IS FUTURE

GIVEN?

ILYA PRIGOGINE

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ILYA PRIGOGINE
Nobel Laureate in Chemistry, 1977

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Ilya Prigogine

Preface

This book about the Future is a souvenir of Professor Ilya Prigogine's visit to Athens to receive Honorary Doctorates from the Departments of Chemical Engineering, Electrical and Computer Engineering and Applied Mathematics and Physical Sciences of the National Technical University of Athens.

These distinctions to Professor Ilya Prigogine were given for his achievements in Non-Equilibrium Physics and Chemistry, which were not only appreciated and used by physicists and mathematicians, but also by engineers, biologists, sociologists, philosophers, and even artists.

Ilya Prigogine showed that Self-Organization appears in Nature far from equilibrium and that Irreversibility and Probability are intrinsic properties of Nature at all levels, from atoms and nuclei to our everyday life up to the cosmological scale. His work is a continuation of the dialogue about Time and Change in Nature, initiated by Heraclitus and Parmenides and continued by Zeno, Epicurus, Lucretius, Kant, Hegel, Begson, Einstein and other eminent thinkers over the centuries.

Thanks to Ilya Prigogine we have now a view of Nature which goes beyond the mechanical timeless automaton which we inherited from classical physics, but also beyond a meaningless random game. Evolution, emergence of structures and creativity are the keynotes of natural processes at all levels.

This view, supported by strong scientific results, terminated the separation between physical sciences on one side and biological sciences and humanities on the other side. Human existence, for Ilya Prigogine, means creativity and active participation in the society. Ilya Prigogine's perspective offers the necessary concepts and tools to face the challenges ahead with optimism and is expected to lead to pioneering results in Science and Technology.

The scientific path of Ilya Prigogine during the last 40 years has been linked with the significant work of the International Solvay Institutes for Physics and Chemistry which he transformed into an Advanced Study Institute for the study of Complexity, adding significant value to their role in the Physics and Chemistry of the 20th century [75], (p. 1). In his exciting talk at the National Technical University of Athens on 26 May 2000, Ilya Prigogine expressed his thoughts about Becoming and concluded with optimistic messages to the new generation (p. 7).

During his visit to the National Technical University of Athens we had the opportunity for constructive discussions. During our personal discussions, his uneasy creative spirit dominated together with his vivid interest on the role of Science in Society today, as well as the foreseeable active role of Science in future. His evaluation that science today is at a "pre-historic" stage of development was particularly impressive. His remarks on the character and role of fundamental science deserve wide attention. The understanding of complexity and the use of the creativity of nature, the continuation of the work of nature are the grand challenges for the scientists of the 21st century.

Ilya Prigogine had further discussions with Theodore Christidis, professor at the University of Thessaly, and the journalists Ioannis Zisis and Maria Adamidou, on the evolution of ideas in Non-equilibrium Physics (p. 21), on the role of time in the epistemology of Complexity (p. 33) and on Life and the Internet (p. 49).

Professor Ioannis Antoniou, a close collaborator of Ilya Prigogine and Deputy Director of the International Solvay Institutes for Physics and Chemistry, was the main lever for the realization of this book. He accepted with enthusiasm my invitation to compile the high quality "shots" of the lecture into a structured text of messages for the general public, knowing himself their meaning in depth and he concluded with an inspired epilogue on the opening to the future.

I would like to thank all those who contributed to the nomination of Ilya Prigogine as Honorary Doctor of the National Technical University of Athens, especially Professor George Metakides who, despite enormous pressure of his important work as coordinator of the European Research in the Science and Technology of Information, managed to find the time and undertook this initiative.

Finally I would like to thank George-Alexander Dimakis, student of the Electrical and Computer Engineering Department for the artistic design of the cover, as well as for his contribution to the translations, Dr. Pavlos Akritas, researcher at the International Solvay Institutes for Physics and Chemistry for his contibution to the translation and the compilation, as well as Mrs. Anne De Naeyer and Mrs. Margaret Kontari for technical support.

Professor Themistoklis Xanthopoulos
Rector of the National Technical University of Athens
Athens, September 2001

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Ilya Prigogine and the International Solvay Institutes for Physics and Chemistry

Ioannis Antoniou
Deputy Director of the International Solvay Institutes for Physics and Chemistry, and
Professor of Mathematics at the
Aristoteles University of Thessaloniki

Professor Ilya Prigogine is the Director of the International Solvay Institutes for Physics and Chemistry and Director of the Ilya Prigogine Center for Studies in Statistical Mechanics and Complex Systems of the University of Texas at Austin, USA.

In 1977 he was awarded the Nobel Prize for Chemistry for his contributions to thermodynamics and non-equilibrium structures, more specifically for the theory of dissipative structures.

Ilya Prigogine's interest in the world of learning has always had a broad basis. At a very early stage, for instance, he sought to apply his findings in thermodynamics to other areas of practicality and is regarded as one of the foremost architects of the new system theory of complexity.

Ilya Prigogine studied at the Université Libre de Bruxelles where he was the disciple of Professor Théophile De Donder, one of the pioneers in the non-equilibrium field. The relation of Ilya Prigogine with De Donder is mentioned in the discussion with Theodore Christidis (p. 21).

Classical science insisted on stability and equilibrium, while today we see everywhere instabilities, fluctuations, evolution. This change of perspective is mainly due to the work of Ilya Prigogine and his collaborators. This new view of Nature is contrary to the deterministic and static image we inherited from classical physics. That is why, during these last years, Ilya Prigogine, and his collaborators devoted their work to find the roots of the flow of time in a new formulation of the fundamental laws of physics. Instead of "certitudes" like in the classical laws, these extended laws are dealing with "possibilities" in conformity with the evolutionary universe we observe around us.

Professor Ilya Prigogine can look back on an exceptional academic and scientific career. He has held numerous chairs at foreign universities and has repeatedly been invited as visiting professor.

Ilya Prigogine is the only Belgian Nobel Prize winner in Physical and Chemical Sciences. He is a member of over 60 national and international academies, and holder of 47 Honorary Degrees. In Greece, Ilya Prigogine was honored not only by the National Technical University of Athens but also by the University of Thrace and the Aristoteles University of Thessaloniki. Ilya Prigogine has obtained an impressive number of prizes and distinctions in the field of science in the USA, the United Kingdom, France, Germany, Sweden, Italy, Japan, Canada, Belgium, Latin America and many other countries and has been made an honorary citizen of major cities in all continents. Five International Centers have been created in his honor: the Ilya Prigogine Center for Studies in Statistical Mechanics and Complex Systems at the University of Texas at Austin, where he is Director; the Centro Latinoamericano Ilya Prigogine at the National University of San Luis (Argentina); the Ilya Prigogine Center for the Mathematical Study of Complex Systems at Moscow State University, where he is Honorary Director; "Istituto di Documentazione e Ricerca Sull'Opera di Ilya Prigogine, Centro Internazionale Di Storia dello Spazio e del Tempo", Brugine-Padoa, Italy; in Brussels the "Haute Ecole Ilya Prigogine". Activities with Ilya Prigogine's name include the "Prigogine's lectures" at Università dell'Insubria (Como, Italy), the "International Hall and Scientific Permanent Exhibition Ilya Prigogine" and the "International Scientific Award Ilya Prigogine" at the Universidad del Salvador (Buenos Aires, Argentina) and the "Prix Ilya Prigogine de Thermodynamique", CERET, France.

In addition to scientific books and numerous articles in the leading international reviews, membership of over sixty national and international academies, Ilya Prigogine always wanted to keep contact with the public through the publications of books such as *Order Out of Chaos* (1984) [4] and *From Being to Becoming: Time and Complexity in the Physical Sciences* (1980) [3], translated into about 20 languages, *The End of Certainty, Time, Chaos and the New Laws of Naure* (1997) [18] and *Modern Thermodynamics: From Heat Engines to Dissipative Structures* (1998) [5].

In 1989, King Baudouin awarded him the personal title of Viscount. For several years, he was a special advisor to the European Commission.

Ilya Prigogine was appointed director of the International Solvay Institutes for Physics and Chemistry in 1958. Since then the Institutes have become an Advanced Study Institute in Non-equilibrium Physics and Complexity [http://solvayins.ulb.ac.be].

The research performed at the Institutes has demonstrated that far from equilibrium matter acquires new properties, which are the basis of a new coherence. This coherence makes possible the emergence of new complex structures and in particular biological structures. These results have led to the ideas of self-organisation which have been applied to a large number of fields including economic and social sciences. Although Ilya Prigogine obtained the Nobel Prize for his fundamental work in non-equilibrium Physics, he is also considered to be "among the most influential traffic theorists since the '60s" [85], because "his way of looking at nature and sociotechnical systems certainly shaped our thinking" [86]. The present Research activities of the Solvay Institutes involve both Fundamental and Applied Problems. The Solvay Institutes coordinate an International Research Network including European, Russian, American, Japanese, Chinese, Indian research institutes.

Fundamental Research is focussed on the Probabilistic Description of different classes of Unstable/Non-Integrable Systems as well as on the Dynamical Foundation of Thermodynamical Systems. For Unstable/Non-Integrable Systems there exist new solutions corresponding to the probabilistic extensions of the evolution equations. These extensions are constructed through the generalised spectral decompositions of the evolution operators, which provide actually a probabilistic Integration of the equation of Dynamics. The Results illustrate the deep connection between Irreversibility, Probability and Non-Integrability/Chaos.

The Solvay Institutes have been recognised as the Belgian scientific institution with the most universal representation.

Founded in 1910 by Ernest Solvay, some years after the foundation of the Nobel Prizes by Alfred Nobel, the International Institutes for Physics and Chemistry aim at organising regular conferences on Physics and Chemistry and encouraging research which could extend our knowledge of the natural phenomena. Since their creation, the Institutes have organised twenty-one conferences on Physics and twenty conferences on Chemistry. In organising the conferences, they are assisted by two Scientific Commissions whose members are chosen among the most famous scientists.

The Solvay Conferences had an extraordinary success. It is not an exaggeration to state that the Physics and Chemistry of the 20th century have been shaped in Brussels during these conferences [75]. Albert Einstein, Marie Curie, Ernest Rutherford, Louis De Broglie and other legendary personalities of modern science participated in these meetings (see photos). As Werner Heisenberg, founder of quantum mechanics, wrote: "there can be no doubt that in these years the Solvay Conferences played an essential role in the history of physics ... the historical influence of the Solvay Conferences was connected with the special style introduced by their founder: a small group of the most competent specialists from various countries discussing the unsolved problems of their field and thereby finding a basis for their solutions."

This activity is still going on. In November 1995, the 20th Solvay Conference in Chemistry was about Femtochemistry, where chemical reactions are studied on a time scale intrinsic to the movements of the atoms in molecules. The 21st Solvay Conference in Physics took place in Kansai, Japan in 1998 and was devoted to the probabilistic description of classical and quantum dynamics. These new extended formulations of the dynamics of complex systems not only establish the bridge between microscopic dynamics and thermodynamics, but also provide new probabilistic tools for the analysis, prediction and control of complex systems.

The first Solvay Conference in Physics of the 21st Century (22nd Conference) took place in Delphi, Greece in November 2001 and was dedicated to "The Physics of Communication".

Is Future Given?
Changes in Our Description of Nature

Ilya Prigogine's Lecture[1],
after the Honorary Doctorates Ceremony,
National Technical University of Athens,
26 May 2000

[1]Here I give an improved version taking into account the progress reached in the last two years.

According to the classical point of view, nature would be an automaton. However, today we discover instabilities, bifurcations, evolution everywhere. This demands a different formulation of the laws of nature to include probability and time symmetry breaking. We have shown that the difficulties in the classical formulation come from a too narrow point of view concerning the fundamental laws of dynamics (classical or quantum). The classical model has been a model of integrable systems (in the sense of Poincaré). It is this model, which leads to determinism and time reversibility. We have shown that when we leave this model and consider a class of non-integrable systems, the difficulties are overcome. We show that our approach unifies dynamics, thermodynamics and probability theory.

Dear Rector, Dear Deans, Colleagues, Friends,

I

I feel very moved by the kindness shown to me. I don't know if I deserve so many honors. I remember that some years ago a Japanese journalist asked a group of visitors why they are interested in science. My answer was that I feel that science is an important way to understand the nature in which we are living and therefore also our position in this nature. I always felt that there are some difficulties in the descriptions of nature you find currently. I would quote three features. First of all, nature leads to unexpected complexity. This is true on all levels. It is true in the case of the elementary particles; it is true for living systems and, of course, for our brain. The second difficulty is that the classical view does not correspond to the historical time-oriented evolution, which we see everywhere around us. The universe is evolving. That is the main result of modern cosmology with the Big Bang. Everywhere we see narrative stages.

They are events in nature. An event is something, which may or not happen. For example, the position of the moon in one million years is not an event as you can predict it, but the existence of millions of insects we observe is an evidence of what we could call creativity of nature. It is indeed difficult to imagine that the necessary information existed already in some way in the early stages of the universe.

These difficulties have led me to look for a different formulation. This problem is a continuation of the famous controversy between Parmenides and Heraclitus. Parmenides insisted that there is nothing new, that everything was there and will be ever there. This statement is paradoxical because the situation changed before and after he wrote his famous poem. On the other hand, Heraclitus insisted on change. In a sense after Newton's dynamics, it seemed that Parmenides was right, because Newton's theory is a deterministic theory and time is reversible. Therefore nothing new can appear. On the other hand, philosophers were divided. Many great philosophers shared the views of Parmenides. But since the 19^{th} century, since Hegel, Bergson, Heidegger, philosophy took a different point of view. Time is our existential dimension.

I want to show you that the dilemma between Heraclitus and Parmenides can now be put on an exact mathematical framework. As you know, we have inherited from the 19^{th} century two different worldviews. The worldview of dynamics, mechanics and the worldview of thermodynamics. Both views are pessimistic. From the dynamical point of view, everything occurs in a predetermined way. From the thermo-dynamic point of view, everything goes to death, the so-called thermal death. Both points of view are not able to describe the features, which I have mentioned before. Matter was generally considered as a kind of ensemble of dust particles moving in disordered way. Of course, we knew that there are forces. But the forces don't explain the high degree of organization that we find in organisms.

For classical physics and also for quantum physics, there is no privileged direction of time. Future and past play the same role. Since we see an evolutionary universe on all levels of observation. The traditional description is deterministic, even in quantum theory. Indeed, once we know the wave function for one time, we can predict it for arbitrary future or past. This I felt always to be very difficult to accept. I liked the statement by Bergson: time is "invention".

But the results obtained by classical or quantum mechanics or classical thermodynamics contain certainly a large part of truth. Therefore, the path which I followed over my whole life, was to show that these descriptions are based on a too restricted form of dynamics. We have to introduce a more general starting point. The first step in this direction was an observation, which I made at the beginning of my PhD, in 1945 [1], that non-equilibrium leads to structure. For example, if you consider a box containing two components, say N_2 and O_2, and you heat it from one side and cool it from the other, you see a difference of concentrations. For example, N_2 may be more concentrated at the hot side. Of course, when you consider the box in thermal equilibrium, the concentrations become uniform. Much later, thanks to the collaboration with Prof. Glansdorff [2], we found that far from equilibrium there appears what we called dissipative structures. These new structures have become quite popular, everywhere one speaks about non-equilibrium structures, self-organization [3–8]. These concepts have been applied to many fields including even social sciences or economic sciences. But I could not stop at this point because thermodynamics is macroscopic physics, so perhaps it is the fact that these systems are large and that we have no exact knowledge of their time evolution and that would give us the illusion of irreversibility. That is the point of view adopted by most people even today. However, my main interest was to show that the difficulty comes from the fact that dynamics, classical or quantum, has to be put on a more general frame.

Let me make here a short excursion on theoretical physics. To describe our nature, we need observables such as space and time. You know that Einstein's great idea was to relate space and time to the properties of matter. But here I do not want to consider relativity, but limit the discussion to classical systems, such as the pendulum, the planetary motion or the motion of particles in a gas. To describe classical systems of this type, we need two kinds of variables: coordinates q and momenta p. In classical theory [9], a dynamical system is described by the so-called Hamiltonian function H. The Hamiltonian is simply the expression of the energy in terms of the observables p and q, $H = H(q, p)$. Once we have the Hamiltonian, we can predict the motion through the so-called canonical equations (the dot means derivative).

$$\dot{p} = \frac{\partial H}{\partial q} \qquad \dot{q} = -\frac{\partial H}{\partial q}$$

At the initial time $t = 0$, the observables are the initial positions and momenta q_0, p_0. As time goes on, they change into $p(t)$, $q(t)$. The observables q, p are called the "canonical variables". Now, a very important point is that there are various choices of canonical variables q and p. This is studied in the basic chapters of classical physics. It is natural to choose the variables q, p, so that the solution of the canonical equations of motion are as simple as possible. It is therefore natural to try to choose them in such a way that we eliminate the potential energy. The Hamiltonian then depends only on the momenta p. We have then $H = H(p)$ and $\dot{p} = 0$. Momenta are constant, therefore the time derivative of the momenta vanishes.

For a long time it was considered that it was always possible to find such "privileged" canonical variables. We could always eliminate the coordinates in the Hamiltonian. But Poincaré, at the end of the 19th century, made a fundamental discovery. He found that this elimination was only possible for a class of dynamical systems, which he called "integrable systems". For example, in a gas with many particles, this transformation would correspond to going to a representation in which each particle moves independently. When this is possible, the momenta p are called also the action variables J and the coordinates q, the angle variables α. I have to be a little more specific. Consider a system in which the Hamiltonian has two parts

$$H(J, \alpha) = H_0(J) + \lambda V(J, \alpha)$$

We have then one part, H_0, which depends only on momenta (the action variables), but there is also a perturbation λV depending on both J and α. λ is a parameter measuring the intensity of the perturbation. By definition, for H_0, we know the action variables. Then for H including λV, we ask if we can construct new action variables, $\bar{J}$, which would depend analytically on the old ones. This means that the Hamiltonian H can be written as $H(\bar{J})$ with $\bar{J} = J + \lambda J^{(1)} + \lambda^2 J^{(2)} + \ldots$

What is the meaning of action variables? They represent *independent* objects, as interactions are eliminated or better to say included in the definition of these objects. This transformation theory has been intensively studied in the 19th and 20th centuries. We can in general introduce new momenta and new coordinates related to p and q by

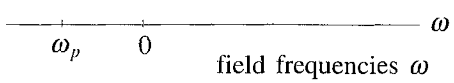
$$\bar{p} = U^{-1}p, \; \bar{q} = U^{-1}q$$

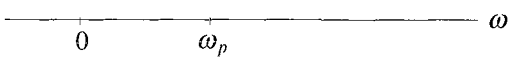
where U is a so-called canonical transformation which preserves the form of the Hamiltonian equations. The analog of U in quantum mechanics is the so-called unitary operator which preserves the form of the Schroedinger equation. U plays an essential role both in classical and quantum mechanics. An important property is the distributivity of U. That means U acting on a product is equal to the product of the transformed entities: $U^{-1}(AB) = (U^{-1}A)(U^{-1}B)$. There are other remarkable properties of unitary transformations, but there is no place here to go further into this [10, 11].

It is remarkable that orthodox quantum mechanics used classical integrable dynamical systems as a model. The basic difference is that the observables are now no more numbers but *operators.* There are again various representations of the operators related by unitary transformations. Let us only remind that, according to every book on quantum mechanics, in the representation in which q is a number, p is the differentiation operator $i\frac{\partial}{\partial q}$ and we have the commutation relation $qp - pq = \frac{h}{i}$. This is the basis of the Heisenberg's uncertainty relations [10, 11]. For non-integrable systems, the situation, as we shall see now, is quite different.

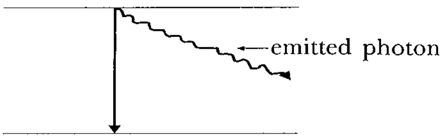
II

After this short introduction to integrable systems, we shall now discuss non-integrable systems. There are of course many classes of non-integrable systems, that is of systems for which we cannot construct a unitary transformation, which eliminates the interactions. We shall consider a specific class of non-integrable systems. That is the class where there exist resonances. What is a resonance? Consider a particle, like a harmonic oscillator, in a field like in electromagnetism. Suppose that the particle frequency is ω_p while the field forms a continuous set of frequencies starting from 0.

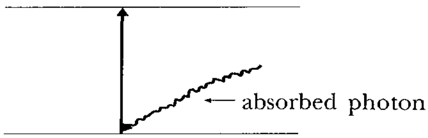




Then there are two situations, either the frequency of the oscillator ω_p is below all the frequencies of the field or the frequency of the oscillator is somewhere in the domain of the frequencies of the field. These are two very different situations. If the frequency of the oscillator is outside the field, nothing special happens. But if it is inside, we have a so-called excited state and this excited state decays by emitting a photon to a ground state.



