The Challenge to Science (1984)

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Our vision of nature is undergoing a radical change toward the multiple, the temporal, and the complex.

Detail from a photo of carvings of dancing Shiva and Matrikas at Aihole, Bagalkot, Karnataka, India. via Wikimedia Commons.

Set 15 of our Radical Thinkers *series brings together four classic works in the history of science, including Ilya Prigogine and Isabelle Stengers'* Order Out of Chaos: Man's New Dialogue With Nature*. First published in 1984, this pioneering book showed how the two great themes of classic science, order and chaos, were being reconciled in a new and unexpected synthesis. Below, we present Prigogine and Stengers' introduction to the book.*

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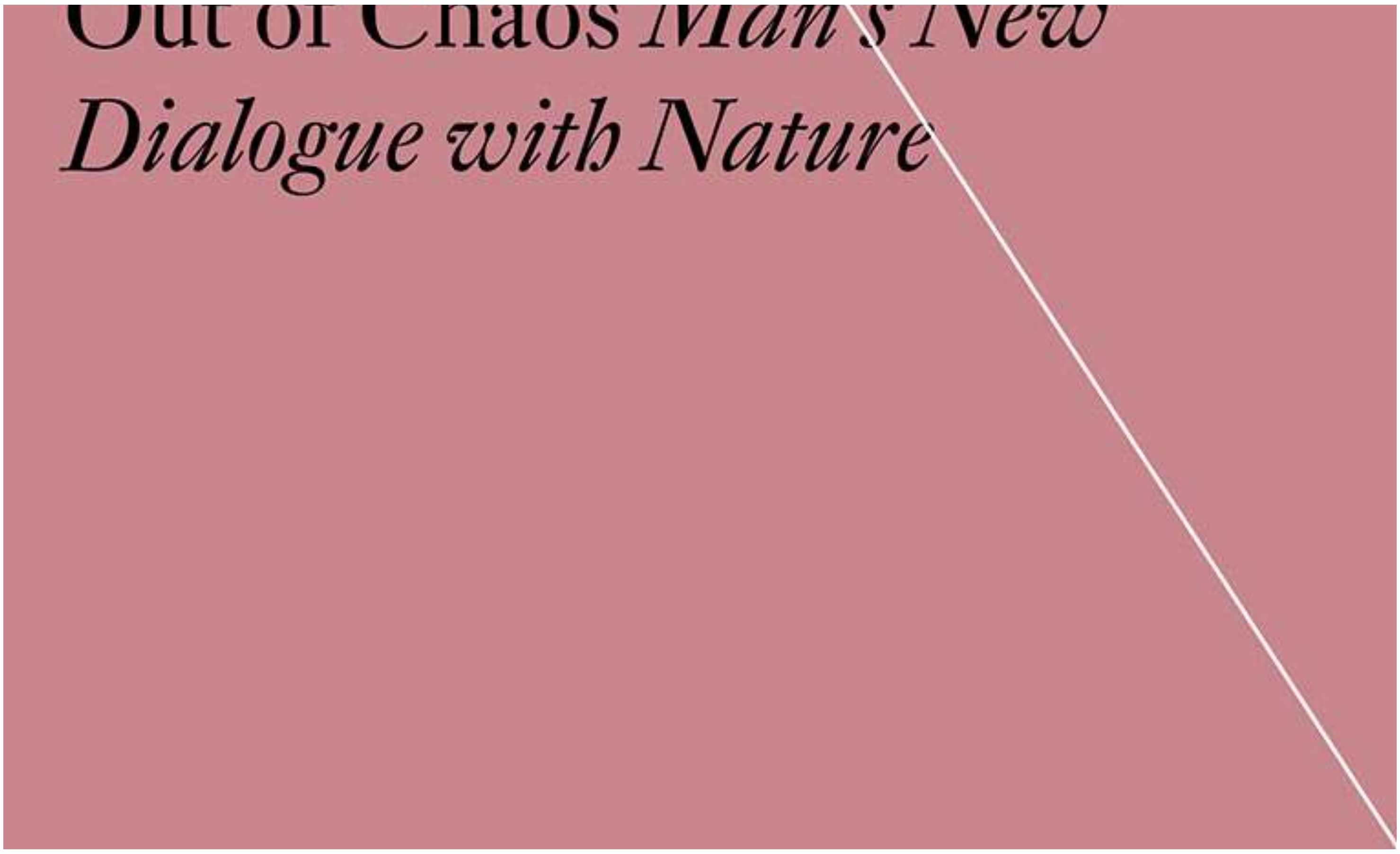

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“A passionate meditation on Man and Universe.”

– Italo Calvino

1.

It is hardly an exaggeration to state that one of the greatest dates in the history of mankind was

April 28, 1686, when Newton presented his *Principia* to the Royal Society of London. It contained the basic laws of motion together with a clear formulation of some of the fundamental concepts we still use today, such as mass, acceleration, and inertia. The greatest impact was probably made by Book III of the *Principia*, titled *The System of the World*, which included the universal law of gravitation. Newton's contemporaries immediately grasped the unique importance of his work. Gravitation became a topic of conversation both in London and Paris.

Three centuries have now elapsed since Newton's *Principia*. Science has grown at an incredible speed, permeating the life of all of us. Our scientific horizon has expanded to truly fantastic proportions. On the microscopic scale, elementary particle physics studies processes involving physical dimensions of the order of 10^{-15} cm and times of the order of 10^{-22} second. On the other hand, cosmology leads us to times of the order of 10^{10} years, the “age of the universe." Science and technology are closer than ever. Among other factors, new biotechnologies and the progress in information techniques promise to change our lives in a radical way.

