing." Like biological systems, matter and energy (of low entropy) flows through the "dissipative" structure. It is primarily the energy and negative entropy that is "dissipated."

This similarity to biological systems (in just one very important thermodynamic respect) was exploited by Prigogine to say he had discovered "new laws of nature" that could connect the natural sciences to the human sciences. Dissipation also implies irreversibility, a very important characteristic of life.

Prigogine had no physical explanation for irreversibility - beyond the fact that his physical "dissipative structures" and biological systems - exhibited it. He generally attacked classical Newtonian dynamics as being time reversible and thus providing no understanding of time. His understanding of time was based on the work of Henri Bergson and the uneven flow of time Bergson called "duration."

Prigogine discounts Boltzmann’s work on the second law, which Eddington called the "Arrow of Time"

Prigogine believed that before him, there was "no direction of time, no distinction between past and future," because even quantum mechanics, in the form of Schrödinger’s deterministic wave equation, could not do so (without invoking a collapse of the wave function). Prigogine introduced what he called a "third time" into physics - time as irreversibility. He saw non-equilibrium, dissipative systems far from equilibrium, as a new source of order giving to the system ill-defined "new space-time properties."

The Nobel committee noted the importance of irreversibility in living systems, and pointed out the work of Lars Onsager on nonlinear thermodynamics, years before Prigogine.

Classical thermodynamics has played a dominant role in the development of modern science and technology. In suffers, however, from certain limitations, as it cannot be used for the study of irreversible processes but only for reversible processes and transitions between different states of equilibrium.
Many of the most important and interesting processes in Nature are irreversible. A good example is provided by living organisms which consume chemical energy in the form of nutrients, perform work and excrete waste as well as give off heat to the surroundings without themselves undergoing changes; they represent what is called a stationary or steady state. The boiling of an egg provides another example, and still another one is, a thermocouple with a cold and a hot junction connected to an electrical measuring instrument.

The Onsager "reciprocity relations" and minimum entropy production

The first investigator who developed a method for the exact treatment of such problems, for example of the thermocouple, was Onsager who received the 1968 Nobel Prize for this contribution. His approach was, however based on assumptions which in principle make it applicable only to systems close to equilibrium. The great contribution of Prigogine to thermodynamic theory in his successful extension of it to systems which are far from thermodynamic equilibrium. This is extremely interesting as large differences compared to conditions close to equilibrium had to be expected. Prigogine has demonstrated that a new form of ordered structures can exist under such conditions, and he has given them the name ”dissipative structures" to stress that they only exist in conjunction with their environment.

> The most well-known dissipative structure is perhaps the so-called Benárd instability. This is formed when a layer of liquid is heated from below. At a given temperature heat conduction starts to occur predominantly through convection, and it can be observed that regularly spaced, hexagonal convection cells are formed in the layer of liquid. This structure is wholly dependent on the supply of heat and disappears when this ceases.
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> Quite generally it is possible in principle to distinguish between two types of structures: equilibrium structures, which can exist as isolated systems (for example crystals), and dissipative structures, which can only exist in symbiosis with their surroundings. Dissipative structures display two types of behaviour: close to equilibrium their order tends to be destroyed but far from equilibrium order can be maintained and new structures be formed.
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> The probability for order to arise from disorder is infinitesimal according to the laws of chance. The formation of ordered, dissipative systems demonstrates, however, that it is possible to create order from disorder. The description of these structures have led to many fundamental discoveries and applications in diverse fields of human endeavour, not only in chemistry. In the last few years applications in biology have been dominating but the theory of dissipative structures has also been used to describe phenomena in social-systems.

Classical thermodynamics, by contrast with nonlinear thermodynamics, can only be used for the study of reversible processes and systems in or near thermal equilibrium. Prigogine’s "dissipative" systems, today more commonly known as complex systems, could be described as "self-organizing," a property that "emergentists" said was a basic property of life, one that could not be explained by "reductionist science.

Prigogine became very popular with "holists" and "vitalists" who were looking for new laws of nature.

Prigogine was a major member of the Brussels School of thermodynamics. The Santa Fe Institute in New Mexico is devoted to the study of complex systems in the natural sciences and the social sciences.

Prigogine is perhaps the most famous name in chaos theory and complexity theory. Although he made very few original contributions to these fields, he is famous for them, nevertheless. His work (especially his 1984 book written with Isabel Stengers, *Order Out Of Chaos*) is a major reference today for popular concepts like "self-organizing, "complex systems," "bifurcation points," "non-linearity,", "attractors," "symmetry breaking," "morphogenesis," "autocatalytic," "constraint," and of course "irreversibility," although none of these terms is originally Prigogine's. The name "dissipative structures" and perhaps the phrase "far from equilibrium" belong to Prigogine, but the thermodynamic concepts were already in Boltzmann, Bertalanffy, and Schrödinger, and perhaps many others.