This is the well known Einstein and Bohr mechanism for the description of spectral lines. It is generally expressed by saying that the particle is dissolved in the continuum. We have a desexcitation process. There exists of course also an excitation process when the photon falls on the ground state.



The interactions between the field and the oscillators are described by resonances. The fundamental result of Poincaré was to show that such resonances lead to difficulties through the appearance of divergent terms due to small denominators. An example is the term:

$$\frac{1}{\omega_k - \omega_l}$$

ω_k is the frequency of the particle, ω_l is the frequency of the field.

This difficulty was already known to Laplace. How to overcome this difficulty? We have shown that the resonances can be avoided by suitable "analytic continuation"; that means that one has to put small quantities in the denominator to avoid the infinities. Of course, there are some specific mathematical problems to be overcome here, but they can be studied in the original papers [3, 12–21].

In short, our key idea was to eliminate the Poincaré divergences by extending the idea of unitary transformations. Instead of the formula we have already written for unitary transformation, $\bar{q} = U^{-1}q$, $\bar{p} = U^{-1}p$, we now have:

$$\bar{q} = \Lambda^{-1}q, \quad \bar{p} = \Lambda^{-1}p.$$

The unitary operator U has been replaced by the operator Λ, which is a star-unitary operator, but that doesn't matter here. The main point is that we have an extension of canonical transformations. In other words, we have now a new representation of observables and an extension of the dynamical theory. Even in classical theory, it is very important to choose the right representation. For example, if you consider a crystal with vibrating atoms, you can always find a representation in which you have normal coordinates, that means independent motions and then you can define the basic frequencies (normal modes). Similarly here by using the new representation, you can come to expressions of motions, classical or quantum, in which there appear quantities such as transport coefficients, reactions rates, approach to equilibrium. Now the Λ transformation, which replaces U, has very interesting new properties. First of all, it is a *non-local* transformation. In other words, classically people were thinking in terms of points, but here we have to speak in terms of ensembles, collections of points. We cannot make a physics of points anymore, we have to make a physics of distributions. This means that we have a statistical description. This also means that we have to give up classical determinism. The second fundamental property of Λ is that we have no more distributivity. More precisely we have $\Lambda^{-1}AB \neq \Lambda^{-1}A \cdot \Lambda^{-1}B$. This opens a whole new domain of classical and quantum physics. We have the appearance of new fluctuations and new uncertainty relations. For example, the Λ operator acting on a product of coordinates is not the product of the transformed coordinates. There is an uncertainty in position. Let me give an example. In statistical physics, an important role is played by the so-called Langevin equation, where γ is the friction, and noise.

$$dp_1(t)/dt = -\gamma p_1(t) - m\omega_1{}^2 x_1(t) + B(t)$$
$$dx_1(t)/dt = -\gamma x_1(t) + p_1(t)/m + A(t)$$

These equations describe the damped harmonic oscillator with random momentum. This corresponds, for example, to the motion of a heavy particle in a thermal medium and it is one of the most important results of statistical physics.

Now recently S. Kim and G. Ordonez have shown [87] that using our new transformation Λ, you derive exactly the Langevin equations and therefore also the basic properties studied in statistical mechanics. The Langevin equation has a broken time symmetry. This is not due to approximation but expresses that $x(t)$ and $p(t)$ are Λ transforms. The Langevin equation corresponds to a system in which resonances between the Brownian particle and the thermal medium play an essential role. We have also obtained the *quantum* Langevin equation using the quantum analogues of Λ transforms. Uncertainty relation can now be established for x and p separately. The whole space-time structure is altered. These are fundamental results. Dynamics and probability theory were always considered as separate domains. In other words, statistical theory, noise, kinetic equations were considered as coming from approximations introduced into dynamics, being classical or quantum. What we show now is that these properties, noise and stochasticity are directly derived from a more general formulation of dynamics. These are consequences of non-integrability while integrable systems, which were used as a model for classical and quantum physics, refer in fact only to exceptional ideal cases. We are living in a nature in which the rule is non-integrability. And in non-integrable systems we have quite new properties. The new properties are: First of all, the appearance of new fluctuations, therefore no more determinism. Secondly, the appearance of a privileged direction of time, that is due to the analytic continuation and third, non-distributivity leading to new uncertainty relations, even in classical physics.

These new properties originate from the fact that we use analytic continuation of the evolution operators. As a result the analytic continuation of a product is not the product of the analytic continuations. When we observe the Langevin equation, the coordinate x and the momentum p have to be understood as non-unitary transforms of the original variables. The new transformed variables are random, leading to stochasticity and probability. In the classical point of view, we may either start from an individual description or with ensembles. Gibbs and Einstein have shown that thermodynamics is based on the theory of ensembles. These ensembles, as we have already mentioned, were obtained from approximations ("coarse graining"). This is no more so, for our class of non-integrable systems. The ensembles point of view is a consequence of the Λ transformation. Λ transforms a phase point into an ensemble. More precisely, the Liouville equation is transformed into a kinetic equation. This, I believe, closes a controversy, which goes back to Boltzmann (1872) [22, 23].

III

Now we want to go to a different aspect. This aspect is related to a different description of elementary processes, unstable particles or quantum transitions. In a sense, it is very nice that these systems are non-integrable. If you could, in the examples of the interaction between the oscillators and the field, apply a unitary transformation, you would not be able to observe the quantum transitions from one level to the others. Electrons, photons are only observable because they interact and participate in irreversible processes. The basic idea of unitary transformation of integrable systems is that you could, in one way or another, eliminate interactions. But interactions are a fundamental part of nature which we observe and, in non-integrable systems, interactions cannot be eliminated. Think about a gas. In a gas, even if it is at equilibrium, collisions continue to occur and interactions are never eliminated. Collisions give rise to thermal motion. There are limits to reductionism. We have applied our method to a number of problems such as unstable particles or radiation damping (details can be found in the original publications) [19–21, 24–26].

IV

Once we have irreversibility it is clear that we have also some form of the second law of thermodynamics, that means entropy increase.

Boltzmann had the ambition to become the Darwin of physics. He studied the collisions in dilute systems and showed that you can find a function, which plays the role of entropy. This led to a lot of controversies. Poincaré wrote that there was a basic contradiction: on one hand, to use classical mechanics; on the other hand, to come out with entropy which is time oriented. We can now understand what was the reason. Boltzmann tried to apply classical mechanics to non-integrable systems. Gases cannot be integrable systems, because then they would never go to equilibrium. For example, all momenta would be invariants of motion, which would prevent the system to approach equilibrium. So we need non-integrable systems. And once we have non-integrable systems, then Boltzmann's equations are exact consequences of the extended dynamics.

Indeed, we have shown, together with Tomio Petrosky, Gonzalo Ordonez, Evgueni Karpov and others, that we can formulate the second law in terms of dynamical processes. There were always two points of view. The point of view of Boltzmann, stating that the second law is probabilistic and comes ultimately from our ignorance and the point of view of Planck that for the second law, the entropy production is a consequence of dynamics. Consider the problem of resonances, which I described a little earlier, where we have shown that the decay of the excited state with the emission of the photon is an irreversible process leading to entropy production. This is not astonishing because, in a sense, an excited state contains "more energy" than the ground state. This supplementary energy can then be distributed on all degrees of freedom of the field. We have shown that the inverse process is also possible; that to bring an atom into an excited state, we need a process which brings negative entropy to the atom, which is then used to excite it. In a sense, our whole vision of the universe around us is an example of non-equilibrium systems. We have particles, with mass, and we have photons, without proper mass. Particles with mass should, from the thermodynamical point of view, dissolve into a continuum. Probably the main event in the history of our universe, in the Big Bang is this differentiation. We have massive particles floating in a bath of zero mass objects like the photons.

Conclusions

We come to a different concept of reality. Laplace and Einstein believed that man is a machine within the cosmic machine. Spinoza said that we are all machines but we don't know it. This does not seem very satisfactory. However, to describe our evolutionary universe, we have only taken very preliminary steps. Science and physics are far from being completed, as some theoretical physicists wants us to believe. On the contrary, I think that the various concepts, which I have tried to describe in my lecture, show that we are only at the beginning. We don't know what exactly corresponded to the Big Bang, we don't know what determines the families of particles, we don't know how the biological evolution is evolving. May I finish my lecture by some general remarks. Non-equilibrium physics has given us a better understanding of the mechanism of the emergence of events. Events are associated with bifurcations. The future is not determined. Especially in this time of globalization and the network revolution, behavior at the individual level is the key factor in shaping the evolution of the entire human species. Just as few particles can alter the macroscopic organization in nature to show the appearance of different dissipative structures. The role of individuals is more important than ever. This leads us to believe that some of our conclusions remain valid in human societies.

A famous saying of Einstein is that time is an "illusion". Einstein was right for integrable systems but the world around us is basically formed by non-integrable systems. Time is our existential dimension. The results described in this paper show that the conflict between Parmenides and Heraclite can be taken out from its metaphysical context and formulated in terms of modern theory of dynamical systems.

Thank you very much.

Acknowledgements

The results described in this paper are the fruit of the work of the Brussels-Austin group. I shall not thank individually each member of this group but I want to make an exception for Prof. Ioannis Antoniou, Dr. Gonzalo Ordonez and Prof. Tomio Petrosky. It is their work, which has led to the formulation of the extension of canonical transformations. I acknowledge the European Commission Grant Nos. HPHA-CT-2000-00015 and HPHA-CT-2001-40002, the Engineering Research Program of the Office of Basic Energy Sciences at the US Department of Energy, Grant No. F-0365, the National Lottery of Belgium, and the Communauté Française de Belgique.

Laws of Nature and Time Symmetry Breaking

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Laws of Nature and Time Symmetry Breaking

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INTRODUCTION: IRREVERSIBLE PROCESSES IN NATURE

In recent years, a radical change of perspective has been witnessed in science since the realization that large classes of systems may exhibit abrupt transitions, a multiplicity of states, coherent structures, or a seemingly erratic motion characterized by unpredictability often referred to as deterministic chaos. Classical science emphasized stability and equilibrium; now we see instabilities, fluctuations, and evolutionary trends in a variety of areas ranging from atomic and molecular physics through fluid mechanics, chemistry, and biology to large scale systems of relevance in environmental and economic sciences.[1,2] Concepts such as "dissipative structures" and "self-organization" have become quite popular. The distance from equilibrium, and therefore the arrow of time, plays an essential role in these processes, somewhat like temperature in equilibrium physics. When we lower the temperature, we have various states of matter in succession. In nonequilibrium physics and chemistry, when we change the distance from equilibrium, the observed behavior is even more varied.

How can these findings be interpreted from the point of view of the basic laws of physics? Newtonian dynamics, relativity, and quantum physics, make no distinction between past and future. Time is simply a bookkeeping parameter without any direction. This puzzle has led to an unending series of controversies. This may be called the time paradox. It is interesting that the time paradox was only identified in the second half of the 19th century. It was then that the Viennese physicist Ludwig Boltzmann tried to emulate what Charles Darwin had done in biology and to formulate an evolutionary approach to physics. But at that time, the laws of Newtonian physics had been accepted as expressing the ideal of objective knowledge. As they imply the equivalence between past and future, any attempt to confer on the arrow of time a fundamental significance was resisted as a threat to the ideal of objective knowledge. Newton's laws were considered final in their domain of application, somewhat as quantum mechanics is today considered to be final by many physicists. How then can we introduce unidirectional time without destroying these amazing achievements of the human mind?

How then to make the bridge with dynamics? We shall describe two popular procedures.

It has been well known ever since the pioneering work of Gibbs and Einstein that we can describe dynamics from two points of view. On the one hand, we have the individual description in terms of trajectories in classical dynamics, or of wavefunctions in quantum theory. On the other hand, we have the collective statistical description in terms of ensembles represented by a probability distribution ρ (a probability density in classical mechanics or a density operator in quantum theory).

The probability ρ satisfies a well-defined equation both in classical and quantum theory. This is the Liouville equation, which is the starting point of statistical physics and which we shall study in the subsequent sections of this paper. The Ehrenfests[3] have introduced, in addition to ρ (called the "fine-grained" distribution), a coarse-grained distribution, ρ_{cg}, which results from averaging ρ over the microscopic states. It is straightforward to see that this coarse-grained distribution leads to equilibrium in the future $t > 0$ as well as in the past $t < 0$, because as the laws of dynamics are time reversible, every conclusion obtained from ρ_{cg} for the future $t > 0$ would be valid for the past $t < 0$. Moreover, the introduction of ρ_{cg} introduces arbitrary approximations and a loss of information. Adopting this point of view, we ourselves assume the responsibility for the appearance of the arrow of time. There is also the "cosmological" argument. For example, in his *Lectures on Physics*, Feyman[4] wrote: "For some reason, the universe at one time had a very low entropy ... that is the origin of all irreversibility ... ." This argument is somewhat strange. Whatever the past history of our universe, we observe today both reversible, time-symmetric processes as well as irreversible processes. Our task, therefore, is to understand the origin of the difference between reversible and irreversible processes that exist at present whatever the assumptions on cosmology.

In our opinion, the only possibility is a formulation of the laws of nature which explicitly includes time symmetry breaking and a characterization of the systems that lead to irreversible processes. Therefore, let us first consider in more detail what we may call a "law of nature."

LAWS OF CLASSICAL AND QUANTUM MECHANICS

As is well known, the laws of classical mechanics describe evolution in terms of point transformations. A point ω in phase space is transformed after a time t into the point $S_t\,\omega$:

$$\omega \mapsto S_t\,\omega \tag{1}$$

In quantum mechanics the situation is different. As is well known the basic equation is the Schrödinger equation:

$$\frac{\partial\psi}{\partial t} = -iH_{\mathrm{op}}\psi \tag{2}$$

The time change is determined by the action of the Hamiltonian operator on the wavefunction ψ. In order to see this action, we need the spectral analysis of the operator H_{op}, that is, the determination of its eigenfunctions and eigenvalues, for example (discrete spectrum),

$$H_{\mathrm{op}} = \sum_n |u_n\rangle\omega_n\langle u_n| \tag{3}$$

where the $|u_n\rangle$ (and the conjugates $\langle u_n|$) are the eigenfunctions and ω_n the corresponding energy levels.

Traditionally,[5] quantum theory was associated with Hilbert space, that is, with functions that are square integrable:

$$\int_{-\infty}^{+\infty} dx |f(x)|^2 < \infty \tag{4}$$

The solution $\Psi \mapsto U_t \Psi$ of the Schrödinger Equation **(2)** preserves the scalar product:

$$\langle f_i, f_j \rangle = \int_{-\infty}^{+\infty} dx\, f_i^*, f_j,$$

Therefore, U_t is a unitary group.

An essential point, to which we shall come back several times, is that the spectral decomposition, Equation **(3)**, depends on the function space. The Hamiltonian operator is "Hermitian" and has therefore only real eigenvalues in the Hilbert space. That leads to eigenfunctions $e^{\pm i\omega t}$ which are time symmetric as they are also eigenfunctions of the unitary group U_t: $U_t\, |u_n\rangle = e^{\pm i\omega_k} |u_n\rangle$.

This symmetry breaks, however, when we extend the evolution beyond the Hilbert space and consider a wider class of functions (often called generalized functions[6,7]). A simple example is the δ-function.[8] As is well known, we have

$$\int dx\, f(x)\delta(x) = f(0) \tag{5}$$

Spectral analysis of operators is the natural tool for the statistical problems associated with the time evolution of the statistical distribution ρ in classical systems as well as for the ones discussed in the Introduction.

In a famous article B.O. Koopman[9] showed that the evolution of probability densities of classical systems is described by a unitary group U_t implemented by the point transformation S_t (Eq. 1):

$$U_t\rho(\omega) = \rho(S_t^{-1}\omega) \tag{6}$$

for all functions ρ in the Hilbert space of square-integrable phase densities. The two descriptions in terms of trajectories and in terms of ensembles involving ρ are equivalent.[10] But this is usually no longer so when we go outside the Hilbert space. Examples will be given in the sections that follow.

In both classical and quantum mechanics, ρ satisfies the Liouville–von Neumann equation (L-N equation)

$$\frac{\partial \rho}{\partial t} = -iL\rho \quad \text{or} \quad \rho(t) = U_t\rho(0) = e^{-iLt}\rho(0) \tag{7}$$

In classsical dynamics L is the differential operator acting on the Hilbert space of square integrable density functions,

$$L\rho = -i\frac{\partial H}{\partial p}\frac{\partial \rho}{\partial q} + i\frac{\partial H}{\partial q}\frac{\partial \rho}{\partial p}$$

whereas in quantum mechanics L is the commutator with the Hamiltonian operator H_{op} acting on the Hilbert-Schmidt space of density operators:

$$L\rho = [H_{op}, \rho]$$

The L-N operator L is Hermitian and e^{-iLt} unitary. As long as we stay in the Hilbert space, the L-N equation gives nothing new with respect to the classical (1) or quantum mechanical (2) descriptions. There is no directed flow of time, but when we go outside the Hilbert space we find spectral decompositions of L that include time symmetry breaking. The L-N equations lead then to new solutions that can no more be implemented by trajectories or wavefunctions. We obtain, then, new dynamical laws that provide the microscopic basis for irreversible processes.

DETERMINISTIC CHAOS: THE BAKER TRANSFORMATION

For the first example we will consider deterministic chaos, in which two trajectories, set as closely as we choose at time $t = 0$, diverge exponentially as time goes on (the Lyapounov exponents). The simplest example that captures the essential characteristics of classical systems is the well-known Baker transformation of the unit square.[1]

Let us begin with a square with sides of length 1; then we cut it in half and build a new square. If we examine the lower part of the square, we see that after one iteration of this process (or mapping), it splits into two bands (see FIG. 1). Moreover, the transformation is reversible. The inverse transformation, which first reshapes the square into a rectangle with length ½ and height 2, returns each point to its initial position. For the Baker map, the equations of motion are very simple. At each step, the coordinates (x, y) become $(2x, y/2)$ for $0 \le x \le 1/2$ and $(2x - 1, (y + 1)/2$ for $1/2 < x \le 1$. To obtain the inverse Baker transformation, we only have to permute x and y.

On the Baker map, the two coordinates play different roles. The horizontal coordinate x is the expanding coordinate, as it is multiplied by 2 (mod 1) at each iteration. The area of the square is preserved, because we have the contracting coordinate y. In the transverse direction, the points draw closer together while the square is being flattened into a rectangle. Because the distance between two points along the horizontal coordinate x doubles with each transformation, it will be multiplied by 2^n after n transformations. If we rewrite 2^n as $e^{n\log 2}$, because the number n of transformations measures time, we see that the Lyapunov exponent is log2.

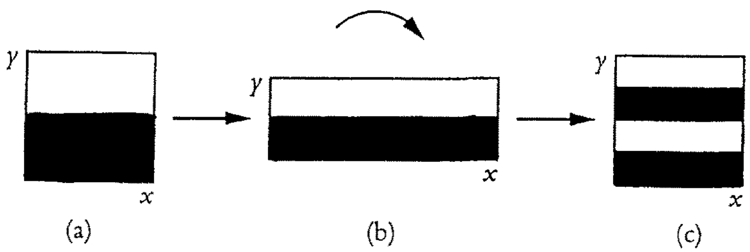

FIGURE 1. The Baker transformation.

There is also a second Lyapunov exponent with the negative value –log2, which corresponds to the contracting direction y (see FIG. 1). Successive iterations of the Baker transformation lead to fragmentation of the shaded and unshaded areas, producing an increasing number of disconnected regions. Let us consider the successive probability distributions. We have

$$\rho_{n+1} = U\rho_n \tag{8}$$

U is called the "Perron-Frobenius" operator.[11] It has been recently shown that there exist two spectral representations for the evolution U^n, $n \in Z$. The first one is in Hilbert space and can be written

$$U^n = \int_{-\infty}^{+\infty} dk\, e^{ikn} |f_k\rangle\langle f_k| \tag{9}$$

Because the eigenvalues are e^{ikn}, there is no time symmetry breaking. This solution is equivalent to the solution of the equation of motion.

But it has been recently established[12,13] that there is a second spectral decomposition outside the Hilbert space:

$$U = \sum_{n=0}^{\infty} |F_n\rangle \frac{1}{2^n} \langle \tilde{F}_n| \tag{10}$$

(We simplify somewhat the actual situation, which involves Jordan blocks; see Appendix.) The main point is that the eigenfunctions F_n and $\tilde{F}_n$ are distributions. The eigenvalues $1/2^n$ are expressing the rates of approach to equilibrium.[d] Here we have a formulation of dynamics that includes the arrow of time. Note that Equation (10) leads to

$$U\rho = \sum_{n=0}^{\infty} |F_n\rangle \frac{1}{2^n} \langle \tilde{F}_n | \rho\rangle \text{ for } t > 0 \tag{11}$$

$\langle \tilde{F}_n|$ being a distribution, this formula is only meaningful when ρ is not a distribution. $\langle \tilde{F} | \rho\rangle$ is the scalar product of $\tilde{F}$ with ρ, such as $\int dx \tilde{F}(x)\rho(x)$, and we have seen in the section on laws of classical and quantum mechanics that products of distributions may lead to divergence. This excludes trajectories that are δ-functions. The initial condition has to be a region of finite dimension (as small as we want). The fundamental quantity is now the probability distribution. Irreversibility is associated with semigroups. The probability distribution ρ tends toward equilibrium for $t \to \infty$. Using Equation (11), $\rho \to \rho_{eq}$, $t \to \infty$.