Running parallel to this quantitative growth are deep qualitative changes whose repercussions reach far beyond science proper and affect the very image of nature. The great founders of Western science stressed the universality and the eternal character of natural laws. They set out to formulate general schemes that would coincide with the very ideal of rationality. As Roger Hausheer says in his fine introduction to Isaiah Berlin's *Against the Current*, "They sought all-embracing schemas, universal unifying frameworks, within which everything that exists could be shown to be systematically — i.e., logically or causally-interconnected, vast structures in which there should be no gaps left open for spontaneous, unattended developments, where everything that occurs should be, at least in principle, wholly explicable in terms of immutable general laws." **1**

The story of this quest is indeed a dramatic one. There were moments when this ambitious program seemed near completion. A fundamental level from which all other properties of matter could be deduced seemed to be in sight. Such moments can be associated with the formulation of Bohr's celebrated atomic model, which reduced matter to simple planetary systems formed by electrons and protons. Another moment of great suspense came when Einstein hoped to condense all the laws of physics into a single “unified field theory.” Great progress has indeed been realized in the unification of some of the basic forces found in nature. Still, the fundamental level remains elusive. Wherever we look we find evolution, diversification, and instabilities. Curiously, this is true on all levels, in the field of elementary particles, in biology, and in astrophysics, with the expanding universe and the formation of black holes.

As we said in the Preface, our vision of nature is undergoing a radical change toward the multiple, the temporal, and the complex. Curiously, the unexpected complexity that has been discovered in nature has not led to a slowdown in the progress of science, but on the contrary to the emergence of new conceptual structures that now appear as essential to our understanding of the physical world — the world that includes us. It is this new situation, which has no precedent in the history of science, that we wish to analyze in this book.

The story of the transformation of our conceptions about science and nature can hardly be separated from another story, that of the feelings aroused by science. With every new intellectual program always come new hopes, fears, and expectations. In classical science the emphasis was on time-independent laws. As we shall see, once the particular state of a system has been measured, the reversible laws of classical science are supposed to determine its future, just as they had determined its past. It is natural that this quest for an eternal truth behind changing phenomena aroused enthusiasm. But it also came as a shock that nature described in this way was in fact debased: by the very success of science, nature was shown to be an automaton, a robot.

The urge to reduce the diversity of nature to a web of illusions has been present in Western thought since the time of Greek atomists. Lucretius, following his masters Democritus and Epicurus, writes that the world is "just” atoms and void and urges us to look for the hidden behind the obvious: "Still, lest you happen to mistrust my words, because the eye cannot perceive prime bodies, hear now of particles you must admit exist in the world and yet cannot be seen.” **2**

Yet it is well known that the driving force behind the work of the Greek atomists was not to debase nature but to free men from fear, the fear of any supernatural being, of any order that would transcend that of men and nature. Again and again Lucretius repeats that we have nothing to fear, that the essence of the world is the ever-changing associations of atoms in the void.

Modern science transmuted this fundamentally ethical stance into what seemed to be an established truth; and this truth, the reduction of nature to atoms and void, in turn gave rise to what Lenoble **3** has called the "anxiety of modern men." How can we recognize ourselves in the random world of the atoms? Must science be defined in terms of rupture between man and nature? "All bodies, the firmament, the stars, the earth and its kingdoms are not equal to the lowest mind; for mind knows all this in itself and these bodies nothing." **4** This "Pensée" by Pascal expresses the same feeling of alienation we find among contemporary scientists such as Jacques Monod:

> Man must at last finally awake from his millenary dream; and in doing so, awake to his total solitude, his fundamental isolation. Now does he at last realize that, like a gypsy, he lives on the boundary of an alien world. A world that is deaf to his music, just as indifferent to his hopes as it is to his suffering or his crimes. **5**

This is a paradox. A brilliant breakthrough in molecular biology, the deciphering of the genetic code, in which Monod actively participated, ends upon a tragic note. This very progress, we are told, makes us the gypsies of the universe. How can we explain this situation? Is not science a way of communication, a dialogue with nature?

In the past, strong distinctions were frequently made between man's world and the supposedly alien natural world. A famous passage by Vico in *The New Science* describes this most vividly:

> ... in the night of thick darkness enveloping the earliest antiquity, so remote from ourselves, there shines the eternal and never failing light of a truth beyond all question: that the world of civil society has certainly been made by men, and that its principles are therefore to be found within the modifications of our own human mind. Whoever reflects on this cannot but marvel that the philosophers should have bent all their energies to the study of the world of nature, which, since God made it, He alone knows; and that they should have neglected the study of the world of nations, or civil world, which, since men had made it, men could come to know. **6**

Present-day research leads us farther and farther away from the opposition between man and the natural world. It will be one of the main purposes of this book to show, instead of rupture and opposition, the growing coherence of our knowledge of man and nature.

2.

In the past, the questioning of nature has taken the most diverse forms. Sumer discovered writing; the Sumerian priests speculated that the future might be written in some hidden way in the events taking place around us in the present. They even systematized this belief, mixing magical and rational elements. **7** In this sense we may say that Western science, which originated in the seventeenth century, only opened a new chapter in the everlasting dialogue between man and nature.

Alexandre Koyré **8** has defined the innovation brought about by modern science in terms of "experimentation." Modern science is based on the discovery of a new and specific form of communication with nature — that is, on the conviction that nature responds to experimental interrogation. How can we define more precisely the experimental dialogue? Experimentation does not mean merely the faithful observation of facts as they occur, nor the mere search for empirical connections between phenomena, but presupposes a systematic interaction between theoretical concepts and observation.

In hundreds of different ways scientists have expressed their amazement when, on determining the right question, they discover that they can see how the puzzle fits together. In this sense, science is like a two-partner game in which we have to guess the behavior of a reality unrelated to our beliefs, our ambitions, or our hopes. Nature cannot be forced to say anything we want it to. Scientific investigation is not a monologue. It is precisely the risk involved that makes this game exciting.

But the uniqueness of Western science is far from being exhausted by such methodological considerations. When Karl Popper discussed the normative description of scientific rationality, he was forced to admit that in the final analysis rational science owes its existence to its success; the scientific method is applicable only by virtue of the astonishing points of agreement between preconceived models and experimental results. **9** Science is a risky game, but it seems to have discovered questions to which nature provides consistent answers.

The success of Western science is an historical fact, unpredictable a priori, but which cannot be ignored. The surprising success of modern science has led to an irreversible transformation of our relations with nature. In this sense, the term "scientific revolution" can legitimately be used. The history of mankind has been marked by other turning points, by other singular conjunctions of circumstances leading to irreversible changes. One such crucial event is known as the "Neolithic revolution." But there, just as in the case of the "choices" marking biological evolution, we can at present only proceed by guesswork, while there is a wealth of information concerning decisive episodes in the evolution of science. The so-called "Neolithic revolution" took thousands of years. Simplifying somewhat, we may say the scientific revolution started only three centuries ago. We have what is perhaps a unique opportunity to apprehend the specific and intelligible mixture of "chance" and "necessity" marking this revolution.

Science initiated a successful dialogue with nature. On the other hand, the first outcome of this dialogue was the discovery of a silent world. This is the paradox of classical science. It revealed to men a dead, passive nature, a nature that behaves as an automaton which, once programmed, continues to follow the rules inscribed in the program. In this sense the dialogue with nature isolated man from nature instead of bringing him closer to it. A triumph of human reason turned into a sad truth. It seemed that science debased everything it touched.

Modern science horrified both its opponents, for whom it appeared as a deadly danger, and some of its supporters, who saw in man's solitude as "discovered" by science the price we had to pay for this new rationality.

The cultural tension associated with classical science can be held at least partly responsible for the unstable position of science within society; it led to an heroic assumption of the harsh implications of rationality, but it led also to violent rejection. We shall return later to present-day antiscience movements. Let us take an earlier example — the irrationalist movement in Germany in the 1920s that formed the cultural background to quantum mechanics. **10** In opposition to science, which was identified with a set of concepts such as causality, determinism, reductionism, and rationality, there was a violent upsurge of ideas denied by science but seen as the embodiment of the fundamental irrationality of nature. Life, destiny, freedom, and spontaneity thus became manifestations of a shadowy underworld impenetrable to reason. Without going into the peculiar sociopolitical context to which it owed its vehement nature, we can state that this rejection illustrates the risks associated with classical science. By admitting only a subjective meaning for a set of experiences men believe to be significant, science runs the risk of transferring these into the realm of the irrational, bestowing upon them a formidable power.

As Joseph Needham has emphasized, Western thought has always oscillated between the world as an automaton and a theology in which God governs the universe. This is what Needham calls the "characteristic European schizophrenia." **11** In fact, these visions are connected. An automaton needs an external god.

Do we really have to make this tragic choice? Must we choose between a science that leads to alienation and an antiscientific metaphysical view of nature? We think such a choice is no longer necessary, since the changes that science is undergoing today lead to a radically new situation. This recent evolution of science gives us a unique opportunity to reconsider its position in culture in general. Modern science originated in the specific context of the European seventeenth century. We are now approaching the end of the twentieth century, and it seems that some more *universal message* is carried by science, a message that concerns the interaction of man and nature as well as of man with man.

3.

What are the assumptions of classical science from which we believe science has freed itself today? Generally those centering around the basic conviction that at some level *the world is simple* and is governed by time-reversible fundamental laws. Today this appears as an excessive simplification. We may compare it to reducing buildings to piles of bricks. Yet out of the same bricks we may construct a factory, a palace, or a cathedral. It is on the level of the building as a whole that we apprehend it as a creature of time, as a product of a culture, a society, a style. But there is the additional and obvious problem that, since there is no one to build nature, we must give to its very “bricks" — that is, to its microscopic activity — a description that accounts for this building process.

The quest of classical science is in itself an illustration of a dichotomy that runs throughout the history of Western thought. Only the immutable world of ideas was traditionally recognized as "illuminated by the sun of the intelligible,” to use Plato's expression. In the same sense, only eternal laws were seen to express scientific rationality. Temporality was looked down upon as an illusion. This is no longer true today. We have discovered that far from being an illusion, irreversibility plays an essential role in nature and lies at the origin of most processes of self-organization. We find ourselves in a world in which reversibility and determinism apply only to limiting, simple cases, while irreversibility and randomness are the rules.

The denial of time and complexity was central to the cultural issues raised by the scientific enterprise in its classical definition. The challenge of these concepts was also decisive for the metamorphosis of science we wish to describe. In his great book *The Nature of the Physical World*, Arthur Eddington **12** introduced a distinction between primary and secondary laws. "Primary laws" control the behavior of single particles, while "secondary laws" are applicable to collections of atoms or molecules. To insist on secondary laws is to emphasize that the description of elementary behaviors is not sufficient for understanding a system as a whole. An outstanding case of a secondary law is, in Eddington's view, the second law of thermodynamics, the law that introduces the "arrow of time" in physics. Eddington writes: “From the point of view of philosophy of science the conception associated with entropy must, I think, be ranked as the great contribution of the nineteenth century to scientific thought. It marked a reaction from the view that everything to which science need pay attention is discovered by a microscopic dissection of objects." **13** This trend has been dramatically amplified today.