There is also a spectral decomposition in which $\rho \to \rho_{eq}$ for $t \to -\infty$. Equilibrium would be reached in the past. We have two different semigroups corresponding to different test functions for the distributions. (More details are given in the APPENDIX.) In accordance with our observations, we choose the semigroup (Eq. 11) that leads to equilibrium in the future.

[d] $1/2^n = e^{-n \lg 2}$; by comparison with Equation (9) this corresponds to k imaginary.

These conclusions can be extended to an important class of dynamic systems, the so-called K flows (K for Kolmogorov). Both formulations (Eq. 10 and Eq. 11) of dynamics are rigorous. Equation (11) applies to the realistic initial condition which corresponds to a finite area. Equation (11) gives us the first example of a classical dynamical law that is not reducible to trajectories and contains the arrow of time.

POINCARÉ INTEGRABILITY

As is well known, a dynamical system is characterized in terms of the kinetic energy of its particles plus the potential energy due to their interactions. The simplest example would be free, noninteracting particles for which there is no potential energy and the calculation of trajectories is trivial. Such systems are by definition integrable. Poincaré then asked the questions, Are all systems integrable? Can we choose suitable variables to eliminate potential energy? By showing that this was generally impossible, he proved that dynamic systems were generally nonintegrable. Poincaré not only demonstrated nonintegrability, but also identified the reason for it: the existence of resonances between the degrees of freedom. We are all more or less familiar with the concept of resonance from elementary acoustics. Also, all radiation processes are related to resonances. Think about atoms where excited states occur when we introduce radiation with frequency ω_k, which coincides with the frequency $\omega_1 - \omega_0$ separating the excited state $|1\rangle$ from the ground state $|0\rangle$. We shall come back to this problem in the section on particles, fields, and irreversibility. The significant fact is that most dynamic systems are not integrable.

In the following section, we shall concern ourselves primarily with nonintegrable, large Poincaré systems (LPS). Poincaré resonances are associated with frequencies corresponding to various modes of motion. A frequency ω_k depends on the wavelength k. (Using light as an example, ultraviolet has a higher frequency ω and shorter wavelength k than infrared light.) When we consider nonintegrable systems in which the frequency varies continuously with the wavelength, we arrive at the very definition of LPS. This condition is met when the volume in which the system is located is large enough for surface effects to be ignored. This is why we call these systems *large* Poincaré systems.

Thermodynamics and entropy are also usually associated with large systems containing a large number of particles. We shall now consider more closely the dynamics of these systems.

THERMODYNAMIC SYSTEMS

Thermodynamic systems are characterized by a large, practically infinite number of degrees of freedom. Note that it is only in the so-called thermodynamic limit

$$N \to \infty \quad V \to \infty \quad \frac{N}{V} = C: \quad \text{finite} \qquad \textbf{(12)}$$

that we obtain a correct formulation of phase transitions.[14] We want to consider the effect of the thermodynamic limit for dynamic systems. We shall show that the interaction between the degrees of freedom leads indeed beyond the Hilbert space structure.

In the thermodynamic limit, we require in addition that there are extensive variables such as the average potential energy U:

$$\lim_{N \to \infty} \frac{\langle U \rangle}{N} = \text{finite} \tag{13}$$

and intensive variables such as the pressure p

$$\lim_{N \to \infty} p = \text{finite} \tag{14}$$

We have recently considered the examples of anharmonic lattices[16] as well as of large systems of interacting particles.[17,18] Let us summarize our results for one-dimensional anharmonic lattices. The equilibrium distance a between two neighboring lattice sites being given, Equation (12) reduces to the limit $N \to \infty$ (as $V = aN$).

Harmonic lattices correspond to integrable systems, as there is no coupling between the normal modes. The potential energy U is given by the quadratic form

$$U - U_0 = \frac{1}{2}\sum_{nn'} A_{nn'} u_n u_{n'} \tag{15}$$

where u_n is the displacement of the nth atom from its equilibrium position (we impose cyclic boundary conditions $u_{n+N} = u_n$). We may solve the dynamical problem either by point transformations using angle–action variables α and J or by the Liouville equation introducing the Hilbert space structure. With obvious notations

$$\rho(J, \alpha) = \sum \rho_{\{n\}}(J) e^{i\Sigma n_k \alpha_k} \tag{16}$$

The Hilbert norm is therefore

$$\|\rho\|^2 = \int dJ \sum_{\{n\}} |\rho_{\{n\}}(J)|^2 \tag{17}$$

To obtain a finite Hilbert norm for $N \to \infty$, well-defined conditions have to be satisfied. Indeed, the norm (Eq. 17) contains terms with $n_k = \ldots, -1_k, 0, 1_k, 2_k, \ldots$

$$\|\rho\|^2 = |\rho_0|^2 + \sum_k |\rho_{1_k}|^2 + \sum_{kk'} |\rho_{1_k 1_{k'}}|^2 + \sum_{kk'k''} |\rho_{1_k 1_{k'} 1_{k''}}|^2 + \ldots \tag{18}$$

which have to converge for $N \to \infty$. This implies

$$\rho_0 \approx 0(1), \quad \rho_{1_k} \approx \frac{1}{\sqrt{N}}, \quad \rho_{1_k} \rho_{1_{k'}} \approx \frac{1}{N} \tag{19}$$

as well as

$$\rho_{1_k 1_{k'} 1_{k''}} \approx \frac{1}{N} \tag{20}$$

for the components with $k + k' + k'' = 0$ or a vector on the reciprocal lattice, and

$$\rho_{1_k 1_{k'} 1_{k''}} \approx \frac{1}{N^{3/2}} \tag{21}$$

for the components not on the reciprocal lattice.

However, if $\rho_{1_k 1_{k'} 1_{k''}}$ is too large, such as $N^{-1/2}$ instead of $1/N$, the Hilbert norm diverges.

Consider then anharmonic lattices. The potential energy is, at the lowest order,

$$U - U_0 = \frac{1}{2}\sum_{nn'} A_{nn'} u_n u_{n'} + \frac{1}{6}\sum_{nn'n''} B_{nn'n''} u_n u_{n'} u_{n''} \tag{22}$$

Higher order terms in the displacement would not introduce any change. The Hamiltonian H becomes

$$H = H_0 + \lambda V \tag{23}$$

where we have introduced the parameter λ for the coupling constant.

We may calculate the value of the average potential energy.

$$\langle V \rangle \approx \sum_{kk'k''}' \int dJ V_{kk'k''} \rho_{1_k 1_{k'} 1_{k''}} \tag{24}$$

Using the value (Eq. 24) of the three-mode correlations (Eq. 20) we obtain

$$\langle V \rangle \approx \sqrt{N} \tag{25}$$

which is incompatible with Equation (13). To obtain Equation (13), we need stronger correlations

$$\rho_{1_k 1_{k'} 1_{k''}} \approx \frac{1}{\sqrt{N}} \tag{26}$$

but then the Hilbert space norm diverges. We refer to the original papers for the description how ρ is "ejected" from the Hilbert space as the result of the interactions.

Our conclusion applies as well to systems of interacting particles in the thermodynamic limit and even to interacting fields (see the section on particles, fields, and irreversibility). However, the extension of the functional space outside the Hilbert space alone does not imply time symmetry breaking. For this, we need in addition nonintegrability in the sense of Poincaré, as applied to large thermodynamic systems (LPS). As is well known, Poincaré's nonintegrability is associated with resonances. This leads to new processes taking place at the statistical level.

We may have processes "destroying" correlations as represented graphically in FIGURE 2. We may also have processes creating correlations (FIG. 3).

As the result of Poincaré resonances, we may have in addition processes relating states corresponding to the same degree of correlation (i.e., ρ_0 to ρ_0) (see FIG. 4). We have called these collision processes.

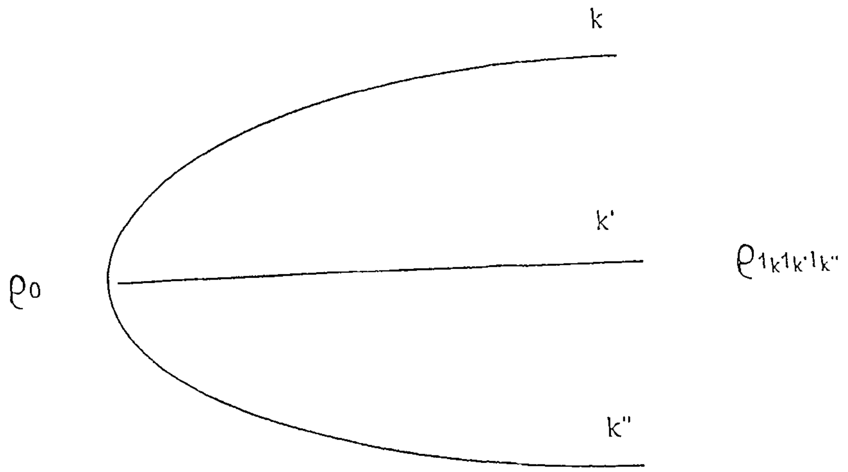

FIGURE 2. Destruction of correlations leading from a three-mode correlation $\rho_{1_k 1_{k'} 1_{k''}}$ to the vacuum of correlation ρ_0.

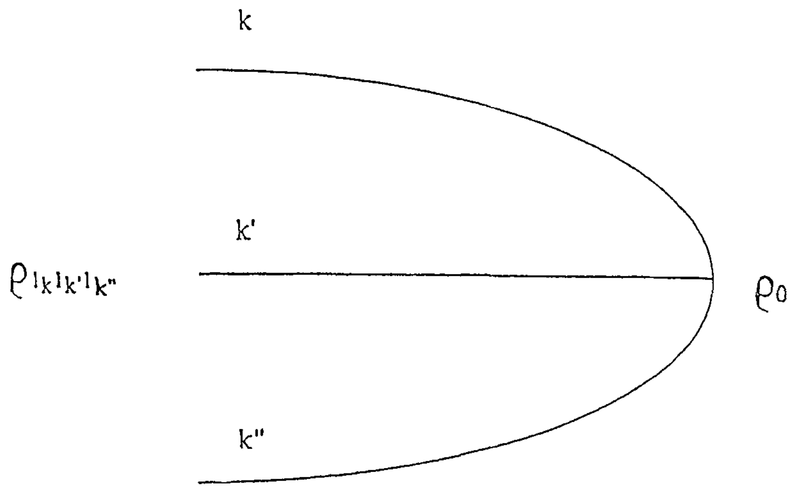

FIGURE 3. Creation of correlations leading from ρ_0 to $\rho_{1_k 1_{k'} 1_{k''}}$.

The collision processes destroy the trajectory description. In FIGURES 2–4, each vertex contains derivative operators $\partial/\partial J$. FIGURE 4 leads therefore to processes containing second-order operators $\partial^2/\partial J^2$ characteristic of diffusive processes.

The main result is that the dynamics of large Poincaré's systems (LPS) are ruled by "Langevin-type" interactions, as they appear, for example, in the Fokker-Planck equation for classical dynamics and in the Pauli's master equation for quantum mechanics. We may qualitatively describe the situation by imagining each observable corresponding to a finite number of degrees of freedom "swimming" in the infinite sea associated with the thermodynamics limit.

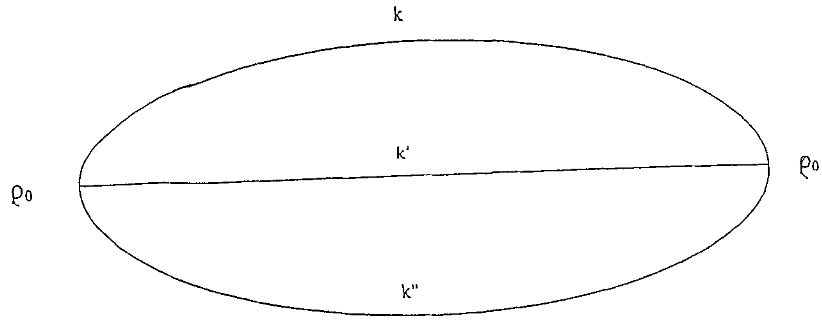

FIGURE 4. Collision processes relating to ρ_0 to ρ_0.

We see that LPS involve new effects not considered in Newtonian or quantum mechanics. As in the case of deterministic chaos, we obtain a formulation of dynamics in terms of probabilities that breaks the time symmetry. LPS can therefore be integrated, not on the level of trajectories or wavefunctions, but at the level of probabilities. This is an important novel aspect we shall briefly describe in the next section.

All these results can easily be extended to quantum mechanics.[18] We then obtain a formulation of quantum mechanics outside the Hilbert space in which the fundamental quantities are density operators and are no longer wave amplitudes.

To go further we have to introduce a class of functions ρ outside the Hilbert space. This class has to include the equilibrium distribution and should not be invariant under time inversion. (This is in contrast with Boltzmann's molecular chaos; indeed, Boltzmann's "molecular chaos" already introduces a privileged direction of time). A class of distributions satisfying these criteria has already been introduced in the monograph "Nonequilibrium Statistical Mechanics"[19] (see also Ref. 20) and is described in detail in recent publications.[16–18]

We shall now describe briefly the spectral representation of the L-N operator when extended outside the Hilbert space.

DYNAMICS OF LARGE POINCARÉ SYSTEMS

We have recently solved the eigenvalue problem for the L-N operator extended outside the Hilbert space. Let's briefly summarize some of the main results. For a system of interacting particles L is given by

$$L = L_0 + \lambda L_V \tag{27}$$

using obvious notations. In classical mechanics L_0 admits eigenfunctions of the form $L_0\ \varphi_k = kp/m\ \varphi_k$, $\varphi_k = e^{ikv}$and a complete set of eigen-projection operators P where

$$L_0 \overset{\vee}{P} = \overset{\vee}{P} L_0 \tag{28}$$

ν is the number of nonvanishing k vectors. More explicitly, we shall use the notation $\overset{\nu}{P}_\alpha$ where α denotes the particles associated with nonvanishing wavevectors and ν the value of the wavevectors. They satisfy the usual completeness and orthonormality relations.

We also introduce the projection operators $\overset{\nu}{Q}_\alpha$:

$$\overset{\nu}{Q}_\alpha = 1 - \overset{\nu}{P}_\alpha, \quad \overset{\nu}{P}_\alpha \overset{\nu}{Q}_\alpha = \overset{\nu}{Q}_\alpha \overset{\nu}{P}_\alpha = 0 \tag{29}$$

In particular $\overset{0}{P}_\rho$ is the velocity distribution that is factorized in a product of individual velocity distribution functions. As is well known, the evolution is non-Markovian for thermodynamic systems. We have the so-called master equation for $\overset{0}{P}$, which can be found in many books.[19,21]

$$i\frac{\partial \overset{0}{P}_\rho}{\partial t} = \int_0^t dt' \tilde{\psi}(t') \overset{0}{P} \rho(t-t') + \overset{0}{D}(t, \rho(0)) \tag{30}$$

$\tilde{\psi}(t)$ is the time-dependent collision operator leading from $\overset{0}{P}$ to $\overset{0}{P}$ (see FIG. 4) and the "destruction fragment" leading from $\overset{\mu}{P} \to \overset{0}{P}$ $(\mu \neq 0)$. This formula includes memory effects ("non-Markovian" behavior). This formula was established by Résibois and Prigogine in 1961.[21] As a result we have three time periods: the Zenon time, the exponential time period, and the long-tail time. A similar classification was introduced earlier for unstable particles.[22]

The experimental discovery of long-tail effects by Alder[23] in the sixties has led to a deep change in the kinetic theory of fluids. The classical kinetic theories (Fokker, Planck, Boltzman) do not contain long tails. This is the subject of the mode–mode coupling theory, which is still in a rather early stage.[21] We shall come back to this question at the end of this section.

In a recent paper[18] we obtained the spectral decomposition of L when applied to the class of functions of the section on Poincaré integrability. We will only quote the result here. The spectral decomposition of the Liouville operator can be written in the form

$$L = \sum_{\nu\alpha} \left| \overset{\nu}{F}_\alpha \gg \overset{\nu}{z}_\alpha \ll \overset{\nu}{\tilde{F}}_\alpha \right| \tag{31}$$

Therefore, nonintegrable systems (in the sense of Poincaré) can be integrated on the Liouville level. The eigenvalues $\overset{\nu}{z}_\alpha$ are complex and satisfy the inequality Im $\overset{\nu}{z}_\alpha \le 0$. There is, therefore, time symmetry breaking. The diagonalization has been obtained on the level of distribution functions outside the Hilbert space. This representation is *nonreducible* in the sense that it involves probabilities and cannot be reduced to trajectories or wavefunctions.

Of course, one could also obtain a spectral decomposition with Im $\overset{\nu}{z}_\alpha \ge 0$ which leads to equilibrium in the past. The main point is that the two spectral decompositions are distinct, and they have different domains. The spectral decomposition leads to the basic intertwining relation

$$\Lambda L \Lambda^{-1} = \Theta \tag{32}$$

The operator L is nonunitary ($L^+ \neq L^{-1}$). The collision operator Θ is diagonal in the $\overset{\nu}{P}_\alpha$ representation

$$\Theta = \sum_\nu P^\nu \Theta P^\nu = \sum_\nu \overset{\nu}{\Theta} \tag{33}$$

Also, we can obtain a complete set of projectors $\overset{\nu}{\Pi}$ for the Liouville operator L.

$$L\overset{\nu}{\Pi} = \overset{\nu}{\Pi}L \tag{34}$$

$$\overset{\nu}{\Pi} = \Lambda^{-1}\overset{\nu}{P}\Lambda \tag{35}$$

It is quite remarkable that each projection $\overset{\nu}{P}\,\overset{\nu}{\Pi}$ leads to a Markovian process that we can write in the following form:

$$\frac{\partial \overset{\nu}{P}\,\overset{\nu}{\Pi}\rho}{\partial t} = -i\,\overset{\nu}{\Theta}\,\overset{\nu}{P}\,\overset{\nu}{\Pi}\rho \tag{36}$$

There is an infinite number of Markovian processes because each distribution function, such as $\overset{0}{P}\rho$ can be written as a superposition of the projection operators $\overset{\nu}{\Pi}$.

$$\overset{0}{P}\rho = \sum_\nu \overset{0}{P}\,\overset{\nu}{\Pi}\rho \tag{37}$$

We want to emphasize the special role of $\overset{0}{\Pi}$. Indeed, $\overset{0}{\Pi}$ is the only part of the distribution function ρ that contains vanishing eigenvalues $\overset{0}{z}_\alpha = 0$. Therefore, it is not astonishing that the equilibrium distribution lies in the $\overset{0}{\Pi}$. At equilibrium,

$$\rho_{eq} = \overset{0}{\Pi}\rho_{eq} = (\overset{0}{C} + \overset{0}{P})\overset{0}{\rho} \tag{38}$$

Also, all classical kinetic equations lie in $\overset{0}{\Pi}$ as well as all invariants of motions such as the Hamiltonian H.

$$H = \overset{0}{\Pi}H = H_0 \tag{39}$$

Causality requires, however, that we take into account $\overset{2}{\Pi}$ (and if necessary $\overset{\nu}{\Pi}$ for $\nu > 2$) for nonequilibrium processes. There are additional points that are important. Instead of the non-Markovian Equation (30), we obtain a superposition of Markovian processes. In this way, the questions left open by the mode–mode coupling approach can be solved (T. Petrosky, private communication). Our approach permits us to introduce causality into kinetic theory. Indeed, $\overset{0}{\Pi}$ leads to correlations over arbitrary distances. Causality is obtained by including the effect of $\overset{2}{\Pi}$ (therefore, $\overset{0}{\Pi}\rho + \overset{2}{\Pi}\rho$). To illustrate this statement consider the time evolution of the binary correlation $g_{12}(r, t)$ with $g_{12}(r, t = 0) = 0$ The results are represented in FIGURES 5 through 7, which show the evolution of the binary distribution functions $g_{12}(r, t)$. Therefore, the classical kinetic theories that retain only $\overset{0}{\Pi}$, always violate causality in the propagation of irreversible processes. To retain $\overset{0}{\Pi}$ is only correct for local properties far from the propagating edge.