It is true that some of the greatest successes of modern science are discoveries at the microscopic level, that of molecules, atoms, or elementary particles. For example, molecular biology has been immensely successful in isolating specific molecules that play a central role in the mechanism of life. In fact, this success has been so overwhelming that for many scientists the aim of research is identified with this "microscopic dissection of objects," to use Eddington's expression. However, the second law of thermodynamics presented the first challenge to a concept of nature that would explain away the complex and reduce it to the simplicity of some hidden world. Today interest is shifting from substance to relation, to communication, to time.

This change of perspective is not the result of some arbitrary decision. In physics it was forced upon us by new discoveries no one could have foreseen. Who would have expected that most (and perhaps all) elementary particles would prove to be unstable? Who would have expected that with the experimental confirmation of an expanding universe we could conceive of the history of the world as a whole?

At the end of the twentieth century we have learned to understand better the meaning of the two great revolutions that gave shape to the physics of our time, quantum mechanics and relativity. They started as attempts to correct classical mechanics and to incorporate into it the newly found universal constants. Today the situation has changed. Quantum mechanics has given us the theoretical frame to describe the incessant transformations of particles into each other. Similarly, general relativity has become the basic theory in terms of which we can describe the thermal history of our universe in its early stages.

Our universe has a pluralistic, complex character. Structures may disappear, but also they may appear. Some processes are, as far as we know, well described by deterministic equations, but others involve probabilistic processes.

How then can we overcome the apparent contradiction between these concepts? We are living in a single universe. As we shall see, we are beginning to appreciate the meaning of these problems. Moreover, the importance we now give to the various phenomena we observe and describe is quite different from, even opposite to, what was suggested by classical physics. There the basic processes, as we mentioned, are considered as deterministic and reversible. Processes involving randomness or irreversibility are considered to be exceptions. Today we see everywhere the role of irreversible processes, of fluctuations. The models considered by classical physics seem to us to occur only in limiting situations such as we can create artificially by putting matter into a box and then waiting till it reaches equilibrium.

The artificial may be deterministic and reversible. The natural contains essential elements of randomness and irreversibility. This leads to a new view of matter in which matter is no longer the passive substance described in the mechanistic world view but is associated with spontaneous activity. This change is so profound that, as we stated in our Preface, we can really speak about a new dialogue of man with nature.

4.

This book deals with the conceptual transformation of science from the Golden Age of classical science to the present. To describe this transformation we could have chosen many roads. We could have studied the problems of elementary particles. We could have followed recent fascinating developments in astrophysics. These are the subjects that seem to delimit the frontiers of science. However, as we stated in our Preface, over the past years so many new features of nature at our level have been discovered that we decided to concentrate on this intermediate level, on problems that belong mainly to our macroscopic world, which includes atoms, molecules, and especially biomolecules. Still it is important to emphasize that the evolution of science proceeds on somewhat parallel lines at every level, be it that of elementary particles, chemistry, biology, or cosmology. On every scale self-organization, complexity, and time play a new and unexpected role.

Therefore, our aim is to examine the significance of three centuries of scientific progress from a definite viewpoint. There is certainly a subjective element in the way we have chosen our material. The problem of time is really the center of the research that one of us has been pursuing all his life. When as a young student at the University of Brussels he came into contact with physics and chemistry for the first time, he was astonished that science had so little to say about time, especially since his earlier education had centered mainly around history and archaeology. This surprise could have led him to two attitudes, both of which we find exemplified in the past: one would have been to discard the problem, since classical science seemed to have no place for time; and the other would have been to look for some other way of apprehending nature, in which time would play a different, more basic role. This is the path Bergson and Whitehead, to mention only two philosophers of our century, chose. The first position would be a “positivistic" one, the second a "metaphysical” one.

There was, however, a third path, which was to ask whether the simplicity of the temporal evolution traditionally considered in physics and chemistry was due to the fact that attention was paid mainly to some very simplified situations, to heaps of bricks in contrast with the cathedral to which we have alluded.

This book is divided into three parts. The first part deals with the triumph of classical science and the cultural consequences of this triumph. Initially, science was greeted with enthusiasm. We shall then describe the cultural polarization that occurred as a result of the *existence* of classical science and its astonishing success. Is this success to be accepted as such, perhaps limiting its implications, or must the scientific method itself be rejected as partial or illusory? Both choices lead to the same result — the collision between what has often been called the "two cultures," science and the humanities.

These questions have played a basic role in Western thought since the formulation of classical science. Again and again we come to the problem, "How to choose?" Isaiah Berlin has rightly seen in this question the beginning of the schism between the sciences and the humanities:

> The specific and unique versus the repetitive and the universal, the concrete versus the abstract, perpetual movement versus rest, the inner versus the outer, quality versus quantity, culture-bound versus timeless principles, mental strife and self-transformation as a permanent condition of man versus the possibility (and desirability) of peace, order, final harmony and the satisfaction of all rational human wishes—these are some of the aspects of the contrast. **14**

We have devoted much space to classical mechanics. Indeed, in our view this is the best vantage point from which we may contemplate the present-day transformation of science. Classical dynamics seems to express in an especially clear and striking way the static view of nature. Here time apparently is reduced to a parameter, and future and past become equivalent. It is true that quantum theory has raised many new problems not covered by classical dynamics but it has nevertheless retained a number of the conceptual positions of classical dynamics, particularly as far as time and process are concerned.