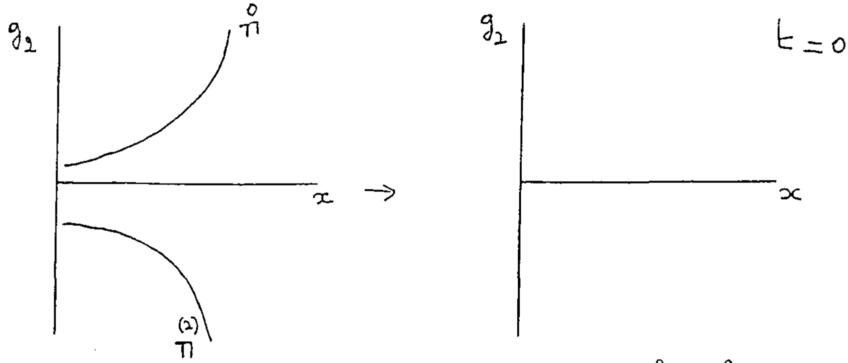

FIGURE 5. $g_2\,(r, t)$ for $t = 0$. (Complete compensation between $\overset{0}{\Pi}$ and $\overset{2}{\Pi}$.)

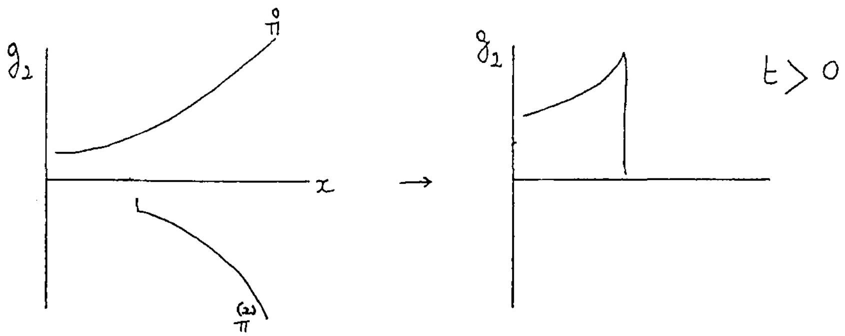

FIGURE 6. $g_2\,(r, t)$ for $t = 0$. (Partial compensation between $\overset{0}{\Pi}$ and $\overset{2}{\Pi}$.)

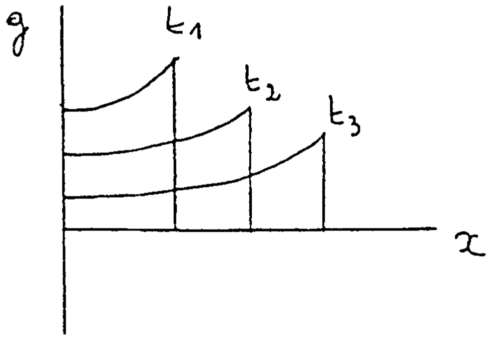

FIGURE 7. Time evolution of $g_2\,(r, t)$, $t_1 < t_2 < t_3$.

Let us summarize this section. The time evolution of thermodynamic systems is given by the L-N equation applied to a class of generalized functions ρ outside the Hilbert space. In contrast with the Baker transformation studied in the section on deterministic chaos, where we had both a time-reversible and a time-irreversible formulation of dynamics, we have for LPS only a formulation of dynamics in which the central quantity is the probability and which has a broken time symmetry. We have achieved in this way a microscopic formulation of the arrow of time. Once this is done, we can construct this entropy on a microscopic basis, but we cannot present this within the framework of this article.

We want now to demonstrate briefly that our approach has fundamental consequences for basic aspects of modern physics.

PARTICLES, FIELDS, AND IRREVERSIBILITY[e]

Atomic, nuclear, and high energy physics deal with excited states, or unstable particles. These objects cannot be eigenfunctions of the Hamiltonian (in contrast with the ground-state or with stable-state particles). Dirac has recognized this situation very well.[8]

> The fact that we had to use the word "approximately" in stating the conditions required for the phenomena of emission and absorption to be able to occur shows that these conditions are not expressible in exact mathematical language. One can give meaning to these phenomena only with reference to a perturbation method. They occur when the unperturbed system (of scatterer plus particle) has stationary states that are closed. The introduction of the perturbation spoils the stationary property of these states and gives rise to spontaneous emission and its converse absorption.

Let us describe in detail this difficulty using the well-known Friedrichs model, which describes the interaction of a two-level atom with radiation. In this model we have a discrete state $|1\rangle$ representing a bare particle coupled to continuous states $|k\rangle$ corresponding to field modes.[1] The Hamiltonian operator is

$$H = H_0 + \lambda V = |1\rangle\, \omega_1 \,\langle 1| + \sum_k |k\rangle\, \omega_k \langle k| + \lambda \sum_k V_k(|k\rangle\langle 1| + |1\rangle\langle k|) \tag{40}$$

The states $|1\rangle$ and $|k\rangle$ are eigenfunctions of H_0. The effect of the perturbation is to lead to the emission or the absorption of a photon (this model neglects virtual transitions). There are two situations, according to whether ω_1 is less than or greater than zero (FIG. 8).

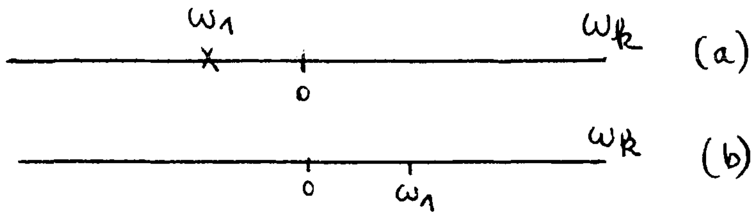

FIGURE 8. **(a)** Bound state; **(b)** resonance.

[e]This section is a summary of a paper by T. Petrosky, G. Ordonez, and I. Prigogine that will appear soon in *Physica A*.

For $\omega_1 < 0$ we have a bound state; for $\omega_1 > 0$ the state $|1\rangle$ will decay, emitting a photon. The case $\omega_1 < 0$ can be treated easily. The interaction transforms $|1\rangle$ into $|\varphi_1\rangle$ which is an eigenstate of H:

$$H|\varphi_1\rangle = \tilde{\omega}_1 |\varphi_1\rangle \tag{41}$$

The exact expression for $|\varphi_1\rangle$ can be shown to be[24]:

$$|\varphi_1\rangle = N_1^{1/2}\left[|1\rangle - \sum_k \frac{\lambda V_k}{\omega_k - \tilde{\omega}_1}|k\rangle\right] \tag{42}$$

where N_1 is a normalization constant.

Formula (42) clearly shows the photon cloud $|k\rangle$ surrounding $|1\rangle$. Similarly we have the dressed photon. The state $|1\rangle$ evolves time going on to $|\varphi_1\rangle$. FIGURE 9 gives an example of the photon distribution around the stable particle. (For the numerical simulation attributed to G. Ordonez, we use $\lambda = 0.1$ $V_k = L^{-1/2}$, $L = 400$. One clearly sees the cloud surrounding $|1\rangle$.

The two smaller peaks traveling away from the particle are superpositions of dressed photons. These photons are created because the energy of the bare particle is greater than the energy of the dressed particle $\omega_1 > \tilde{\omega}_1$. As the dressed particle emerges, the photons carry away the excess energy.

Now let us consider the case of resonance (see FIG. 8). Friedrichs has shown that then we have the spectral decomposition[24]

$$H = \sum \omega_k |\varphi_k^F\rangle\langle\varphi_k^F| \tag{43}$$

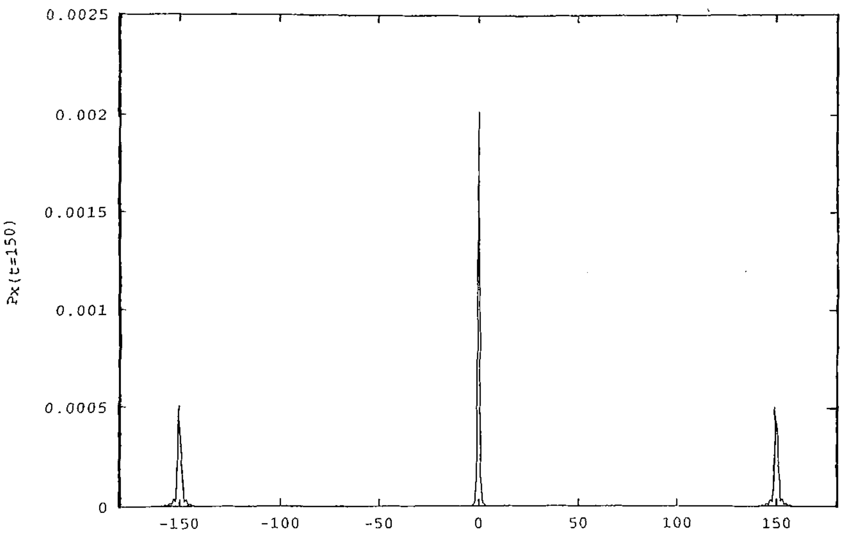

FIGURE 9. Photon distribution around a stable particle ($t = 150$).

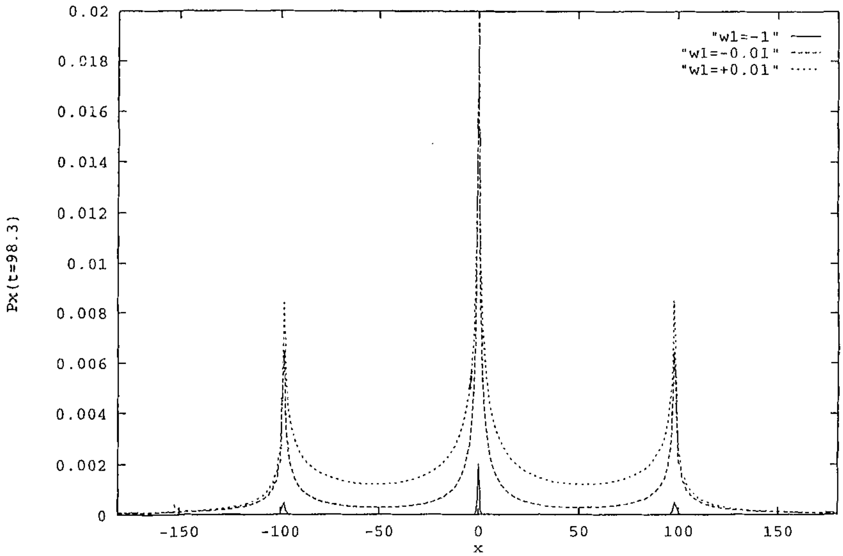

FIGURE 10. Photon distribution near the transition point.

where the $|\varphi_k^F\rangle$ are outgoing waves satisfying completeness and orthonormality. The excited state does not appear explicitly in Equation (43).

As mentioned previously (see FIG. 8), the transition from bound state to resonance takes place at $\omega_1 = 0$. We may visualize the transition through the computer plots shown in FIGURE 10.

In FIGURE 10, we plot the photon space distribution for three cases: (a) $\omega_1 = -1$, (b) $\omega_1 = -0.01$, and (c) $\omega_1 = +0.01$. Case (a) we have already considered. It is given here for reference. Cases (b) and (c) are close to the branching point $\omega_1 = 0$. Case (b) corresponds to the stable particle and (c) to the unstable particle.

It is obvious that the photon distributions are very similar. The resonance also has a photon cloud, but this state (which is the continuation of $|\varphi_1\rangle$) is not an eigenfunction of H. It is interesting how this state is formed. At $t = 0$, we have a wave packet approaching the atom in the ground state. After the contact the atom is excited and then decays exponentially.

Note the asymmetry between the formation period and the decay. This clearly indicates the irreversible character of the process. The question is, What is the nature of the "decaying state" (which appears for $t = 500$ in FIGURE 11)? We can apply the Liouville formulation and show that this state is in Π subdynamics. It is therefore a combination of eigenfunctions of the L-N operator. The main point is that the resonances are described by density operators (and not wavefunctions) that evolve irreversibly. The central quantity is again probability.

This example shows that our theory is an extension of quantum theory, which avoids the difficulty stated by Dirac. It is also interesting to notice that irreversibility appears on the microscopic level. Resonances and excited states are closely related to unstable particles. Let us close this section with some remarks on the relationship between fields and particles.

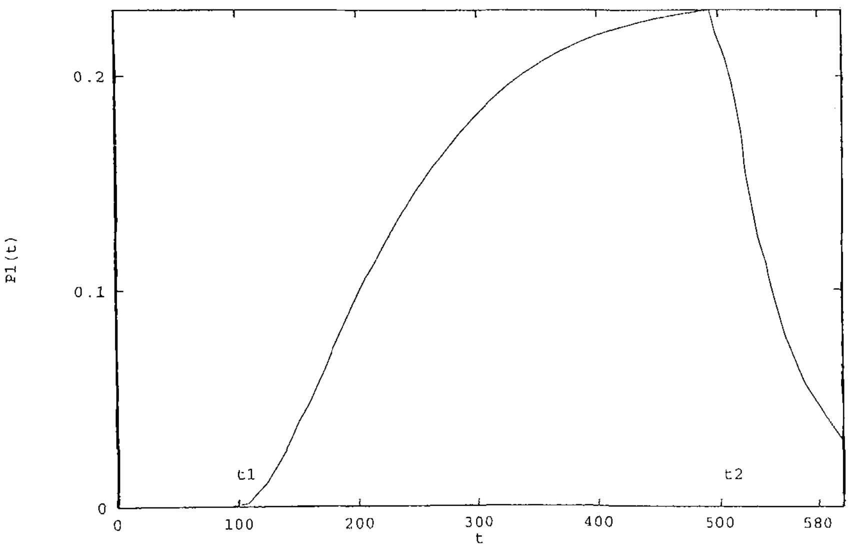

FIGURE 11. Formation decay of a bare particle.

A fundamental problem of modern physics is the relationship between particles and fields. This is the central problem of second quantization. A free quantum field is a *superposition of oscillators*. For the electrodynamic field, the corresponding particles are the photons. We have $H = \Sigma_k \omega_k (n_k + ½)$. Free quantum fields are integrable systems, and the occupation number n_k are invariants. However, as there are no free fields in nature, interactions lead to *nonintegrable systems* where the occupation numbers vary in time.

Nonintegrable fields are systems of an infinite number of degrees of freedom with persistent interactions. There is therefore a strong analogy with thermodynamic systems. Exactly as for thermodynamic systems, we can integrate the equations of motion on the Liouville level of probabilities. (In our presentation we avoid ultraviolet divergencies by means of suitable form factors.) Exactly as for thermodynamic systems, we have to go outside the Hilbert space. (The condition $\langle V \rangle / N$ finite is replaced here by the condition that the zero point energy E_0 of interesting fields E_0 satisfies the condition $V \to \infty$, $E_0/V =$ finite.)

In this way, field theory is deeply changed. According to G. Källen:

> It appears to me that one basic feature of a pure S-matrix theory and also of some of the more extreme versions of the axiomatic approach is just that one completely forgets the development in time. Of course, it is true that many experimental situations, perhaps nearly all of them, can conveniently be described in terms of scattering processes. However, a pure S-matrix theory goes further and assumes that everything can be described as a *scattering during an infinite time interval*.[25]

We can now overcome this difficulty and obtain an evolution equation valid for finite times. Moreover, this introduces time symmetry breaking, which explains the fact that most elementary particles are unstable.

FROM BEING TO BECOMING

The results summarized in this paper show that irreversibility plays a much more important role than had been previously anticipated. The most striking result concerns the dynamics of large systems, thermodynamic systems and fields. Here the laws of classical physics or quantum physics are replaced by the probabilistic Liouville equation associated with the extended Liouville operator beyond the Hilbert space:

$$F = ma$$

$$\frac{\partial \psi}{\partial t} = -iH_{\text{op}}\psi \qquad \xrightarrow[N \to \infty]{} \qquad \frac{\partial \rho}{\partial t} = -iL^{\text{ext}}\rho$$

Here L^{ext} is the extension of the Liouville operator outside the Hilbert Space. Therefore, the basic laws of physics for large systems are radically different from the classical and quantum mechanics of integrable systems. Our results can be extended to relativity where the Poincaré group splits into two semigroups.[26,27] The main entity is probability, and the time symmetry is broken. Nature evolves as a semigroup. Note also that the conventional approach associated irreversibility and entropy with ensembles of particles, each of which if taken in isolation would satisfy the deterministic laws of classical or quantum mechanics. Now the particles themselves are the outcome of a time symmetry broken formulation except for the ground state.

The inclusion of irreversibility changes our view of nature. The future is no longer given. Our world is a world of continuous "construction" ruled by probabilistic laws and no longer a kind of automaton.

We are led from a world of "being" to a world of "becoming." Nevertheless, why nature has a broken time symmetry is a difficult question. It may be due to the interaction between gravitation and the other fundamental forces. But at this point we are at the frontiers of present science.

ACKNOWLEDGMENTS

We acknowledge Dr. Tornio Petrosky and Dr. Gonzalo Ordonez for their contribution to this work as well as the European Commission ESPRIT Project CTIAC 21042/DGIII, the "Communauté française de Belgique," the Belgian Interuniversity Attraction Poles, and the National Lottery of Belgium for their financial support.

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APPENDIX

Time-Asymmetric Spectral Decomposition of the Baker Transformation

The Brussels-Austin groups have shown[12,13] that there is also a new spectral decomposition of the Frobenius-Perron operator U of the Baker transformation involving Jordan blocks:

$$V = |F_{00}\rangle\langle\tilde{F}_{00}| + \sum_{\nu=1}^{\infty}\left\{\sum_{r=0}^{\infty}\frac{1}{2^{\nu}}|F_{\nu,r}\rangle\langle\tilde{F}_{\nu,r}|\sum_{r=0}^{\nu=1}|F_{\nu,r+1}\rangle\langle\tilde{F}_{\nu,r}|\right\}$$

The vectors $|F_{\nu,r})$ and $(f_{\nu,r}|$ form a Jordan basis

$$(f_{\nu,r}|V = \begin{cases} \frac{1}{2^{\nu}}\{\tilde{F}_{\nu,r}| + (\tilde{F}_{\nu,r}|\}, & r = 0, \ldots, \nu - 1 \\ \frac{1}{2^{\nu}}\{\tilde{F}_{\nu,r}|, & r = \nu \end{cases}$$

(A.1)

$$V|F_{\nu,r} = \begin{cases} \frac{1}{2^{\nu}}\{F_{\nu,r}) + |F_{\nu,r})\}, & r = 1, \ldots, \nu \\ \frac{1}{2^{\nu}}|F_{\nu,r}), & r = 0, \end{cases}$$

$$(\tilde{F}_{\nu,r}|F_{\nu',r'}) = \delta_{\nu\nu'}\delta_{rr'}$$

$$\sum_{\nu=0}^{\infty}\sum_{r=0}^{\nu}|F_{\nu,r})(\tilde{F}_{\nu,r}| = I$$

The principal vectors $\tilde{F}_{\nu,j}$ and $F_{\nu j}$ are linear functionals over the spaces $L_x^2 \times P_y$ and $P_x \times L_y^2$, respectively. Here, L_x^2 is the space of square integrable functions in the x-variable, and P_y is the space of polynomials in the y-variable.

As a result, the spectral decomposition (Eq. A.1) defines an extension of the Frobenius-Perron operator to the space of functionals over the test functions $L_x^2 \times P_y$. However, only the positive powers U^n, $n = 1, 2, \ldots$, can be extended to the same space. The negative powers U^n, $n = -1, -2, -3, \ldots$, can be extended to the space of linear functionals over the test functions: $P_x \times L_y^2$. Therefore the original unitary group U^n, $n = \pm 1, \pm 2, \ldots$, when extended, splits[13] into two distinct semigroups corresponding to the forward and backward direction of time. The computation of autocorrelation functions using the spectral decomposition (Eq. A.1) gives rise to polynomial contributions to the exponentially decaying components associated with the resonances 2^{-n}, as a result of the Jordan blocks structure. Apart from the intrinsic irreversibility and the natural decomposition of the evolution in terms of the decaying contribution associated with resonances, we can also prove[13] that the trajectories $\delta_{(xy)}(x',y') = \delta((x',y') - (xy))$ are excluded from the domain of the spectral decomposition (Eq. A.1), that is, we cannot compute the deterministic evolution associated with the initial condition localized at the point (x, y) because the expectation value,

$$(U^n\,\delta|f) = \int_0^1 dx \int_0^1 dy\ \ \delta((x, y) - B^{-n}(x', y'))f(x'y')$$

diverges. Therefore, the irreversible extension of Baker's dynamics is moreover intrinsically probabilistic. It allows only for predictions associated with probabilities. This is also another generic characteristic of the extended spectral decompositions of unstable or nonintegrable systems.