As early as at the beginning of the nineteenth century, precisely when classical science was triumphant, when the Newtonian program dominated French science and the latter dominated Europe, the first threat to the Newtonian construction loomed into sight. In the second part of our study we shall follow the development of the science of heat, this rival to Newton's science of gravity, starting from the first gauntlet thrown down when Fourier formulated the law governing the propagation of heat. It was, in fact, the first quantitative description of something inconceivable in classical dynamics — an irreversible process.

The two descendants of the science of heat, the science of energy conversion and the science of heat engines, gave birth to the first “nonclassical" science — thermodynamics. The most original contribution of thermodynamics is the celebrated second law, which introduced into physics the arrow of time. This introduction was part of a more global intellectual move. The nineteenth century was really the century of evolution; biology, geology, and sociology emphasized processes of becoming, of increasing complexity. As for thermodynamics, it is based on the distinction of two types of processes: reversible processes, which are independent of the direction of time, and irreversible processes, which depend on the direction of time. We shall see examples later. It was in order to distinguish the two types of processes that the concept of entropy was introduced, since entropy increases only because of the irreversible processes.

During the nineteenth century the final state of thermodynamic evolution was at the center of scientific research. This was equilibrium thermodynamics. Irreversible processes were looked down on as nuisances, as disturbances, as subjects not worthy of study. Today this situation has completely changed. We now know that far from equilibrium, new types of structures may originate spontaneously. In far-from-equilibrium conditions we may have transformation from disorder, from thermal chaos, into order. New dynamic states of matter may originate, states that reflect the interaction of a given system with its surroundings. We have called these new structures *dissipative structures* to emphasize the constructive role of dissipative processes in their formation.

This book describes some of the methods that have been developed in recent years to deal with the appearance and evolution of dissipative structures. Here we find the key words that run throughout this book like leitmotivs: nonlinearity, instability, fluctuations. They have begun to permeate our view of nature even beyond the fields of physics and chemistry proper.

We cited Isaiah Berlin when we discussed the opposition between the sciences and the humanities. He opposed the specific and unique to the repetitive and the universal. The remarkable feature is that when we move from equilibrium to far-from-equilibrium conditions, we move away from the repetitive and the universal to the specific and the unique. Indeed, the laws of equilibrium are universal. Matter near equilibrium behaves in a “repetitive" way. On the other hand, far from equilibrium there appears a variety of mechanisms corresponding to the possibility of occurrence of various types of dissipative structures. For example, far from equilibrium we may witness the appearance of chemical clocks, chemical reactions which behave in a coherent, rhythmical fashion. We may also have processes of self-organization leading to nonhomogeneous structures to nonequilibrium crystals.

We would like to emphasize the unexpected character of this behavior. Every one of us has an intuitive view of how a chemical reaction takes place; we imagine molecules floating through space, colliding, and reappearing in new forms. We see chaotic behavior similar to what the atomists described when they spoke about dust dancing in the air. But in a chemical clock the behavior is quite different. Oversimplifying somewhat, we can say that in a chemical clock all molecules change their chemical identity *simultaneously*, at regular time intervals. If the molecules can be imagined as blue or red, we would see their change of color following the rhythm of the chemical clock reaction.

Obviously such a situation can no longer be described in terms of chaotic behavior. A new type of order has appeared. We can speak of a new coherence, of a mechanism of “communication” among molecules. But this type of communication can arise only in far-from-equilibrium conditions. It is quite interesting that such communication seems to be the rule in the world of biology. It may in fact be taken as the very basis of the definition of a biological system.

In addition, the type of dissipative structure depends critically on the conditions in which the structure is formed. External fields such as the gravitational field of earth, as well as the magnetic field, may play an essential role in the selection mechanism of self-organization.

We begin to see how, starting from chemistry, we may build complex structures, complex forms, some of which may have been the precursors of life. What seems certain is that these far-from-equilibrium phenomena illustrate an essential and unexpected property of matter: physics may henceforth describe structures as adapted to outside conditions. We meet in rather simple chemical systems a kind of prebiological adaptation mechanism. To use somewhat anthropomorphic language: in equilibrium matter is "blind," but in far-from-equilibrium conditions it begins to be able to perceive, to "take into account," in its way of functioning, differences in the external world (such as weak gravitational or electrical fields).

Of course, the problem of the origin of life remains a difficult one, and we do not think a simple solution is imminent. Still, from this perspective life no longer appears to oppose the “normal” laws of physics, struggling against them to avoid its normal fate — its destruction. On the contrary, life seems to express in a specific way the very conditions in which our biosphere is embedded, incorporating the nonlinearities of chemical reactions and the far-from-equilibrium conditions imposed on the biosphere by solar radiation.

We have discussed the concepts that allow us to describe the formation of dissipative structures, such as the theory of bifurcations. It is remarkable that near-bifurcations systems present large fluctuations. Such systems seem to “hesitate" among various possible directions of evolution, and the famous law of large numbers in its usual sense breaks down. A small fluctuation may start an entirely new evolution that will drastically change the whole behavior of the macroscopic system. The analogy with social phenomena, even with history, is inescapable. Far from opposing “chance" and "necessity," we now see both aspects as essential in the description of nonlinear systems far from equilibrium.

The first two parts of this book thus deal with two conflicting views of the physical universe: the static view of classical dynamics, and the evolutionary view associated with entropy. A confrontation between these views has become unavoidable. For a long time this confrontation was postponed by considering irreversibility as an illusion, as an approximation; it was man who introduced time into a timeless universe. However, this solution in which irreversibility is reduced to an illusion or to approximations can no longer be accepted, since we know that irreversibility may be a source of order, of coherence, of organization.