Time in Non-equilibrium Physics

Discussion of Ilya Prigogine with
Theodore Christidis

TC: The distinction of earlier and later is very mysterious. Either time is introduced by us, and it is psychological, or it is an objective property of nature. Did you ever discuss your views on time with physicists, like Bohr or Heisenberg?

IP: Yes, but they never expressed their opinion about my work. However, Bohr seemed to be very interested, when we discussed it in the 60's. But I could not see very strong reaction. You see, my own ideas were still not very clear. The successive stages of my work, see for example my book with Isabelle Stengers [4], were to make irreversibility a property of nature and not a property that you have to add to nature. There was always a difference between gravitation and irreversibility. For gravitation nobody doubts that it is part of nature and not introduced by us into nature. When we speak about irreversibility and probability, we mean that they are concepts that were traditionally introduced by us into nature. However, even this was no longer possible since quantum mechanics. All we can know about radioactivity is the mean life-time. Nobody can calculate how many atoms will disintegrate in a given interval. We calculate only averages. Therefore, quantum mechanics has rightly been said to mark the demise of determinism.

If we discuss about the famous Copenhagen School, we have to speak about the reaction of Pauli. I met Pauli in the Solvay Conference of 1954, where I presented the work with Klein on Harmonic oscillators [27]. He was quite impressed. Of course harmonic oscillator models can be solved at the level of interacting normal modes. It was Schroedinger who started working on this problem [28]. We continued actually his work.

The history of the problem is as follows: I was always interested in statistical mechanics, because I introduced entropy production [2–5] which also appears already in Boltzmann's description. I wanted to be sure that entropy production can be calculated from kinetic theory. My first work on the statistical theory of irreversibility, is the calculation of entropy production in the framework of kinetic theory. This started about 1949 and studying it further, I looked at how entropy production is modified because of the non-equilibrium conditions due to the non-linear character of the chemical reactions.

TC: It is amazing that at that time everybody was jumping into applications of quantum mechanics and quantum field theory. Why had you chosen to deal with thermodynamics?

IP: I was interested in thermodynamics, because thermodynamics is the science in which the arrow of time plays the key role.

TC: So, you did not care about these applications of quantum mechanics and all these new possibilities, because time was not involved?

IP: I was mainly interested in time, but I was also interested in molecular processes. My two directions of research at that time were: non-equilibrium statistical mechanics and thermodynamics. I wrote a book, which appeared in 1957, 'Molecular Theory of Solutions' [29], which is still used. Many predictions have been verified, including the quantum mechanical result on the zero point energy of mixtures, which leads to phase separation. This is a very important result, still quoted, as in the case of the mixture of helium 3 and helium 4 or the mixture of hydrogen and neon. The results were in very good agreement with experiments and even led to industrial applications. I presented this result obtained together with Jeener and Bellemans [29] at a seminar in Yale in 1953.

TC: That was equilibrium physics. But you were also working at that time in non-equilibrium processes.

IP: My main interest was always non-equilibrium physics. My Thèse d'Agrégation defended in 1945 [1], among many results, includes the principle of entropy production. What is important in the principle of entropy production, is that the non-equilibrium steady state is characterized still by a variation principle, which is not equivalent to maximum entropy. Therefore, there is structure created by irreversibility. That structure created by irreversibility was really a very important problem for me, because these structures do not appear at random. The key question was how these non-equilibrium structures appear in physical theories. The simplest example close to equilibrium is the emergence of minimum entropy production. That was very interesting for me. I was influenced by biological analogies and by the very good school of Biology in Brussels. I published a small paper with the biologist Jean-Marie Wiame [30] on the biological implications of minimum entropy production. Therefore, the problem of emergence of structures in relation to irreversibility is a problem, which was in my mind since 1945.

TC: What was the influence of Th. De Donder on your early work?

IP: De Donder introduced a formalism [31], which was not an equilibrium formalism. He introduced the affinity, which is different from the chemical potential. So the next step was to put the affinity equal to zero, and to recover equilibrium. But he did not go far towards the non-equilibrium case. He considered that you cannot understand thermodynamics if you look only on equilibrium. A very good argument for this is, for example, stability. Stability for Gibbs was studied in terms of the fluctuations, which you introduce into the equilibrium state. Note that these fluctuations obviously did not lead to non-equilibrium situations. Fluctuations from equilibrium are simply damped out. Non-equilibrium situations did not appear. So, De Donder was very opposed to the idea that equilibrium was the only field where you can apply thermodynamics. When you study stability, you introduce a perturbation, and when you have a perturbation, you go out of equilibrium. Thus, essentially, De Donder's formalism is a formalism, in which, after having formulated things in non-equilibrium terms using local equilibrium conditions, he put affinity equal to zero, and he is back to the usual equilibrium formulation. But, to my knowledge, he has not obtained any really new application far from equilibrium.

TC: Then, he did not anticipate, for example, the instability of the thermodynamic branch?

IP: No, not at all. He had also not anticipated the theorem of minimum entropy production. One of his main contributions is the definition of affinity. This really is very important. In the recent book I have written with Kondepudi [5], which is a kind of overall review of thermodynamics from the beginning till now, I emphasized the role of affinity. When you have heat conduction, which is proportional to the gradient of temperature, you can say that the gradient of temperature is a cause for the heat flow. So chemists, for many many years, tried to introduce also thermodynamics in terms of a chemical force which would drive chemical reactions. That chemical force is the affinity of De Donder, in the sense that if the affinity is positive, the reaction goes to one direction, if it is negative, it goes to the opposite direction, and if the affinity is zero, you have equilibrium. De Donder contributed of course to the general formalism of non-equilibrium systems, I don't want to decrease his importance. I only want to say that the specificities of non-equilibrium was not his field, his contributions were rather a preparation for the Non-equilibrium Physics. I always emphasized how grateful I am to De Donder [5].

TC: So, after 1953 you work to develop in parallel the non-equilibrium thermodynamics and non-equilibrium statistical mechanics?

IP: Yes. I had my first contact with non-equilibrium statistical mechanics, to justify the entropy production. There, I came to the problem of how chemical reactions modified development. Then, I came to non-equilibrium statistical mechanics, more on the traditional way. After the war, various theories appeared, which claimed that we can make a general statistical mechanics. Not in Boltzmann's way, but in the general statistical mechanics of Yvon, Born, Green, Kirkwood and Bogolubov [32–34, 12]. My first work in this direction was to try to apply Born's and Green's theory to one-dimensional systems for which we can calculate exactly the partition function. So, we applied it. And we showed that Born's and Green's theory does not give any consistent results. So, we were trying to have consistent results. We studied the lattice of harmonic oscillators [27]. In this situation of course, we have no irreversibility. However, there is a flow of information, which brings the system as close as you want to equilibrium as the number of oscillators increases. In the limit of infinite oscillators, information disappears at infinity and in this sense you have approach to equilibrium[35]. So, I was very impressed by this result which, to some extent, continues the work of Schrödinger [28] and gave me one of the basic ideas, which I was to develop in my book *Non-equilibrium Statistical Mechanics* [12] that essentially, irreversibility is a flow of correlations.

TC: You mean that all these ideas were already in this paper with Klein [27]?

IP: Yes, they were in this paper [27]. The flow of normal modes at the particle level corresponds as we have shown to the flow of correlations at the probability level. So, I became interested in this problem.

TC: That was the first hint in the right direction?

IP: Yes. Then I started to work on anharmonic lattices [12]. At that time I was in contact with Leon Van Hove who considered himself to be my student. Van Hove came to me one day to say that he obtained a good result by retaining, in the anharmonic solution, only the term with $\lambda^2 t$. The anharmonic solution to all orders in the coupling parameter λ could only be studied much later [36]. Van Hove introduced the $\lambda^2 t$ approximation in statistical mechanics [37]. He derived essentially the Pauli Master Equation [38]. Then we have significant development in this direction [12, 39].

TC: What was the reaction of Pauli?

IP: When I first spoke to Pauli about the lattice of harmonic oscillators, he was rather negative, saying 'what do you expect? There is no dissipation'. But afterwards he changed his mind. He was very enthusiastic about the work of Van Hove. But still, there remained a mystery which was also underlined by Hugenholtz recently, in a conference devoted to Van Hove. The mystery lies in the fact that the semigroup evolution obtained by the $\lambda^2 t$-approximation of Van Hove, is in contradiction with Quantum Mechanics, because if you add the omitted terms you will recover the time symmetric Quantum Mechanical solution. That was also Pauli's opinion.

TC: What about the $\lambda^2 t$-approximation in Classical Mechanics?

IP: It is very similar. We developed this with Brout in 1956 [12, 40] in terms of action-angle variables.

TC: What was the main outcome of your book [12]?

IP: We gave a very simple pictorial representation of irreversibility as a flow of correlations. Correlations evolve from second to third, then to fourth order and so on. The physical direction of time is the direction in which the correlations increase. As time goes on, more and more particles become correlated. You see, we have two phenomena which are coupled: to create correlations and destroy order in momentum space approaching the Maxwell-Bolzmann equilibrium distribution in the simple cases, or to destroy correlations and create order in momentum space. When particles collide, the distribution of momenta becomes more random and correlations increase. When you inverse time, correlations are destroyed and order in momenta is produced. The choice of one of the two temporal directions is a fact of observation. The main point is that the two directions of time can be distinguished.

TC: Were you satisfied with the $\lambda^2 t$-approximation theory?

IP: No, although this theory gave Boltzmann's equation, the Fokker-Planck equation and the Pauli Master equation, we felt it was only a starting point. Why $\lambda^2 t$? Why not to go to higher order of approximation? That was the work, which I did with Balescu, Resibois and Henin mainly. It is presented in my book *Non-equilibrium Statistical Mechanics* [12].

TC: How did you address the difficulty concerning the $\lambda^2 t$-approximation?

IP: The quantum systems for which the $\lambda^2 t$-approximation applied are Large Non-integrable Poincaré Systems in which the invariants of motion are destroyed. This destruction makes the approach to equilibrium possible [12, Ch. 14]. Both integrable and non-integrable systems have a probabilistic description of the evolution which may be decomposed into subdynamics. For integrable systems the subdynamics are rather trivial, corresponding to the evolution of the independent modes. For non-integrable systems however, each subdynamics corresponds to an irreversible Markov process [41, 42, 3]. We arrive at a description which shows both the unity and the difference between the reversible, integrable systems and the intrinsically irreversible systems which are non-integrable.

TC: How does subdynamics explain Irreversibility?

IP: The relation between dynamics and dissipation was for the first time clearly explained by Misra and coworkers [43,3]. We introduced the Time and Entropy operators. Misra's work is very interesting, because it shows how to go from the dynamical evolution to a stochastic evolution by non-unitary transformations, without losing information. In addition, the Time Operator is an intrinsic property of all chaotic systems. And is still useful as we can expand the probabilistic evolution in terms of age eigenfunctions [3, 44–46]. The Time Operator moreover allows to explain the Time-Energy uncertainty relation in Quantum Mechanics [3, 47] and to discuss quantum decay [48].

TC: What was lying behind subdynamics?

IP: Subdynamics is a decomposition of the evolution, which applies to both integrable and non-integrable systems. For non-integrable systems we obtain spectral decompositions at the probabilistic level. However we have to go beyond the Hilbert space formulation.

The mathematical tools are spectral theory of operators in Rigged Hilbert spaces. This development followed our discussion of the Poincaré theorem with Tomio Petrosky [49]. First we studied scattering resonances [13, 15]. Then we applied subdynamics to chaotic maps [50–55] and we realized that we do not have to apply the non-unitary intertwining transform to obtain Irreversibility as the extended spectral decomposition is time asymmetric [52–55]. Then came the extension to the thermodynamic limit for classical [16] and quantum systems [17], the 3-body problem [56] and interacting bosons [57]. Now, we are involved in the extension of field theory and the

Fock space. Here, essentially, we come always to the problem of the relation between irreversibility and non-locality.

TC: How is Irreversibility related to non-locality?

IP: The extended evolution is intrinsically probabilistic. In classical systems, for example, evolution cannot be localized to points. In quantum systems the extended evolution cannot be associated to pure wavefunctions. We have to consider density matrices which, as I mentioned, lead to description beyond the Hilbert space. In concluding, I would say that the whole point is to make irreversibility part of nature, to make probability part of nature. That was always in my mind from the very beginning.

TC: So, from the very beginning, since you obtained your PhD, there was a clear objective in your mind, to put irreversibility and probability in their proper place as intrinsic properties of nature, and not of our consciousness or ignorance. All your work has been guided by this objective?

IP: Yes. This essentially involves revision of physics, as probability theory (Kolmogorov) and mechanics (Newton, Schrödinger) are two different mathematical theories.

TC: At first you had the motivation to understand life through thermodynamics. Once this was done, then you wanted to put irreversibility and probability into dynamics.

IP: Yes. The first step is that entropy production far from equilibrium leads to bifurcations, Figure 1. Once you have bifurcations, you have probability, Figure 2. Therefore, irreversibility leads to probability. Irreversibility leads to complex structures [2–5].

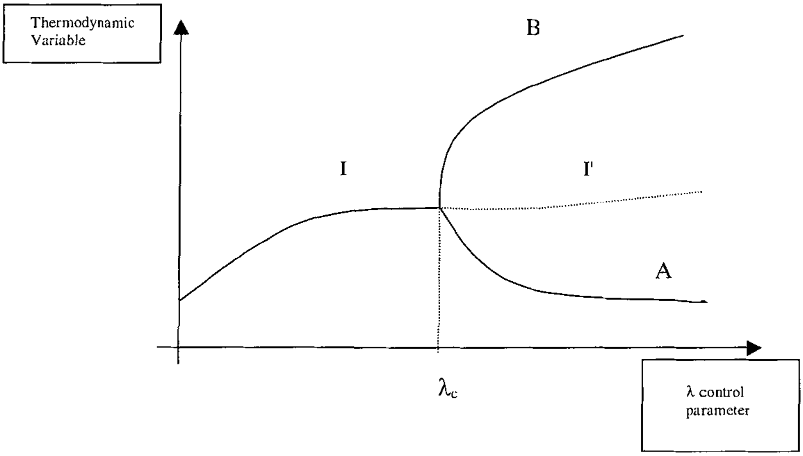

Figure 1: Bifurcations and order. At the critical point λ_c the initial solution (I) becomes unstable (I′) and two new stable solutions A, B appear which correspond to the appearance of new order.

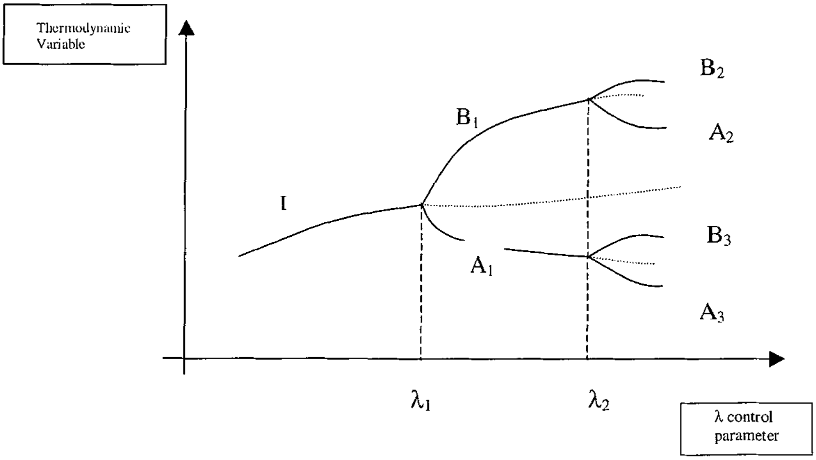

Figure 2: The Irreversible order through Fluctuations. The selection for the dynamical paths A_i, B_i at the critical points λ_i, $i = 1, 2, \ldots$ is not deterministic because it depends on fluctuations. Different dynamical paths like I, B_1, $A_2, \ldots$ or I, A_1, $B_3, \ldots$ are chosen by probability in an irreversible manner.

TC: Irreversibility and probability appear through the emergence of order, through fluctuations, at bifurcation points far from equilibrium. Then you realized that you have to put irreversibility and probability as intrinsic properties of nature at the fundamental level of description.

IP: Yes, or you can say that probability appears through bifurcations, because you don't know which branch the system will follow. It was my intention to make explicit that Time has meaning only in a Probabilistic World. You see, in Boltzmann's Stosszahlansatz [22, 23] probability is introduced *ad hoc*. The issue is to use probability, because trajectories are not relevant. That is the main point. I started with the idea of the origin of complexity. The origin of complexity can only be understood by irreversibility. Irreversibility means the role of semi-groups, the role of time. And the role of time can only be understood if there is probability. If not, the role of time is rather meaningless.

TC: I would like to add something from Heraclitus. There is fragment, which is of great importance, concerning your thinking. Heraclitus says: 'The wise is to know how that all things are governed through all things'. This means the persistent interactions between all things are the unique reason for any change happening in the world.

IP: This is a very good remark. You see, essentially this is a characteristic feature of nature, individualities emerge from the global. A town emerges from the countryside, in which it is embedded. This is against the idea that evolution is independent of the environment. Life needs air and water all the time. We have "life" interacting with "no-life" all the time.

Time in the Epistemology of Complexity

Discussion of Ilya Prigogine with Ioannis Zisis

IZ: It is a special pleasure, an inspiring fear I would say, to discuss with a historic personality of the 20th century, a personality who opened pathways for the 21st century, in science, research, civilization and intellectual life. This is Professor Ilya Prigogine, Nobel laureate in chemistry, in 1977, with very wide interdisciplinary contributions, director of the International Solvay Institutes for Physics and Chemistry. Professor Prigogine, welcome to Greece. Welcome to a place we believe you honor with your contribution.

IP: I consider it a privilege to be here, especially because the problems I was interested always, had been formulated for the first time by Greeks. I think about the conflict between Parmenides and Heraclitus. Parmenides said that everything was there, nothing new can appear, while Heraclitus claimed, as everybody knows, that all things are in progress and nothing remains still, that you can never step twice in the same river. I have always considered Parmenides paradoxical because his own book was itself something new. To claim that nothing is new and write a book that by itself is something new is contradictory. Therefore I have always considered this as a kind of paradox. For example, if the view of Parmenides was true, then essentially our discussion would be an illusion because it would be already prescribed since the Big Bang, this is very unlikely.

IZ: Can you say a few words about the arrow of time that you introduced in fundamental science? What are the innovations introduced by the arrow of time? What are the next bifurcations that you envision?

IP: Classically, you had two views: the basic laws, which were time reversible and deterministic and entropy increase (second law of thermodynamics) which was considered an approximation. But all around earth we see the arrow of time: be it in biology, be it in cosmology, be it in our own life. The arrow of time exists, it is the irreversible succession of events.

The question is, are there events in physics? Many people have shown and I have also shown [2–5] forty years ago or so, that when you go far from equilibrium you have bifurcations and something new appears, Figures 1, 2. Therefore from the phenomenological point of view there is no doubt about the arrow of time. In Greek universities there are many studies of non-equilibrium structures. The question is therefore how to introduce non-equilibrium physics into the microscopic level of description. I think this question has been solved in the last years. I am very glad that Ioannis Antoniou is with us, because he was one of those who contributed to its resolution [51, 54, 55, 14, 15, 58]. You can introduce an individual description in terms of wavefunctions or trajectories or you can define a population description as in thermodynamics. The key question is can we reduce the population dynamics to individual behavior? Just as in sociology can we reduce the behavior of a society from the collective level to the level of individual behavior? We know the answer: the population dynamics described by a probability distribution is reducible when the probability distribution is in the Hilbert space formulation. The Hilbert space is a space of functions, like the Euclidean space of 3-dimensional vectors studied in high school. Functions are like infinite dimensional vectors. Outside the Hilbert space there can be situations, and that is the majority, where this reduction cannot be achieved. Then population dynamics becomes generally non-reducible to individual descriptions. Therefore, the question is to decide when the population dynamics become non-reducible and time-oriented and when they do not. It appears that essentially population dynamics is reducible in simple situations like planetary motion, or the pendulum. But in more general situations it is not reducible. Then the probabilistic collective description becomes fundamental. Therefore you arrive at a view of the universe which is probabilistic and time-oriented and is in my opinion much more satisfactory.

IZ: You mentioned Hilbert spaces, you have in mind the relation between mathematics and physics. Do you see mathematics as an essential element in the new description of nature?

IP: Without any doubt. In quantum mechanics observables are operators transforming the wavefunctions. For each operator we have wavefunctions that do not change, called eigenfunctions. The operator acts on them as a multiplication by a number called the eigenvalue associated with the eigenfunction. Therefore the question is whether the operator describing the evolution of the population has eigenfunctions, in the Hilbert space or outside the Hilbert space. This question can be, partly at least, considered resolved [58]. The eigenfunctions of every integrable system, every simple system, are typically in Hilbert space. There are, however, three known examples that give rise to eigenfunctions outside the Hilbert space, namely: chaotic systems, thermodynamical systems and unstable particles or excited quantum states. Without any mathematics you can't understand irreversibility. Irreversible processes like viscosity and diffusion in kinetic theory, cannot be described in Hilbert space where the eigenfunctions are usually periodic. In irreversible processes there are no periodicities, but phenomena like exponential decay. It is therefore clear that you have to change something fundamentally, otherwise the whole existence of kinetic theory would be a paradox.

IZ: Can we speak about the arrow of time before the Big Bang?

IP: That is a very speculative question. My simplified view is based on phase transitions. For example when you take water and you cool it at some point, perhaps –10 degrees Celsius, it becomes an ice crystal. I always had this analogy in mind with the Big Bang. Is the Big Bang an irreversible transition from some quantum vacuum to matter? It is not clear what we had before the Big Bang. I am simply saying that whatever we had before the Big Bang, the appearance of the universe is an irreversible process, an entropy fluctuation. The existence of what we see around us is a mystery if we don't have the arrow of time. Biology is an evolutionary science. Cosmology is an evolutionary science. If the basic principles of physics were time reversible that would be very strange.

I think we see a different universe when we see a universe that is time oriented and far from equilibrium. The main question is therefore how it happens that the universe is far from equilibrium. In our case, here on Earth, it is very simple because we have the solar radiation which is responsible for the appearance of life. Therefore we see non-equilibrium related to the complexity on earth. However, we don't know what keeps the universe as a whole far from equilibrium. How it happens that the universe is time-oriented and out of equilibrium? That must mean that at the moment of the Big Bang there was already an arrow of time. Of course that is a very difficult problem. But you have always non-equilibrium structure formation when a significant part of dissipation is transformed to structures. We see that plants transform light into life through dissipation. We have now at least a qualitative understanding of the variety of things that we see around, because new structures appear at bifurcation points triggered by fluctuations [3–5]. Therefore, I think that in order to understand even qualitatively the universe around us, we need a theory which incorporates irreversibility, the time arrow.

IZ: Would you agree with Leon Brillouin that the laws of life and biology are more general and should include the laws of physics? Of course Brillouin said this before the emergence of complexity.

IP: The physical universe comes closer now to the biological universe. The emergence and evolution of stars and galaxies are non-equilibrium processes like self-organization in biology. In both cases you have billions of particles, which follow each other to form complex non-equilibrium structures. The question of how complex structures arise from the underlying interactions of particles is to some extent solved in principle once the arrow of time is included in dynamics. Physics has come, in the sense of complexity, closer to biology.

IZ: Is there some relation between the anthropic principle and complexity?

IP: The anthropic principle [59] is one of the biggest mistakes I have seen in my life because it re-introduces a duality. Take the book by Stephen Hawking [60]: the world is explained by geometrical arguments as a medium with no boundaries. But then in order to introduce human life (human complexity) you need the anthropic principle. Therefore we are at the same situation as Descartes who said that the universe could only be understood by a duality. Physics on one hand as the study of Space, Motion and Matter, Intelligence on the other hand as the study of Thinking. That is essentially the same message as the anthropic principle. If you add the anthropic principle you destroy the unity of the universe. We want to have a universe that is not divided into two separate fields. What we want is a concept of the universe that comprises thinking and biology without any contradiction with physics. We are, after all, the evolutionary product of nature. Therefore if you accept the anthropic principle, then we are outside nature. It is very difficult for me to admit that.

IZ: Although you are always careful when you speak about the relation between science and philosophy, following the scientific path with Occam's razor, you have also accepted Bergson and Teilhard de Chardin. How do you combine them?

IP: Bergson was innovative in his period because he said that we could understand the outside world by observing our internal world. Our internal world is temporal. Take, for example, our creativity and our artistic expression. Bergson noticed that this is opposed to the physics of his time because dynamics has no time direction. Physics was formulated from the patterns of regularity of the celestial sphere, the regularities of the sun and so on. That gives a view of the universe which is periodical. However, the evolutionary view and especially our own internal world is not periodic. Creation is a key element. That is why Bergson called his famous book "Evolutionary Creation" [61]. Bergson was not so naive as he is presented now. He had a famous discussion with Einstein and everybody said that he was defeated. That was, however, not so clear because although his criticism with regard to relativity was not correct, Einstein also did not understand what Bergson meant with his priviledged direction of time. Einstein maintained throughout his life that time as evolution is an illusion. But then our life is an illusion. That is very strange because how can a life which is an illusion pretend to lead to an exact science? The very existence of science is opposed to the idea that our life is an illusion. Therefore, to some extent, I believe that Bergson was right. Teilhard de Chardin, although not a scientist, was also rightly insisting on evolution. As a believer, a Catholic priest, Teilhard de Chardin was aspiring for a better and better world. The main difference between Bergson, Teilhard de Chardin and our school is that we approached this problem in terms of physics and mathematics. The problem has been around, as I said, since Heraclitus and Parmenides and has been discussed by all great philosophers like Kant, Hegel and Heidegger. However these discussions were at the philosophical level. It is a characteristic of our school that we deal with philosophical questions from a scientific point of view.

IZ: You have emphasized the limitations of Relativity because it cannot include the arrow of time. You have pointed out the incompleteness of Quantum Mechanics with respect to measurement and decay [3 4, 18]. Now that you introduce a new theory do you see any limitations or future challenges?

IP: First of all, limitation is not the right word. Extension is a better word. In Classical Mechanics, for example, we can now integrate systems, which are not integrable in the conventional Hamiltonian description of trajectories, by extending the dynamical formulation to the Liouville space [18]. We can now also solve some problems of quantum mechanics, which could not be solved in the conventional von Neumann formulation [10], like the problem of measurement, the problem of unstable particles, the problem of approach to thermodynamic equilibrium [18]. I want to say that there are two great paradoxes. The first paradox was pointed out by Boltzmann who had a correct idea about the evolution of the universe. However, strong objections were raised because classical dynamics was in conflict with Boltzmann's conclusions. I mention just the Velocity Inversion argument of Loschmidt and the Recurrence argument of Poincaré and Zermelo [3, 4]. The tragedy of Boltzmann is that he was not aware that dynamical systems may have different qualitative properties. Another tragic fact is that while Poincaré knew these differences, because he demonstrated the non-integrability of the 3-body problem [9], he did not realize the connection between irreversibility and non-integrability. This connection was established later [18]. The second tragedy is Gibbs who introduced the interpretation of equilibrium thermodynamics in terms of statistical ensembles or populations [32]. Although this idea was the basis of statistical mechanics [33, 34], Gibbs maintained that statistical ensembles arise from our lack of knowledge or from approximations to the dynamical evolution. It is paradoxical to say that thermodynamics arises from ignorance or approximation of dynamics because then, macroscopic physics would be either a subjective illusion or would depend on our approximation scheme. Thermodynamics is not based just on statistical estimations on ensembles but on the limit of ensembles for an infinite number of particles. The thermodynamic limit condition specifies the type of statistical ensembles needed to describe irreversibility. Gibbs says on one hand that we need statistical ensembles in order to describe thermodynamics, on the other hand that statistical ensembles are an approximation of dynamics. That is very strange. History is full of this kind of misunderstanding. Spectral theory outside the Hilbert space is an example of extension of the dynamical formulation which allows to include probability and the arrow of time in the theories of dynamics. In this way the above-mentioned problems and paradoxes are to some extent eliminated [18]. I think we are only at the beginning of science. We are at the beginning of studying the complexity of Nature. The classical universe was a simple, quiet universe. And now we see, we only conceive the extraordinary complexity of nature, like for example the complexity of the gene expression. We still don't understand completely the structure of the gene. Yet I don't think that once we understand the structure of the gene we shall see the meaning of man, because the genetic content of a mouse and a man are very similar. Therefore the non-genetic part of biology is very important. But we know little about it. Although we understand a lot about the gene, genes are only a small part of the individual. The same genes produce large people, small people, beautiful people and ugly people.

IZ: Do you see a conflict between fundamental research and technology?

IP: Traditional science was an elitistic occupation. Modern science has developed molecular biology and information science, which are very close to society. The aim of traditional science was to preserve science against the society. Now it is very different. Today, we need science to preserve our culture, our vegetation, to protect Nature. In addition I would say there is no fundamental science. Every scientific work may be as fundamental as the other. A Nobel prize may be given to somebody who has found a new particle, a new quark or to somebody who found a new astrophysical object or to a biophysicist. It is very difficult to say which discovery is more fundamental. In the old days it was very clear: atomic theory was the fundamental theory. But now it is not so clear. If you discover a new quark it is not such a big deal, it may be a big deal for the high-energy physics community. High-energy physics is of course very interesting, but to say that high energy is the only fundamental science, is not very convincing. Many scientists are interested in the energy level in which we live, that is a very low energy level. The structures of life are formed in low energy. The influence of quarks on systems of low energy is negligible. Therefore I think there is no reason to establish a kind of hierarchy of scientific work.

IZ: What will be the frontline scientific issues of the 21st century? How do you see the improvement of our knowledge in connection with these issues?

IP: I think that we have to understand the historical universe. In traditional science the universe was considered to be a geometrical entity. Now we add a narrative element, we know that everything ages in the same direction: you age, I age, the rocks age. But the mechanism of ageing and the mechanism of discovery are not known. We have now the discovery of dissipative structures [2–5] ; but that is a very simple situation. We do not know how life evolves. Obviously when fish came to earth, not all fish came to earth. When monkeys became human, not all monkeys became human. Therefore it is certainly a problem of probability for which we don't have the slightest idea. We have very little understanding of the events after the Big Bang. I want to emphasize that the direction of time is the most fundamental property of the universe. The universe acts as a whole and is evolving. It is still very surprising because our universe seems to evolve more rapidly with acceleration as predicted by Einstein's simple cosmological model. Nobody knows how to unify gravitation with the other forces and with quantum mechanics. In my view gravitation maintains the universe out of equilibrium, but we don't know how. Our universe is far from equilibrium, nonlinear and full of irreversible processes. In the absence of gravitation the universe would go to thermal death, a dead universe, an equilibrium universe, but that is not at all what we see. We see stars being born, other stars die and all kinds of non-equilibrium structures, but we do not understand how the universe remains far from equilibrium.

IZ: Do you see a validation of your view of the arrow of time in the fact that the quantum vacuum seems to prefer the creation of matter versus antimatter?

IP: That is a very good point because close to equilibrium situations, you can show that for a large class of processes, there will be as much matter as antimatter. But far from equilibrium you can show that there are only two non-equivalent solutions. In one there is a very large amount of matter and very little antimatter, in the other we have the converse. Therefore the matter-antimatter example is a very nice demonstration of the fact that the universe is out of equilibrium.

IZ: A critical issue for science in the 21st century is the issue of morality with respect to the applications of knowledge. We had in the past the movements of Russel and Schweitzer towards the peaceful use of technology to prevent a destructive nuclear war. What will be the moral issues in the next century?

IP: That is impossible to say because the moral issues change as science evolves. For example, cloning. There is a moral issue on cloning. Are you against cloning or are you for cloning? There are arguments supporting both sides. As science has become closer to humanity, ethics and science come nearer. The scientists have the right to give their opinions like other people. Scientists have no ethical privilege. The new problems are very complex. For example, the use of genetic information, the issue of privacy in the Networked Society. I would like to emphasize that ethics and science have come closer than ever, because science has come closer to society.

IZ: Are you concerned about the emergence of a sort of cult around irreversibility and the arrow of time or a sort of religion? Do you see the emergence of a sort of global plan?

IP: No. You see, in my view, the universe is evolving and the creation of structures can be, at least in simple cases, understood as a result of non-equilibrium. There is no mystical element coming to it. But the fact that we have a probabilistic world means that we have not such a transparent world as Newton's world. This was already known in Quantum Mechanics, because we cannot predict where an electron is. We can only calculate the probability that the electron is in a region of space. Therefore the probabilistic view, in a sense, has some relevance to theological problems. If the universe is a deterministic machine, then you need some outside spirit or God to make it work. But if it is self-organized, it may be a non-equilibrium world which can follow its own plans, there is no need for an outside force or plan. Therefore in a sense you have two possibilities. What choice you take is not my problem.

IZ: The Holy Grail of physics is claimed to be the unification of fundamental forces. What are the main gaps in this unification? How do you view this quest of unification?

IP: I don't believe in this unification because I think that gravitation plays a more complementary role than a unifying role. In other words gravitation keeps things going. In thermodynamics, gravitation disturbs equilibrium, you cannot speak about equilibrium including gravitational forces. That comes from the long range character of the gravitational forces. There has been a partial unification, but since then not much progress has been achieved. I think we go more towards, as I already mentioned, a historical universe. Some unity is brought by the historical point of view, but the language and the details are different. For example history, as I mentioned before, has bifurcations and Nature with its particles and antiparticles also has bifurcations. But of course you cannot say that the bifurcations of human beings have the same underlying mechanism as bifurcations of matter/ antimatter. Of course we don't have yet the final picture in particle physics. Why do we have so many elementary particles? What is the difference between leptons and baryons? Nobody knows.... There are at present many speculations (string theory/multiple dimensions).

IZ: Do you see any direction of unification between physics, biology, and psychology?

IP: What is common of course is the direction of time and the study of processes. Obviously in our own life we have followed important events which lead to bifurcations, for example, a marriage is an irreversible event, which may be the outcome of a bifurcation: you may be attracted to and love two girls and then you select one. Bifurcations appear in human life, bifurcations appear in civilization. I would say that European civilization is characterized by a large number of bifurcations. European music is changing every 100 years while Chinese music has remained much more traditional, there is not much change. In this sense I would say that Greek civilization has been a model. Consider, for example, the transition from the Archaic civilization to the Hellenistic civilization from 750 to 350 BC. You have an enormous change. Look what happened during the same period in China or in Egypt. European civilization is very flexible and creative. I would not like to exaggerate, because the Chinese produced many magnificent things but then to some extent they stopped, while, in Europe, things have been going on and on. I was always very impressed by the idea of Democracy which introduces the value of the individual in society. That is characteristic for Greece and to some extent for Western Europe in general.

IZ: Your work has opened many directions in different disciplines. But the main issue is the way of thinking: you seem to be very persistent and very innovative. Many have spoken about the interdisciplinarity or transdisciplinarity of your work. On the other hand you reject a quick and easy synthesis. How do you see the synthesis of different disciplines?

IP: I don't think we should make a synthesis because Psychology will always be different from Physics. The only thing is to establish a non-contradictory view, a universe in which Biology is not in contradiction with Physics. Biology is an evolutionary science while Classical as well as Quantum Physics are deterministic and time reversible sciences. Therefore there is a gap. You can say that this is because the universe is not unified. You may even say that the universe is contradictory. My point of view was to show that there is no contradiction. But I don't want to identify Physics with Biology.

IZ: On the other hand complexity has enormously contributed in interdisciplinary research.

IP: Yes but that is part of the problem. Because complexity is generally related also to the arrow of time. What do you call complexity? Complexity is a property of systems that for given boundary conditions have more than one possible solutions. Also in complex systems long range correlations appear between components with very short-range local interactions. Take for example the famous Belousov–Zhabotinski reaction [2–5]. You have a homogenous solution in which you mix two substances, they remain mixed until as a result of bifurcations, you have collective oscillations of the concentration. The solution becomes blue and red periodically. This collective effect indicates the presence of correlations between the molecules. Near equilibrium you have a stable solution which minimizes the free energy. Far from equilibrium, however, you have a new oscillating solution. After the bifurcation the oscillatory solution becomes stable and the equilibrium solution becomes unstable. The equilibrium solution is still there, only it becomes unstable. The main point here is that nature always tries to create and eventually selects the stable/sustainable solution. Bifurcations only appear far from equilibrium and therefore complexity is a phenomenon (that occurs only) far from equilibium.

IZ: There is a trend towards becoming one world, becoming one planet. For example, the prefecture of Fthiotis would like to restore Amphiktionies on a planetary level. In this context they proposed to host the first Solvay conference of the 21st century.

IP: As Director of the Solvay Institutes I am very grateful and I think this is very appropriate as western science was born in Greece. Of course the Egyptians and Chinese knew many things before. But Egyptian and Chinese geometry were mainly observational. They did not develop any theory or proof as Greeks had introduced. I think it is very appropriate that the first Solvay conference of the 21st century will be held in Greece and especially in this place. I can only be very grateful.

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Life and the Internet

Discussion of Ilya Prigogine with Maria Adamidou

MA: How can there be order out of chaos?

IP: When you take a system that is in equilibrium, then molecules run in all directions in a disorderly way, described by the Maxwell-Boltzmann statistics. When you take, for example, a layer of liquid and you heat it from below you observe a thermal disorder, which is chaotic. But when you heat it more and more, when the layer is not very thick you observe that there comes a point when vortices are built. Vortices give rise to organized situations known as Benard cells [3, 4] in which billions of molecules follow billions of molecules to form the vortices. Therefore non-equilibrium leads to order. And that can be seen in many situations. When I was young I was very impressed with the so-called thermal diffusion [5]. For example, if you heat a liquid from one side, you observe diffusive motion towards the other side. Similarly, in a gaseous mixture of two non-interacting molecules, say blue and red molecules, you may have more blue molecules on one side and more red molecules on the other side, i.e. a sort of structure formation. You cannot observe these effects at equilibrium where you have uniform mixture of the red and blue molecules. The main point is that structure formation and complexity are non-equilibrium phenomena and that non-equilibrium is related to irreversibility. That is why I always thought that irreversibility is the basis of the structures that we see in the universe. We see all kinds of structures. We see the structure of the sun, the structure of the earth, the geological structures formed in non-equilibrium conditions, in an irreversible way [2–5].

MA: The Internet provides these days the mechanism for communication and correlation of events on a planetary scale. Can you highlight some implications of this new situation?

IP: The Internet gives us a lot of information and it leads probably to a new form of society but we don't know what kind of society it will be. Certainly it leads to more interactions and produces mass culture. For example, it leads to interactions between black people of Brazil and black people in the USA. My son in Brazil saw in the houses of black people in Brazil pictures of Martin Luther King and Nelson Mandela. Therefore the Internet creates links between people who have been isolated. In my opinion the whole meaning of civilization since the Greeks, is the production of more communication between people. When you go from the Paleolithic to the Neolithic age which means to go from the Aztecs to Egypt, Babylon, Rome, division of work introduces Kings, Pharaohs and Slaves. You have a theocratic or selective society. Now society is completely different. The information explosion, through the Internet, together with television and radio, enables people to participate in culture. We are only at the verge of a new transition in which more people are expected to be involved in culture. The Internet produces indeed mass culture but we should not overlook that it may also decrease creativity because many people look for information and they have no time to think by themselves. There are very interesting analogies with ants which indicate some dangers. There are small ant societies, a few hundreds as well as large ant societies that number in millions. The behavior is different. In small ant societies each individual ant has an essential role, it is independent and finds food for itself. In large ant societies there are collective processes, the individual is less important. In many of these societies the ants are blind.

MA: What is the role of the individual today? How can the individual sustain all these rapid changes in the global society and the networked economy?

IP: The role of the individual remain very important. For example, a few individuals worked on the physics that was necessary to create the information society. Forty years ago there were only a few hundreds. Now there are probably millions of people working in one way or another to contribute to information society. Therefore it has propagated more rapidly compared to Christianity or Buddhism. You can say that we are in a large society that is an open non-linear system and that what you are doing influences what I do and vice versa. A large society has much more possible instabilities than a small society. A small society can moreover be much more conservative. For example, the natives of New Guinea are small societies that are very conservative. Now, curiously, in large societies, the role of the individual has increased because individual initiatives lead to changes which lead to social fluctuations. For example, the role of Henry Ford in automatization and management, the role of Alan Turing in computation. A large society doesn't necessarily make the individuals powerless. The main danger today is to create a difference between people who know and people who do not. Therefore the main point is education. Education is very important, also permanent education. The world is changing so fast, that we need to update continuously our knowledge in order to adapt.

MA: How far do you think we have deciphered the secret of life and what are the next targets in this direction?