We can no longer avoid this confrontation. It is the subject of the third part of this book. We describe traditional attempts to approach the problem of irreversibility first in classical and then in quantum mechanics. Pioneering work was done here, especially by Boltzmann and Gibbs. However, we can state that the problem was left largely unsolved. As Karl Popper relates it, it is a dramatic story: first, Boltzmann thought he had given an objective formulation to the new concept of time implied in the second law. But as a result of his controversy with Zermelo and others, he had to retreat.

> In the light of history — or in the darkness of history — Boltzmann was defeated, according to all accepted standards, though everybody accepts his eminence as a physicist. For he never succeeded in clearing up the status of his H-theorem; nor did he explain entropy increase. ... Such was the pressure that he lost faith in himself. ... **15**

The problem of irreversibility still remains a subject of lively controversy. How is this possible one hundred fifty years after the discovery of the second law of thermodynamics? There are many aspects to this question, some cultural and some technical. There is a cultural component in the mistrust of time. We shall on several occasions cite the opinion of Einstein. His judgment sounds final: time (as irreversibility) is an illusion. In fact, Einstein was reiterating what Giordano Bruno had written in the sixteenth century and what had become for centuries the credo of science: "The universe is, therefore, one, infinite, immobile. ... It does not move itself locally. ... It does not generate itself. ... It is not corruptible. ... It is not alterable. ..." **16** For a long time Bruno's vision dominated the scientific view of the Western world. It is therefore not surprising that the intrusion of irreversibility, coming mainly from the engineering sciences and physical chemistry, was received with mistrust. But there are technical reasons in addition to cultural ones. Every attempt to "derive" irreversibility from dynamics necessarily had to fail, because irreversibility is not a universal phenomenon. We can imagine situations that are strictly reversible, such as a pendulum in the absence of friction, or planetary motion. This failure has led to discouragement and to the feeling that, in the end, the whole concept of irreversibility has a subjective origin. We shall discuss all these problems at some length. Let us say here that today we can see this problem from a different point of view, since we now know that there are different classes of dynamic systems. The world is far from being homogeneous. Therefore the question can be put in different terms: What is the specific structure of dynamic systems that permits them to "distinguish" past and future? What is the minimum complexity involved?

Progress has been realized along these lines. We can now be more precise about the roots of time in nature. This has far-reaching consequences. The second law of thermodynamics, the law of entropy, introduced irreversibility into the macroscopic world. We now can understand its meaning on the microscopic level as well. As we shall see, the second law corresponds to a selection rule, to a restriction on initial conditions that is then propagated by the laws of dynamics. Therefore the second law introduces a new irreducible element into our description of nature. While it is consistent with dynamics, it cannot be derived from dynamics.

Boltzmann already understood that probability and irreversibility had to be closely related. Only when a system behaves in a sufficiently random way may the difference between past and future, and therefore irreversibility, enter into its description. Our analysis confirms this point of view. Indeed, what is the meaning of an arrow of time in a deterministic description of nature? If the future is already in some way contained in the present, which also contains the past, what is the meaning of an arrow of time? The arrow of time is a manifestation of the fact that the future is not given, that, as the French poet Paul Valêry emphasized, “time is construction." **17**

The experience of our everyday life manifests a radical difference between time and space. We can move from one point of space to another. However, we cannot turn time around. We cannot exchange past and future. As we shall see, this feeling of impossibility is now acquiring a precise scientific meaning. Permitted states are separated from states that are prohibited by the second law of thermodynamics by means of an infinite entropy barrier. There are other barriers in physics. One is the velocity of light, which in our present view limits the speed at which signals may be transmitted. It is essential that this barrier exist; if not, causality would fall to pieces. Similarly, the entropy barrier is the prerequisite for giving a meaning tọ communication. Imagine what would happen if our future would become the past for other people! We shall return to this later.

The recent evolution of physics has emphasized the reality of time. In the process new aspects of time have been uncovered. A preoccupation with time runs all through our century. Think of Einstein, Proust, Freud, Teilhard, Peirce, or Whitehead.

One of the most surprising results of Einstein's special theory of relativity, published in 1905, was the introduction of a local time associated with each observer. However, this local time remained a reversible time. Einstein's problem both in the special and the general theories of relativity was mainly that of the “communication” between observers, the way they could compare time intervals. But we can now investigate time in other conceptual contexts.

In classical mechanics time was a number characterizing the position of a point on its trajectory.

But time may have a different meaning on a global level. When we look at a child and guess his or her age, this age is not located in any special part of the child's body. It is a global judgment. It has often been stated that science spatializes time. But we now discover that another point of view is possible. Consider a landscape and its evolution: villages grow, bridges and roads connect different regions and transform them. Space thus acquires a temporal dimension; following the words of geographer B. Berry, we have been led to study the “timing of space."

But perhaps the most important progress is that we now may see the problem of structure, of order, from a different perspective. As we shall show in Chapter VIII, from the point of view of dynamics, be it classical or quantum, there can be no one time-directed evolution. The "information" as it can be defined in terms of dynamics remains constant in time. This sounds paradoxical. When we mix two liquids, there would occur no "evolution” in spite of the fact that we cannot, without using some external device, undo the effect of the mixing. On the contrary, the entropy law describes the mixing as the evolution toward a "disorder,” toward the most probable state. We can show now that there is no contradiction between the two descriptions, but to speak about information, or order, we have to redefine the units we are considering. The important new fact is that we now may establish precise rules to go from one type of unit to the other. In other words, we have achieved a microscopic formulation of the evolutionary paradigm expressed by the second law. As the evolutionary paradigm encompasses all of chemistry as well as essential parts of biology and the social sciences, this seems to us an important conclusion. This insight is quite recent. The process of reconceptualization occurring in physics is far from being complete. However, our intention is not to shed light on the definitive acquisitions of science, on its stable and well-established results. What we wish to do is emphasize the conceptual creativeness of scientific activity and the future prospects and new problems it raises. In any case, we now know that we are only at the beginning of this exploration. We shall not see the end of uncertainty or risk. Thus we have chosen to present things as we perceive them now, fully aware of how incomplete our answers are.