IP: The biological structures that we see around are the result of fluctuations acting on bifurcations far from equilibrium [2–5], Figures 1, 2. But the fluctuations that led to life are not very well known. There is some part which is genetic. It is very remarkable that the genetic code is the same everywhere. On the other hand there are differences between chimpanzees and humans. Some people think that once we know about the genes we shall know the life forms and the human being. That is a very reductionist point of view. We see a lot of irreversible processes involved in the transcription of genetic information to create the embryo, as well as a lot of irreversible processes going on after birth. Therefore the non-genetic aspect is very important. We have to develop non-genetic biology based on the theory of Complexity. Therefore if you think that cloning will give you two identical individuals, that is probably not true. Because individuals develop very much after birth. As I see it in general, we have very simple examples of structure formations, but we do not know yet the origin of life. A lot of people believe that life comes from another planet, but we still don't know the origin of the Universe. The theory of the Big Bang is the most widely accepted theory, but what is the Big Bang? Is it a transition from the primordial quantum vacuum to matter? Many people believe that it is an ignition, that the Big Bang has a special function, that it contains all information, including our discussion. That is very unlikely. I think it is much more likely that matter and life appeared as an irreversible succession of non-equilibrium processes, initiated by a fluctuation of the quantum vacuum that created entropy. Irreversibility leads to collective probabilistic descriptions, which cannot be reduced to individual trajectories or wavefunctions corresponding to Newtonian or Quantum mechanics. Reducibility, that is possible for very simple systems, is not possible for complex thermodynamic systems and is not likely to be possible for the universe. We see that the universe is changing, it is growing with acceleration. I think the arrow of time is a common element for every entity in our universe. You age, I age, the trees age, the stars age, but we do not age in the same way. Ageing involves progress and novelty. Nobody can doubt Michelangelo was an innovator, a creator. This is also true for scientists.

MA: Why did you join science?

IP: Some join science because they like to solve puzzles. My reason is the same as Einstein's. We do science because we are astonished, we are surprised because we do not see a clear relation between science and the Universe. The Universe is far too complicated, far more rich and fascinating than our classical theories anticipated. The models we first studied give a picture of the Universe as a deterministic eternal automaton. To understand reality we have to study the mechanisms of fluctuations in astrophysics, in biology and even in human societies. We are at the beginning. I always say that we are at the beginning of a new science, not at the end of science.

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Epilogue

Irreversibility, Probability, Instability

These are the three keywords Ilya Prigogine likes to use in order to summarize the essence on Non-Equilibrium Physics. The remarkable progress of Ilya Prigogine's school, achieved mainly in the second half of the 20th century, was based on persistent effort to cope with 2 paradoxes which resulted after the formulation of the Second Law of Thermodynamics, namely:

(I) The paradox of Life
(II) The paradox of Dynamics

(I) How can Living Forms appear and self-organize by reducing their Entropy, defying the universality of the Second Law of Thermodynamics? It was Schrödinger [62] among others who emphasized the need to extend Thermodynamics far from equilibrium in order to find possible ways to avoid the apparent contradiction between the self organization of Living Forms and the entropy increasing approach to equilibrium. In fact the non-linear equations describing non-equilibrium systems, as Prigogine showed, give rise to structural instabilities associated with bifurcations. As a result we have pattern formation and Self-organization [1–5]. At the critical non-equilibrium transitions, long range correlations appear and fluctuations play the dominant role. The principle of "order through fluctuations" describes how patterns emerge far from equilibrium, where there is no global extremum principle. The system "finds its way" through attractors and repellers, experiencing critical transitions as the order parameters change, driven by fluctuations.

(II) How can Entropy increase irreversibly in a System of Atoms interacting with reversible and conservative forces?

Although the problem was posed scientifically by Boltzmann in the previous century [22, 23], the extra-dynamical ideas go back to Epicurus and Lucretius [3, 4, 18]. Prigogine could not accept any extra-dynamical argument (ignorance, approximation), because the Irreversible emergence of Order far from equilibrium is achieved through the Entropy Flow, supported by the internal Entropy production as prescribed by the Second Law [2–5]. Therefore Irreversibility should be an objective property of Nature. As probability (fluctuations) is also involved in non-equilibrium transitions (Fig. 2) producing the diverse forms of nature, Prigogine could not imagine Irreversibility without Probability, even at the fundamental level of dynamical description. His strategic remark was that Irreversibility and Probability should be objective properties of Unstable and/or Non-Integrable Dynamics. This is in fact the case. Unstable and/or Non-Integrable systems admit extensions of the Dynamical Evolution which are both intrinsically Irreversible and intrinsically Probabilistic [18]. Extensions of Dynamics can of course be constructed also for stable and integrable systems, but they are always reversible and non-probabilistic. Therefore the classification of Dynamics in terms of stability and integrability is very crucial. This classification applies not only to microscopic and macroscopic processes, but also to the Universe as a whole. For example, several observable consequences have been predicted in cosmological models with instabilities due to negative curvature [63–65]. The analysis of recent observations suggests strongly that our universe has negative curvature, i.e. chaotic character [66].

Probabilistic Analysis of Complexity. Extended Spectral Decompositions and Time Operator

The Irreversible, Probabilistic extensions of dynamics are constructed through the spectral decomposition of the evolution operators and acquire meaning in suitable spaces of generalized functions [58]. In other words rather sophisticated mathematics, namely spectral theory of operators in Topological Vector spaces, provide the Foundations of Non-Equilibrium Physics.

This is not so unexpected. As Ilya Prigogine emphasized in his discussion with Theodore Christidis (p. 21), Probability and

Mechanics are two different mathematical theories. The understanding of the relation between probability and mechanics has been stated by Hilbert to be "a problem in the first rank" when he delivered the famous address on the 26 Mathematical Problems in 1900 [67]. In Problem 6 "Mathematical Treatment of the Axioms of Physics", Hilbert also mentions Boltzmann's work and he even contributed himself later (1912) to Kinetic theory [68].

However, the questions of Statistical Mechanics could not be posed adequately in terms of the mathematics of Differential Equations and Topological Dynamics. Caratheodory was the first to see, in 1919, that Measure theory is the natural language to formulate and discuss the problems of Statistical Mechanics, when he completed [69] the Proof of Poincaré's Recurrence theorem, by reformulating it as follows: The volume preserving dynamical transformations of the phase space have the property that almost all points (except possibly a subset of zero volume) in any region of positive volume, will return back into the region after some finite time. This strategic remark of Caratheodory opened the way for the proper mathematical treatment of Statistical Mechanics in terms of Measure theory and Functional Analysis [70]. In fact Birkhoff and Koopman pointed out in 1932 [71] that "Caratheodory's paper [69] was the first entrance into the realm of dynamics of the modern theory of real variables". The problems of Statistical Physics were originally formulated in the frame of Hilbert Spaces [72, 73] intensively studied in the 30's as they provided the foundation of Quantum Mechanics [10].

The need to use function spaces beyond Hilbert spaces has been stated not only by Dirac [11] but even by von Neumann himself. Birkhoff quoted [74] the following remarkable statement of von Neumann: "I would like to make a confession which may seem immoral: I do not believe in Hilbert space any more." On the other hand, the spectral theory of Operators in Topological Vector spaces is not as developed as the Hilbert space theory. The resulting spectral expansions for Complex Systems demand further elaboration of the extension theory of Operators [58].

The Time Operator mentioned by Ilya Prigogine during the discussion with Theodore Christidis is canonically conjugate to the evolution operators V_t [3]

$$TV_t = V_tT + tV_t$$

Here V_t stand for the Koopman Operators in classical dynamics or the Heisenberg Operators in quantum dynamics.

In other words the relation between the Time Operator T and the evolution operator V_t, is like the relation between the Position Operator and the spatial translations V_α in Quantum Mechanics. For example, in the simple one-dimensional case:

$$\begin{aligned} V_\alpha\psi(x) &= \psi(x-\alpha),\ \alpha \text{ real parameter} \\ Q\psi(x) &= x\psi(x) \\ QV_\alpha &= V_\alpha Q + \alpha V_\alpha \end{aligned}$$

The decomposition of the statistical evolution in terms of the eigenfunctions of the Time Operator, is just the canonical decomposition of Non-predictable processes in terms of successive stages of Innovation [44]. For predictable processes, like the motion of the pendulum, there is no innovation. The Algebra of Observables is constant in time and the Time Operator is trivially zero. However, for complex systems, the Algebra of Observables increases in time as new information is produced [44]. Innovation is just this new information produced at each stage of evolution.

The Spectral Decomposition and the Time Operator are the two main mathematical tools developed by the Brussels-Austin Groups for the statistical analysis of complex systems, related by a generalized Fourier Transform analogous to the Momentum and Position representations in Quantum Mechanics.

Complexity — Results and Perspectives

In the recent *Review of 20th Century Physics* the ideas developed in Ilya Prigogine's school on Non-Equilibrium Physics, have been characterized as "certainly unconventional and thought-provoking. Within the physics community they produce a mixture of scepticism, elation and concern: an ideal mixture for further progress" [75, Vol. I, p. 622].

The main outcomes of Ilya Prigogine's work are:

1) The clarification of the general physical conditions for the emergence of Complexity at the macroscopic and microscopic level;
2) The development of the probabilistic analysis of Complex Systems. Probability is an assessment of the uncertainty inherent in Complex Systems.

Natural Complexity gives rise to problems with computational complexity [76]. Complex Systems demand the development of unconventional Algorithms [77]. These Algorithms may be transferred from one discipline to another for mutual cross fertilization. For example, Mathematical Models for the Immune System [78, 79] provide new computational platforms or even an Immune System for Computer Networks, important for Network Security [80, 81]. Biology is not only the great challenge of the 21st century (Non Genetic Biology mentioned by Ilya Prigogine) but also provides a lot of ideas for Complexity Theory and Information Technology. Let us only mention, in addition to Immune Networks, the Neural Networks, the Evolutionary Automata, the Swarm Intelligence [81]. The recently proposed Social Networks [82] are useful for the Internet, epidemics, even the structure of scientific collaborations [83]. Information Society itself may be viewed as a Complex System [84].

We are living in a most exciting era, full of challenges and possibilities. The Future is not determined. It is paved by our effort and our ability to capture critical fluctuations and transform them to innovations. The work of Ilya Prigogine is a continuation of the dialogue between Heraclitus and Parmenides, as the Rector mentioned in the Preface. This dialogue is open and will continue most creatively in Greece where it started.

On behalf of the International Solvay Institutes for Physics and Chemistry, as well as personally, I would like to thank those who contributed to the realization of this distinctive event. Professor George Metakides conceived the idea. The Rector Professor Themistoklis Xanthopoulos embraced the idea with enthusiasm and supported it throughout. The Vice Rectors Professors Efstratios Galanis and Eleftherios Papagiannakis and the Presidents of the three departments, Professors Dimitrios-Marinos Kouris, Dimitrios Koutsouris and Dimitrios Kravvaritis, all contributed and gave their support. I would also like to thank the Council, the professors and students of the National Technical University of Athens for their warm participation.

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In Memorium

Farewell to Ilya Prigogine

Ilya Prigogine passed away on 28 May 2003 shortly before the publication of this volume. The Memorial address by his student, colleague and friend, Ioannis Antoniou, at the Royal Academy of Belgium on 6 June 2003 is added to this last book of Ilya Prigogine.

Professor Prigogine,

This moment was certain, but not predictable when I joined your group, 21 years ago. Just like atomic transitions that excited you so much. Every week you gathered us in your office to discuss different problems. Those who actively engaged themselves in the issue were the authors of the papers. Self Organized Delegation. You always tried to get the best from people, deliberately ignoring the irrelevant and the destructive, never losing the vision and the goal.

After my PhD, I was advised by other senior scientists to stay away from your group because it could be too risky for the career a young researcher to deal with exotic unclear subjects, far from the mainstream. I was desperate, so I decided to get your reaction. Quite unexpectedly you told me: "They are right. Mainstream research is safe, but you should not expect to get results of great significance. Outside the mainstream you may get something really interesting. Moreover, you have a little time for creative thinking. But there is a high risk to be lost and isolated. Research is like horse betting, interesting return is with the outsiders, but there is high risk to lose everything."

Indeed, your work in the early stages was outside the mainstream. When you tried to find the dynamical basis of Self Organization and Irreversibility, Wigner advised you "not to lose your time in such strange research, because nature is anyway reversible at the microscopic fundamental level". I asked you: "How did you find the strength to persist and go on?" You said: "If they are right then Nature must be schizophrenic. The unity of nature, should imply a unified description of nature as well. I always believed that the objective character of Self Organization and Irreversibility should be based on some qualitative properties of Dynamics." Indeed, *you* found that Non-Integrability and Chaos are the key properties of Dynamics which give rise to Irreversibility without any approximations, subjective evaluations or loss of information.

Those of us in Brussels and Austin who helped you a little are most happy and proud. Your vision is now reality. We have new results in Physics, new Mathematics, even applications appreciated by the present scientific community. But on top of that we have, thanks to you, an optimistic vision for our universe. As you like to say, "Universe is a construction in progress, in which we participate."

When I presented our work 10 years ago at a Conference in Italy, another Nobel prizewinner attacked me violently. After a hot discussion, during dinner he approached me saying, "I like your work on the Time Operator, but why do you lose your time with the strange ideas of Prigogine?" Quite upset, I decided again to report it to you. Your response was another surprise: "I am most happy, Ioannis, because this shows that my work attracts attention. When you propose something original you should expect to have good friends and good enemies, as well. No reaction means that your work is perceived as insignificant."

You always emphasized that science is a social activity. Thanks also to your efforts in the '80's, the European Research Area is now reality.

Under your direction, thanks to your inspiration, the International Solvay Institutes have been transformed into an Advanced Research Center for Non-Equilibrium Physics and Complexity.

In the early '90's you initiated the Euro-Russia Collaboration on complexity. Mother Russia helped us a lot. Many talented Russian scientists came to Brussels. Strong personal links were established. A lot of new results were obtained. Professor Kadyshevsky, the Director of the International Institute for Nuclear Research at Dubna, Professor Sadovnichy, the Rector of Lomonosov Moscow State University and Professor Verbitskaya, the Rector of St. Petersburg State University on behalf of your beloved friends and collaborators, about 500, commit themselves to continue the fruitful collaboration in our international network, to develop your ideas further.

You have quoted many times the dialogue between Parmenides and Heraclitus, Being and Becoming. The honours offered to you by Hellenic Universities and Authorities are simply expressions of the appreciation and love of Greek scientists and intellectuals. Your friends, Rector Antonopoulos from the Aristotle University of Thessaloniki, Rector Xanthopoulos from the National Technical University of Athens and Vice-Rector Tsalidis from Democritus University of Thrace will support the further development of your ideas in Greece.

We all believe that your thoughts will mark the science of the 21st century. Your groups in Brussels and Austin, will continue to work inspired by your refreshing vision and innovative ideas.

Although you never had any particular opinion about religious matters, you always appreciated what you like to call "the mystery of experience of transcendence". You considered this mysterious experience to be the source of creative innovative activity in science and art. When I asked you a few months ago: "What are the future challenges of science as now the issue of Irreversibility and Self-Organization is more or less clear?", I was astonished to hear you say: "Ioannis, if I was a young researcher now, I would study the Mind/Body problem. This is the great challenge of the 21st century."

Bon voyage Professor Prigogine, in this great bifurcation.

Ilya Prigogine at a physics course given to 12-year-old children at the "Collège des Maristes", in La Cordeille d'Ollioules, near Toulon, France, in February 1987.

Ilya Prigogine and Ioannis Antoniou at the Aristoteles University of Thessaloniki (1998).

Curriculum Vitae of Ilya Prigogine

Born: January 25, 1917; Moscow, Russia

Nationality: Belgian

Married: Marina Prokopowicz; February 25, 1961

Children: Yves Prigogine; July 5, 1945
Pascal Prigogine; February 6, 1970

Title: Hereditary nobility and the personal title of Viscount, awarded by His Majesty, the King of Belgium, 21 July 1989

Awarded: Nobel Prize for Chemistry, 1977

Education: (Université Libre de Bruxelles)
Licencié en Sciences Chimiques, 1939
Licencié en Sciences Physiques, 1939
Docteur en Sciences Chimiques, 1941
Agrégé de l'Enseignement Supérieur en Chimie Physique, 1945

Activities:

Director, International Institutes of Physics and Chemistry founded by E. Solvay, since 1959

Director, Ilya Prigogine Center for Studies in Statistical Mechanics and Complex Systems, The University of Texas at Austin, since 1967

Professor of Physics and Chemical Engineering, The University of Texas at Austin, since 1967; Regental Professor, since 1977; Ashbel Smith Professor, since 1984

Chargé de Cours, Université Libre de Bruxelles, 1947; Professeur Extraordinaire, 1950; Professeur Ordinaire,1951; Professeur Honoraire, since 1987

Directeur d'Etudes associé à l'Ecole des Hautes Etudes en Sciences Sociales, France, 1987

Special Advisor to the European Community, Brussels, Belgium, 1993

Honorary Member of the World Commission of Culture and Development of UNESCO, chaired by Perez de Cuellar, 1993

Honorary Chairman of the Centro de Estudios Latinoamericano Ilya Prigogine, Universidad Nacional de San Luis, Argentina, 1995

Honorary President of the Institute for Mathematical Study of Complex Systems at the Lomonosov Moscow State University, 1995

Honorary Chairman of the Istituto di Documentazione e Ricerca Sull'Opera di Ilya Prigogine, Fondo Archivisto "Ferruccio Rossi Landi", CISST Brugine-Padova, Italy, 1996

Creation of the Haute Ecole Libre Ilya Prigogine, Brussels, Belgium, 1996

Honorary Chairman of the Institute of Complex Systems, Thrace, Greece, 1996

Honorary President of the "Centro de Fisica No Lineal y Sistemas Complejos" de Universidad de Santiago, Chili, 1996

"Ilya Prigogine Chair of the Philosophy of Sciences" (School of Humanities and Social Sciences), Universidad de Palermo, Argentine, 1996

Honorary Director of the International Institute of Scientific Investigation, University of Salvador, Buenos Aires, 1996

Honorary President of the International Academy of Science/ Council for Scientific Development, Jenbach in Tirol, Austria, 1996

President of the Ilya Prigogine seminar "Penser la Science", ULB, 1997 (2nd seminar in 1999)
Honorary Director, "International Institute for Research", Universidad del Salvador, Buenos Aires, Argentina, 1999

Distinguished National Awards:
Médaille de la Résistance, Belgium
Commander of the Order of Léopold II, Belgium, 1961
Commander of the Order de la Couronne, Belgium, 1968
Médaille Civique de Première Classe, Belgium, 1972
Holder of the Grand Cross of the Order of Léopold II, Belgium, 1977
Commander of the National Order of Merit, France, 1977
Commander of the Order of Arts and Letters, France, 1984
Commander of the Legion of Honor, France, 1989
Member of the Imperial Order of the Rising Sun, honored with the Gold and Silver Medals, Japan, 1991
Friend of the Democritus University of Thrace, Komotini, Greece, 1996
Medal of Ibaraki University in Mito, Japan, 1997
Norbert Weiner Gold Medal, Ukbridge, 1999
Medal of Member of the European Academy of Yuste, 2000
Commander of the World Order "Science. Culture. Education." European Academy of Information, 2002

Memberships:
Membre correspondant de la Classe des Sciences de l'Académie Royale des Sciences, Lettres et Beaux-Arts de Belgique, 1953
Membre Titulaire de l'Académie Royale de Belgique, 1958
Honorary Foreign Member of the American Academy of Arts and Sciences, USA, 1960
Membre correspondant de l'Académie de la République Populaire de Roumanie, 1965
Member of the Royal Society of Sciences, Uppsala, Sweden, 1967
Membre correspondant de la Société Royale des Sciences de Liége, 1967

Foreign Associate of the National Academy of Sciences, USA, 1967

Président de la Classe des Sciences de l'Académie Royale des Sciences, Lettres et Beaux-Arts de Belgique, 1968 à 1970

Member of the Deutsche Akademie der Naturforscher Leopoldina Halle, Germany, 1970

Corresponding Member in Physics and Mathematics of the Academy of Sciences of Göttingen, Germany, 1970

President, International Council for Scientific Development, Munich, 1970

Member of the Östereichische Akademie der Wissenschaften, Vienna, 1971

Honorary Member, Chemical Society of Poland, 1971

Member of the International Academy of the Philosophy of Science, 1973

American Chemical Society Centennial Honorary Foreign Fellow, 1976

Foreign Fellow of the Indian National Science Academy, 1979

Member of the Rheinische-Westfähliche Akademie der Wissenschaften, Düsseldorf, 1980

Foreign Member of the Akademie der Wissenschaften der DDR, Berlin, 1980

Member and Vice-President, Académie Européenne des Sciences, des Arts et des Lettres, Paris, 1980

Member of the Accademia Mediterranea delle Scienze, Catania, Italy, 1982

Foreign Member of the Academy of Sciences of the U.S.S.R., 1982

Member of the Honorary Committee of Archives of Psychology, Geneva University, 1982

Membre du Conseil d'Administration de la Fondation Erasme, Brussels, 1983

Member of Honor of the Society for Studies on Entropy of Japan, 1983

Member, Académie Internationale de Prospective Sociale, Geneva 1983

Member, Haut Conseil de la Francophonie, Paris, 1984
Membre Scientifique Extraordinaire of the Max Planck Foundation of the Federal Republic of Germany, 1984
Honorary President, Université Philosophique Européenne, Paris, 1985
Founding Member, European Council of Research Libraries, Lausanne, Switzerland, 1985
Honorary Member, Biophysical Society, People's Republic of China, 1986
Fellow, World Academy of Art and Science, 1986
Honorary Member, International Society for General Systems Research, Louisville, Kentucky, 1988
Membre d'Honneur of the Société Royale de Chimie de Belgique, 1987
Foreign Fellow of the Academia des Ciencias de Lisboa, Lisbon, Portugal 1988
Member of the Consultative Council of the Scientific Section of the Fondazione dell'Istituto Bancario San Paolo di Torino per la cultura, la scienzia e l'arte, Turin, Italy, 1988
First Honorary Member of the Washington Evolutionary Systems Society, Washington, D.C., 1988
Honorary Member, International Academy of the History of Science, 1989
Member of the Academie Europaea, an extension of the Royal Academy of London, 1989
Member of the Argentine Academy of Science, 1989
Member of the National Academy of Engineering, Argentina, 1989
Honorary Member, Physical Society and Chemical Society of Tunisia, 1989
Member of the Editorial Board of the Ukrainian Physical Journal, USSR, 1990
Scientific Adviser of the International Academy for Biomedical Drug Research, 1990
Honorary Member of the Natural Sciences Academy of the Federal Republic of Russia, 1991

President, "Academia Nazionale delle Scienze" de la Republica di San Marino, Italy, 1991

Honorary Member, Academia Nazionale di Scienze Lettere e Arti, Modena, Italy, 1992

Honorary Member, Romanian Academy, Burcarest, Romania, 1994

Member of Comité de Patronage of the Special Olympics, Belgium, 1994

Senior Advisor of Keihanna Plaza-Kansai Science City, Japan, 1994

International Advisor de l'International Institute for Advanced Studies, Kyoto, Japan, 1994

Membre de l'Assemblé Europénne des Sciences et des Technologie, Communauté Européenne, 1994

Foreign Member of Academy of Sciences of Belarus (Minsk, Russia), 1995

Member, Honorary Board of the International Society for Theoretical Chemical Physics, Nuremberg, Germany, July 1995

Member of the Advisory Board, Kothari Centre for Science, Ethics and Education of the University of Delhi, India, 1995

Member, Society for Design and Process Science, Austin, Texas, April 1996

Member, Citizens for Europe, Belgium, April 1996

Honorary Member, Korean Society of Chemistry, Seoul, Korea, 1996

Member, International Scientific Advisory Board (ISAB), UNESCO, 1996

Member Honorary Editorial Board, *Dynamics of Continous, Discrete, and Implusive Systems,* 1996

Honorary President of the Editorial Board of the *International Journal of Chaos Theory & Applications,* 1997

Honorary Foreign Member of Korean Academy of Science and Technology, 1997

Member of International Academic Council, Universidad del Salvador, Buenos Aires, 1997

Member of the "Conseil du Futur", created by the UNESCO, September 1999

Member of the Ukraine National Academy of Sciences, April 2000

Member of the London Diplomatic Academy, 2002

Honoray President, Italian Institute for Philosophic Studies, Naples, 2002

Honorary Member of the World Innovation Foundation, Huddersfield, United Kingdom, November, 2002.

Honorary President of the Internataional Comission on Distance Education, created by the Committee of Non-governmental Organizations of the Economic and Social Council of United Nations, 2003

Prizes:

Van Laar Prize of the Société Chimique de Belgique, 1947

A. De Potter Prize of the Académie Royale de Belgique, 1949

A. Wetrems Prize of the Académie Royale de Belgique, 1950

Annual Prize of the Académie Royale de Belgique, Classe des Sciences, 1952

Francqui Prize of the Francqui Foundation, Brussels, 1955

E. J. Solvay Prize of the Fonds National de la Recherche Scientifique, Brussels, 1965

Swante Arrenius Gold Medal of the Royal Academy of Sciences of Sweden, 1969

Bourke Medal of the Chemical Society of Great Britain, 1972

Cothenius Gold Medal of the Deutsche Akademie der Naturforscher Leopoldina, Halle, 1975

Medal of the Association for the Advancement of Sciences, Paris, 1975

Annual First Prize of the Southwest Science Forum of the New York Academy of Science, 1976

Rumford Gold Medal of the Royal Society of London, 1976

American Chemical Society Centennial Fellow, 1976

Nobel Prize in Chemistry, Royal Academy of Sweden, 1977

Karcher Medal of the American Crystallographic Association, 1978

Descartes medal of the Université Descartes, Paris, 1979
Prix du Haut Comité de la Langue Française, scientific and technical category, Paris, 1981 (for *Order Out of Chaos*, with Isabelle Stengers)
Honda Prize of the Honda Foundation, Tokyo, 1983
Honorary Citizen of the City of Dallas, Texas, 1983
Citoyen d'Honneur de la Ville de Monpellier, France, 1983
Citoyen d'Honneur de la Commune d'Uccle, 1984
Commandeur dans l'Ordre des Arts et des Lettres, France, 1984
Umberto Biancamano Prize, Italy, 1987
Gold Medal of the Ville de Pavie, Italy, 1987
Gold Medal of the Ville d'Ostende, 1987
Award of the Gravity Research Foundation, for the essay "Thermodynamics and Cosmology", with J. Géhéniau, E. Gunzig and P. Nardone, 1988
Medal of the University of Padua, Italy, 1988
Commander of French Legion of Honor, 1988
Awarded the title Viscount by the King of Belgium for outstanding contributions to science, July 1989
National Science Foundation Distinguished Lecturer, 1989
Distinguished Service Medal, Austin, Texas, 1989
International Foundation for Artificial Intelligence Award for Scientific Achievement, Tokyo, 1990
Medal of the Imperial Order of the Rising Sun (gold and silver stars), 1991
First Homer Smith Medal, New York University School of Medicine, 1991
Gold Medal, Nice, France, 1991
Medal of the Ville de Milan, 1993
Medal of the Ville de Trieste, 1993
Summa Prize, Université Laval, Cite Universitaire, Quebec, 1993
Gold Medal of the Univeristy of Pavie, Italy, 1994
Professeur Kampé de Fériet Medal, Paris, 1994
Gold Medal of l'Ecole Normale Supérieure, Paris, 1995
Medal Piotr Kapitza, the Academy of Natural Science, Moscow, Russia, 1995

Honorary citizen of the City of Lubbock, Texas, 1995.
Honorary citizen of the town of Thessaloniki, Greece, 1996
Honorary citizen and gold medal, Athens, Greece, 1996
Medal of the town of Xanthi, Greece, 1996
Medal of the Hellenic Parliament, Greece, 1996
Creation of the Haute Ecole Libre Ilya Prigogine, Brussels, Belgium, 1996
Honorary Chairman of the Institute of Complex Systems, Thrace, Greece, 1996
Honorary President of the "Centro de Fisica No Lineal y Sistemas Complejo" de Universidad de Santiago, Chili, 1996
"Illya Prigogine Chair of the Philosophy of Sciences" (School of Humanities and Social Sciences), Universidad de Palermo, Argentine, 1996
Russian Friendship Scientific Prize, presented by President of Russia, 1996
Prize of the International Neural Network Society of Italy, 1997
Medal of the University of Messine, Italy, 1997
Scientific Prize of the President of the Italian Senate, Italy, 1997
Diamond Prize, Calabria, Italy, 1997
Calabria Prize for the book, "La Fin des Certitudes", 1997
Médaille de l'Université de Reggio di Calabria, Italy, 1997
Medal of the President of the Italian Senate awarded by the "Pio Manzu Internaitonal Research Center", Italy, 1997
Médaille AMPERE, Luxembourg, 1998
Medal of the University of Verona, Italy, 1998
Gold Medal "La Rosa Commacina" city of Pescara, Italy, 1999
Honorary citizen of the city of Pescara, Italy, 1999
First "N.N. Bogolyubov Prize", Joint Institute for Nuclear Research (Dubna), 1999
Creation of "Prigogine Lectures", Università dell'Insubria (Université Lombarde), Como, Italy, 1999
Targa Giuseppe Piazzi, Palermo, Italy, 1999
Prix Ilya Prigogine de Thermodynamique, awarded by the CERET (Centre de Recherche sur la Thermodynamique), Paris, France, 1999

Creation of the International Scientific Award Professor Prigogine, Universidad del Salvador, Buenos Aires, Argentina 1999

Gold Medal of Odessa State Medical University, Ukraine, 2000

V. I. Vernadskiy Silver Medal, The Academy of Natural Sciences of Russia, 2001

University Peace and Science Gold Medal, Albert Schweitzer International University, 2001

Antonio Roberti International Prize, Italian Institute for Philosophic Studies, Naples, 2002

Gold Medal Lomonosov, Interantional Academy of Information, Russia, 2003

Honorary Degrees:

D. Honoris Causa, University of Newcastle Upon Tyne, England, 1966

D. Honoris Causa, Université de Poitiers, France, 1966

D. Honoris Causa, University of Chicago, 1969

D. Honoris Causa, Université de Bordeaux, 1972

D. Honoris Causa, Université de Liège, Belgium, 1977

D. Honoris Causa, University of Uppsala, Sweden, 1977

D. Honoris Causa, Université de Droit, d'Economie et des Sciences, Aix-Marseille, 1979

D. Honoris Causa, Georgetown University, 1980

D. Honoris Causa, Stevens Institute of Technology, 1981

D. Honoris Causa, University of Krakow, Poland, 1981

D. Honoris Causa, University of Rio de Janeiro, 1981

D. Honoris Causa, Universidad Nacional Educación a Distancia, Madrid, 1985

D. Honoris Causa, Heriot-Watt University, Edinburgh, 1985

D. Honoris Causa, François Rabelais Université de Tours, 1986

D. Honoris Causa, Nanjing University, People's Republic of China, 1986

Honorary Professor, Nanjing University, People's Republic of China, 1986

D. Honoris Causa, Beijing University, People's Republic of China, 1986

Honorary Professor, Benares Hindu University at Varasani, India, 1988

D. Honoris Causa, University of Buenos Aires, Argentina, 1989

D. Honoris Causa, Gustavus Adolphus College of the University of Minnesota, 1990

D. Honoris Causa, University of Cagliari, Sardinia, Italy, 1990

D. Honoris Causa, University of Siena, Italy, 1990

D. Honoris Causa, University of Nice-Sophia-Antipolis, Nice, France, 1991

D. Honoris Causa, University of Santiago, Chile, 1991

D. Honoris Causa, Tucumán, Argentina, 1991

D. Honoris Causa, University of Philippines System, Quezon City, Philippines, 1992

D. Honoris Causa, Lomonosov University of Moscow, Russia, 1993

D. Honoris Causa, Universitatea "Al. I. Cuza", Iasi, Romania, 1993

D. Honoris Causa, Universidad Nacional de San Luis, Argentina, October 1994

D. Honoris Causa, Universidad de Palermo, Buenos Aires, Argentina, October 1994

D. Honoris Causa, Binghamton University, Binghamton, New York, April 1995

D. Honoris Causa, Universidad de Valladolid, Spain, May 1995

D. Honoris Causa, Institut National Polytechnique de Lorraine, Nancy, France, June 1995

D. Honoris Causa, Vrije Universiteit Brussel, Brussels, Belgium, May 1995

D. Honoris Causa de "International Association of University Presidents", Seoul, Republic of Korea, 1995

Doyen d'honneur Honoris Causa de l'Institut Royal des Elites du Travail de Belgique Albert 1er, Brussels, Belgium, 1995

D. Honoris Causa, University of Kerala, India, 1995

D. Honoris Causa, Universita' degli Studi Istituto Filosofia, Urbino, Italy, 1996

D. Honoris Causa, University of St. Petersburg, Russia, 1996

D. Honoris Causa, Engineering Faculty (University of Xanthi), Greece, 1996

D. Honoris Causa, University of Salvador, Buenos Aires, Argentina, 1996

D. Honoris Causa in Philosopy, Aristotle University of Thessaloniki, Greece, 1998

D. Honoris Causa in Science, Aristotle University of Thessaloniki, Greece, 1998

D. Honoris Causa in Applied Science, Aristotle University of Thessaloniki, Greece, 1998

D. Honoris Causa, National Institute of Astrophyics, Optics and Electronics, Puebla, Mexico, 1998

D. Honoris Causa, Wroclaw University of Technology, Poland, 1998

D. Honoris Causa, Universidad Nacional Autónoma de México, Mexico City, 1998

D. Honoris Causa, Department of Chemical Engineering, National Polytechnic School, Athens, Greece, 2000

D. Honoris Causa, Department of Electrical Engineering and Computer Engineering, National Polytechnic School, Athens, Greece, 2000

D. Honoris Causa, Department of Applied Mathematics and Physical Sciences, National Polytechnic School, Athens, Greece, 2000

D. Honoris Causa, Odessa Medical University, Ukraine, 2000

Honorary Professor of the International Albert Schweitzer University, Geneva, Switzerland, 2001

D. Honoris Causa, the Academy of Slovak Republic, 2002

Monographs:

Contribution a l'étude spectroscopique dans l'infra-rouge proche de la liaison d'hydrogène et la structure des solutions (Académie Royale de Belgique, Classe des sciences), *Mémoires* **20**, 1943.

I. Prigogine and R. Defay, *Traité de Thermodynamique Conformément aux Méthodes de Gibbs et de Donder*, Vol. I. *Thermodynamique Chimique* (first edition, 1944; second edition, 1950); Vol. II.

Tension Superficielle et Adsorption (Desoer: Liège, 1951). Translations in English, German, Russian, and Japanese.

I. Prigogine, *Étude Thermodynamique des Phénomènes Irréversibles,* Ph.D. Thesis, presented in 1945 (published by Dunod, 1947).

I. Prigogine, *Introduction to Thermodynamics of Irreversible Processes* (Charles C. Thomas Publisher (American Lecture Series): 1954; Second edition: John Wiley & Sons [Interscience Division]: New York, 1962; Third edition, idem., 1967). Translations in Russian, Serbo-Croatian, French, Italian and Spanish.

I. Prigogine and R. Defay, *Chemical Thermodynamics,* Longmans Green & Co., 1954.

I. Prigogine, A. Bellemans and V. Mathot, *The Molecular Theory of Solutions* (North-Holland Publishing Co.: Amsterdam, 1957).

I. Prigogine, *Nonequilibrium Statistical Mechanics* (John Wiley & Sons [Interscience Division]: New York, 1962).

P. Glansdorff and I. Prigogine, *Thermodynamic Theory of Structure, Stability and Fluctuations* (John Wiley & Sons [Interscience]: New York, 1971). Translations in French, Russian and Japanese.

I. Prigogine and R. Herman, *Kinetic Theory of Vehicular Traffic* (Elsevier: New York, 1971).

G. Nicolis and I. Prigogine, *Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuations* (John Wiley [Interscience]: New York, 1977). Translations in Russian, Japanese, Italian and Chinese.

I. Prigogine and I. Stengers, *La Nouvelle Alliance — Les Métamorphoses de la Science* (Gallimard: Paris, 1979, 1981, 1986). English version: *Order Out of Chaos* (Bantam: New York, 1984). Translations in 18 languages.

I. Prigogine, *From Being to Becoming: Time and Complexity in the Physical Sciences* (W. H. Freeman & Company: San Francisco, 1980). Translations in 8 languages.

I. Prigogine, *Tan Sólo una Ilusión? Una Exploración del Caos al Orden* (Tusquets Editiones: Madrid, 1983).

I. Prigogine and G. Nicolis, *Exploring Complexity* (W. H. Freeman: New York, 1989); German translation: *Die Erforschung des Komplexen* (R. Piper & Co. Verlag: München, 1987); Chinese translation: *Tansuo Fuzaxing* (Sechuan Education Publishing House, Chengdu, 1987); Translations in 6 languages.

I. Prigogine and I. Stengers, *Entre le Temps et l'Éternité* (Librairie Arthème Fayard: Paris, 1988); second edition, Flammarion, Paris, 1992. Translations in 5 languages.

I. Prigogine, *Les Lois des Chaos*, Collection "Nouvelle Bibliothèque Scientfiques" (Flammarion, Paris, France, 1994).

I. Prigogine, *Time, Chaos and the Laws of Chaos* (Ed. Progress, Moscow, 1994).

I. Prigogine and I. Stengers, *The End of Certainty — Time's Flow and the Laws of Nature* (The Free Press, New York, 1997). Translations in 19 languages.

D. Kondepudi and I. Prigogine, *Modern Thermodynamics, From Heat Engines to Dissipative Structures* (John Wiley & Sons, Chichester, 1998). "Thermodynamique — Des moteurs thermiques aux structures dissipatives", Editions Odile Jacob, Paris, France, 1999 (French translation). Also translated into Greek, Russian, Chinese and Japanese.

I. Prigogine, *L'homme devant l'incertain* (Editions Odile Jacob, Paris, 2001).

Publications since 1964:

(with P. Glansdorff) "On a General Evolution Criterion in Macroscopic Physics", *Physica* **30** (1964) 351–374.

(with P. Résibois) "Temps et Irréversibilité en Physique Statistique", Estratto Dagli Atti del Simposio Lagrangiano, *Accademia delle Scienze di Torino* (1964) 1–42.

"Steady States and Entropy Production", *Physica* **31** (1964) 719–724.

(with P. de Gottal) "Relativistic Effects in Statistical Hydrodynamics", *Physica* **31** (1965) 877–887.

(with P. Glansdorff) "Variational Properties and Fluctuations", *Physica* **31** (1965) 1242–1256.

(with F. Henin) "On a Reformulation of Classical Electron Theory", *Mémoires Académie Royale Belg., Cl. des Sc.* **35** (1965) 7.

(with F. Henin, P. Realbeig and M. Watabe) "Kinetic Equations, Quasi-Particle Renormalization, and Kinetic Theory", *Physics Letters* **16** (1965) 253–254.

"Transport Processes, Correlation Functions and Reciprocity Relations in Dense Media", *Liquids, Structure, Properties of Solid Interactions* (Elsevier: 1965) 142–151.

(with G. Nicolis and J. Misguich) "Local Equilibrium Approach to Transport Processes in Dense Media", *Journal of Chemical Physics* **43** (1965) 4516–4521.

"Sur la Théorie Mathématique de Traffique Véhiculaire", *Cahiers du Centre d'Etudes de Recherche Operationnelle* **7** (1965) 3–4.

"Quelques Remarques sur la Structure de la Physique", *Rev. Int. de Philosophie* **73** (1965) 74.

"Entropy and Gravitation", *Nature* **209** (1966) 602–603.

(with G. Severne) "On the Statistical Mechanics of Gravitational Plasmas", *Physica* **32** (1966) 1376–1396.

"Evolution Criteria, Variational Properties and Fluctuation", in *Non-Equilibrium Thermodynamics: Variational Techniques and Fluctuations* (Chicago University Press: 1966) 3–16.

(with F. Henin and Cl. George) "Entropy and Quasiparticle Description of Anharmonic Lattices", *Physica* **32** (1966) 1873–1900.

(with F. Henin) "On the Entropy of Strongly Interacting Systems", *Physics Letters* **20**, 3 (1966) 255–257.

(with F. Mayné) "On the Application of Non-Equilibrium Statistical Mechanics to Quantum Field Theory", *Physics Letters* **21**, 1 (1966) 42–44.

(with F. Henin, Cl. George and F. Mayné) "Kinetic Equations and Quasi-particle Description", *Physica* **32** (1966) 1828–1872.

"Temps, Structure et Entropie", *Bull. Cl. Sc. Acad. Roy. Belg.* **53** (1967) 273–287.

(with G. Nicolis) "On Symmetry-Breaking Instabilities in Dissipative Systems", *Journal of Chemical Physics* **46**, 9 (1967) 3542–3550.

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IS FUTURE GIVEN?

In this book, after discussing the fundamental problems of current science and other philosophic concepts, beginning with controversies between Heraclitus and Parmenides, Ilya Prigogine launches into a message of great hope: the future has not been determined. Contrary to globalisation and the apparent contemporary mass culture society, individual behaviour is beginning to increasingly become the key factor which governs the evolution of both the world and society as a whole. It is a message that challenges existing widespread views, implicitly or explicitly, through mass communication; moreover the importance of the individual's actions implies a reflection of each person on the responsibilities that each one assumes when taking or acting upon a decision. This responsibility is associated with the freedom of thought as well as a critical analysis of fashions, customs, preconceived ideas, and ideologies, externally imposed: exactly contrary to the ideas of those who wish us to be "perfect consumers" in a world dominated only by monetary wealth.

Challenging this drive towards the elimination of freedom of thought in the individual is now imperative if we are to save man and his planet from catastrophe, which seems to be ever imminent and (unfortunately) irreversible.

This last book of Ilya Prigogine provides a small, disputable, but nonetheless valuable contribution towards that end.

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