5.

Erwin Schrödinger once wrote, to the indignation of many philosophers of science:

> ... there is a tendency to forget that all science is bound up with human culture in general, and that scientific findings, even those which at the moment appear the most advanced and esoteric and difficult to grasp, are meaningless outside their cultural context. A theoretical science unaware that those of its constructs considered relevant and momentous are destined eventually to be framed in concepts and words that have a grip on the educated community and become part and parcel of the general world picture—a theoretical science, I say, where this is forgotten, and where the initiated continue musing to each other in terms that are, at best, understood by a small group of close fellow travellers, will necessarily be cut off from the rest of cultural mankind; in the long run it is bound to atrophy and ossify however virulently esoteric chat may continue within its joyfully isolated groups of experts. **18**

One of the main themes of this book is that of a strong interaction of the issues proper to culture as a whole and the internal conceptual problems of science in particular. We find questions about time at the very heart of science. Becoming, irreversibility — these are questions to which generations of philosophers have also devoted their lives. Today, when history — be it economic, demographic, or political — is moving at an unprecedented pace, new questions and new interests require us to enter into new dialogues, to look for a new coherence.

However, we know the progress of science has often been described in terms of rupture, as a shift away from concrete experience toward a level of abstraction that is increasingly difficult to grasp. We believe that this kind of interpretation is only a reflection, at the epistemological level, of the historical situation in which classical science found itself, a consequence of its inability to include in its theoretical frame vast areas of the relationship between man and his environment.

There doubtless exists an abstract development of scientific theories. However, the conceptual innovations that have been decisive for the development of science are not necessarily of this type. The rediscovery of time has roots both in the internal history of science and in the social context in which science finds itself today. Discoveries such as those of unstable elementary particles or of the expanding universe clearly belong to the internal history of science, but the general interest in nonequilibrium situations, in evolving systems, may reflect our feeling that humanity as a whole is today in a transition period. Many results we shall report in Chapters V and VI, for example those on oscillating chemical reactions, could have been discovered many years ago, but the study of these nonequilibrium problems was repressed in the cultural and ideological context of those times.

We are aware that asserting this receptiveness to cultural content runs counter to the traditional conception of science. In this view science develops by freeing itself from outmoded forms of understanding nature; it purifies itself in a process that can be compared to an "ascesis" of reason. But this in turn leads to the conclusion that science should be practiced only by communities living apart, uninvolved in mundane matters. In this view, the ideal scientific community should be protected from the pressures, needs, and requirements of society. Scientific progress ought to be an essentially autonomous process that any "outside" influence, such as the scientists' participation in other cultural, social, or economic activities, would merely disturb or delay.

This ideal of abstraction, of the scientist's withdrawal, finds an ally in still another ideal, this one concerning the vocation of a "true" researcher, namely, his desire to escape from worldly vicissitudes. Einstein describes the type of scientist who would find favor with the “Angel of the Lord" should the latter be given the task of driving from the "Temple of Science" all those who are “unworthy" — it is not stated in what respects. They are generally

> ... rather odd, uncommunicative, solitary fellows, who despite these common characteristics resemble one another really less than the host of the banished.
>
> What led them into the Temple?... one of the strongest motives that lead men to art and science is flight from everyday life with its painful harshness and wretched dreariness, and from the fetters of one's own shifting desires. A person with a finer sensibility is driven to escape from personal existence and to the world of objective observing (Schauen) and understanding. This motive can be compared with the longing that irresistibly pulls the town-dweller away from his noisy, cramped quarters and toward the silent, high mountains, where the eye ranges freely through the still, pure air and traces the calm contours that seem to be made for eternity.
>
> With this negative motive there goes a positive one. Man seeks to form for himself, in whatever manner is suitable for him, a simplified and lucid image of the world (Bild der Welt), and so to overcome the world of experience by striving to replace it to some extent by this image. **19**

The incompatibility between the ascetic beauty sought after by science, on the one hand, and the petty swirl of worldly experience so keenly felt by Einstein, on the other, is likely to be reinforced by another incompatibility, this one openly Manichean, between science and society, or, more precisely, between free human creativity and political power. In this case, it is not in an isolated community or in a temple that research would have to be carried out, but in a fortress, or else in a madhouse, as Duerrenmatt imagined in his play *The Physicists*. **20** There, three physicists discuss the ways and means of advancing physics while at the same time safeguarding mankind from the dire consequences that result when political powers appropriate the results of its progress. The conclusion they reach is that the only possible way is that which has already been chosen by one of them; they all decide to pretend to be mad, to hide in a lunatic asylum. At the end of the play, as Fate would have it, this last refuge is discovered to be an illusion. The director of the asylum, who has been spying on her patient, steals his results and seizes world power.

Duerrenmatt's play leads to a third conception of scientific activity: science progresses by reducing the complexity of reality to a hidden simplicity. What the physicist Moebius is trying to conceal in the madhouse is the fact that he has successfully solved the problem of gravitation, the unified theory of elementary particles, and, ultimately, the Principle of Universal Discovery, the source of absolute power. Of course, Duerrenmatt simplifies to make his point, yet it is commonly held that what is being sought in the "Temple of Science" is nothing less than the “formula” of the universe. The man of science, already portrayed as an ascetic, now becomes a kind of magician, a man apart, the potential holder of a universal key to all physical phenomena, thus endowed with a potentially omnipotent knowledge. This brings us back to an issue we have already raised: it is only in a simple world (especially in the world of classical science, where complexity merely veils a fundamental simplicity) that a form of knowledge that provides a universal key can exist.

One of the problems of our time is to overcome attitudes that tend to justify and reinforce the isolation of the scientific community. We must open new channels of communication between science and society. It is in this spirit that this book has been written. We all know that man is altering his natural environment on an unprecedented scale. As Serge Moscovici puts it, he is creating a “new nature." **21** But to understand this man-made world, we need a science that is not merely a tool submissive to external interests, nor a cancerous tumor irresponsibly growing on a substrate society.

Two thousand years ago Chuang Tsu wrote:

> How (ceaselessly] Heaven revolves! How [constantly) Earth abides at rest! Do the Sun and the Moon contend about their respective places? Is there someone presiding over and directing those things? Who binds and connects them together? Who causes and maintains them without trouble or exertion? Or is there perhaps some secret mechanism in consequence of which they cannot but be as they are? **22**

We believe that we are heading toward a new synthesis, a new naturalism. Perhaps we will eventually be able to combine the Western tradition, with its emphasis on experimentation and quantitative formulations, with a tradition such as the Chinese one, with its view of a spontaneous, self-organizing world. Toward the beginning of this Introduction, we cited Jacques Monod. His conclusion was: “The ancient alliance has been destroyed; man knows at last that he is alone in the universe's indifferent immensity out of which he emerged only by chance.” **23** Perhaps Monod was right. The ancient alliance has been shattered. Our role is not to lament the past. It is to try to discover in the midst of the extraordinary diversity of the sciences some unifying thread. Each great period of science has led to some model of nature. For classical science it was the clock; for nineteenth-century science, the period of the Industrial Revolution, it was an engine running down. What will be the symbol for us? What we have in mind may perhaps be expressed best by a reference to sculpture, from Indian or pre-Columbian art to our time. In some of the most beautiful manifestations of sculpture, be it in the dancing Shiva or in the miniature temples of Guerrero, there appears very clearly the search for a junction between stillness and motion, time arrested and time passing. We believe that this confrontation will give our period its uniqueness.

Notes

1.I. Berlin, *Against the Current*, selected writings ed. H. Hardy (New York: The Viking Press, 1980), p. xxvi.

2. See Titus Lucretius Carus, *De Natura Rerum*, Book I, v. 267–70. ed. and comm. C. Bailey (Oxford: Oxford University Press 1947, 3 vols.)

3. R. Lenoble, *Histoire de l'idée de nature* (Paris: Albin Michel, 1969).

4. B. Pascal, “Pensées," frag. 792, in *Oeuvres Complètes* (Paris: Brunschwig-Boutroux-Gazier, 1904–14).

5. J. Monod, *Chance and Necessity* (New York: Vintage Books, 1972), pp. 172-73.

6. G. Vico, *The New Science*, trans. T. G. Bergin and M. H. Fisch (New York: 1968), par. 331.

7. J. P. Vernant et al., *Divination et rationalité*, esp. J. Bottero, “Symptômes, signes, écritures" (Paris: Seuil, 1974).

8. A. Koyré, *Galileo Studies* (Hassocks, Eng.: The Harvester Press, 1978).

9. K. Popper, *Objective Knowledge* (Oxford: Clarendon Press, 1972).

10. P. Forman, “Weimar Culture, Causality and Quantum Theory, 1918–1927; Adaptation by German Physicists and Mathematicians to an Hostile Intellectual Environment," *Historical Studies in Physical Sciences*, Vol. 3 (1971), pp. 1-115.

11. J. Needham and C. A. Ronan, *A Shorter Science and Civilization in China*, Vol. I (Cambridge: Cambridge University Press, 1978), p. 170.

12. A. Eddington, *The Nature of the Physical World* (Ann Arbor: University of Michigan Press, 1958), pp. 68-80.

13. Ibid., p. 103.

14. Berlin, op. cit., p. 109.

15. K. Popper, *Unended Quest* (La Salle, Ill.: Open Court Publishing Company, 1976), pp. 161-62.

16. G. Bruno, 5th dialogue, "De la causa,” *Opere Italiane*, I (Bari: 1907); cf. I. Leclerc, *The Nature of Physical Existence* (London: George Allen & Unwin, 1972).

17. P. Valéry, *Cahiers*, (2 vols.) ed. Mrs. Robinson-Valéry, (Paris: Gallimard, 1973-74).

18. E. Schrödinger, "Are there Quantum Jumps?," *The British Journal for the Philosophy of Science*, Vol. III (1952), pp. 10910; this text has been quoted with indignation by P. W. Bridgmann in his contribution to *Determinism and Freedom in the Age of Modern Science*, ed. S. Hook (New York: New York University Press, 1958).

19. A. Einstein, "Prinzipien der Forschung, Rede zur 60. Geburstag van Max Planck" (1918) in *Mein Weltbild*, Ullstein Verlag 1977, pp. 107-10, trans. *Ideas and Opinions* (New York: Crown, 1954), pp. 224-27.

20. E. Dürrenmatt, *The Physicists*. (New York: Grove, 1964).

21. S. Moscovici, *Essai sur l'histoire humaine de la nature*, Collection Champs (Paris: Flammarion, 1977).

22. Quoted in Ronan, op. cit., p. 87.

23. Monod, op. cit., p. 180.