Only an Illusion

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Professor Prigogine's most recent work in English is *From Being to Becoming: Time and Complexity in the Physical Sciences;* his monographs have been translated into many languages. He has received eleven honorary degrees and numerous scientific awards and medals; in 1977, Professor Prigogine was awarded the Nobel Prize in Chemistry.

I

Let me start with a recollection of Werner Heisenberg when, as a young man, he took a walking tour with Niels Bohr. This is Heisenberg's account of what Bohr said when they came to Kronberg Castle.

> Isn't it strange how this castle changes as soon as one imagines that Hamlet lived here? As scientists we believe that a castle consists only of stones, and admire the way the architect put them together. The stones, the green roof with its patina, the wood carvings in the church, constitute the whole castle. None of this should be changed by the fact that Hamlet lived here, and yet it is changed completely. Suddenly the walls and the ramparts speak a different language . . . . Yet all we really know about Hamlet is that his name appears in a thirteenth-century chronicle . . . . But everyone knows the questions Shakespeare had him ask, the human depths he was made to reveal, and so he too had to be found a place on earth, here in Kronberg.[1]

Obviously this story brings us to a question which is as old as humanity itself: *the meaning of reality.*

This question cannot be dissociated from another one, the meaning of time. To us time and human existence, and therefore also reality, are concepts which are undissociable. But is this necessarily so? I like to quote the correspondence between Einstein and his old friend Besso. In the latter years Besso comes back again and again to the question of time. What is time, what is irreversibility? Patiently Einstein answers again and again, irreversibility is an *illusion,* a subjective impression, coming from exceptional initial conditions.

[1] Gordon Mills, *Hamlet's Castle* (Austin: University of Texas Press, 1976).

Besso's death only a few months before Einstein's own was to interrupt this correspondence. At Besso's death, in a moving letter to Besso's sister and son, Einstein wrote: "Michele has preceded me a little in leaving this strange world. This is not important. For us who are convinced physicists, the distinction between past, present, and future is only an illusion, however persistent."[2]

"Only an illusion." I must confess that this sentence has greatly impressed me. It seems to me that it expresses in an exceptionally striking way the symbolic power of the mind.

In fact, in his letter 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.* One, I say, is the absolute possibility, one the act, one the form or soul, one the matter or body, one the thing, one the being, one the maximum and optimum; which is not capable of being comprehended; and yet is without end and interminable, and to that extent infinite and interminate, and consequently immobile. *It does not move itself locally,* because it has nothing outside itself to which it might be transported, it being understood that it is all. *It does not generate itself* since there is no other thing into which it could desire or look for, it being understood that it has all the beings. *It is not corruptible,* since there is no other thing into which it could change itself, it being understood that it is everything. It cannot diminish or increase, it being understood that it is infinite, thus being that to which nothing can be added, and that from which nothing can be subtracted, for the reason that the universe does not have proportional parts. *It is not alterable* into any other disposition because it does not have anything external through which it could suffer and through which it could be affected.[3]

[2] Einstein–Besso, *Correspondance,* ed. by Speziali (Paris: Herman, 1972), pp. 537–39.

[3] G. Bruno, *5ème* dialogue, *De la causa, Opere Italiane,* I (Bari 1907); cf. I. Leclerc, *The Nature of Physical Existence* (London: George Allen & Unwin, 1972), p. 88.

For a long time Bruno's vision was to dominate the scientific view of the western world. It was to lead to the "mechanical world view with its two basic elements":

a. changeless substances such as atoms, molecules or elementary particles;

b. locomotion.[4]

Of course many changes came through quantum theory, to which I shall return, but some basic features of this conception remain even now. But how to understand this timeless nature which puts man outside the reality he describes? As Carl Rubino has emphasized, Homer's *Iliad* centers around the problem of time, Achilles *embarks in a search for something permanent and immutable.* "But the wisdom of the *Iliad,* a bitter lesson that Achilles, its hero, learns too late, is that such perfection can be gained only at the cost of one's humanity: he must lose his life in order to gain this new degree of glory. For human men and women, *for us,* immutability, freedom from change, total security, immunity from life's maddening ups and downs will come only when we depart this life, by dying, or becoming gods: the gods, Horace tells us, are the only living beings who lead secure lives, free from anxiety and change."[5]

Homer's *Odyssey* appears as the dialectical counterpart to the *Iliad.*[6] Odysseus has the choice; he is fortunate enough to be able to choose between agelessness, immortality — remaining forever the lover of Calypso — or the return to humanity, and ultimately to old age and death: Still he chooses time over eternity, human's fate over god's fate.

Let us still stay in literature but come closer to our time. In his *Cimetiére marin* Paul Valéry describes man's struggle to come

[4] Ibid.

[5] Carl Rubino, "Winged chariots and black holes: Some reflexions on science and literature," preprint.

[6] J. P. Vernant, "Le refus d'Ulysse," *Le temps de la réflexion* III (1982).

to terms with time as duration, with its limited span open to us. In his "Cahiers" — those numerous volumes of notes he used to write in the early mornings — he comes back again and again to the problem of time: Duration, science to be constructed.[7] There is a deep feeling for the unexpected in Valéry, why things are happening as they do. Obviously Valéry could not be satisfied with simple explanations such as schemes implying a universal determinism which supposes that in some sense *all is given.* Valéry writes:

> Le déterminisme — subtil anthropomorphisme — dit que tout se passe comme dans une machine telle qu'elle est comprise par moi. Mais toute loi mécanique est au fond irrationnelle — expérimentale. . . . Le *sens du mot déterminisme est du même degré de vague que celui du mot liberté. . . Le déterminisme rigoureux est profondément déiste. Car il faudrait un dieu pour apercevoir cet enchaînement infini complet.* Il faut imaginer un dieu, un front de dieu pour imaginer cette logique. C'est un point de vue divin. De sorte que le dieu retranché de la création et de l'invention de l'univers est restitué pour la compréhension de cet univers. Qu'on le veuille ou non, un dieu est posé nécessairement dans la pensée du déterminisme — et c'est une rigoureuse ironie.[8]

Valéry is making an important remark to which I shall return — determinism is only possible for an observer outside his world, while we describe the world from within.

[7] Paul Valéry, *Cahiers* I (1973), II (1974), Bibliothèque de la Pléiade (Paris: Editions Gallimard).

[8] Paul Valéry, *Cahiers* I, pp. 492, 531, 651: "Determinism — subtle anthropomorphism — says that everything occurs as if in a machine as understood by myself. But every mechanical law is irrational at base — experimental. . . . *The meaning of the word determinism is vague to the same degree as that of the word freedom. . . . Rigid determinism is profoundly deistic.* Because you have to have a god to be able to see the entire infinite chain. It is necessary to imagine a god, the face of a god, to be able to imagine this logic. It is a divine point of view. So that the god who was confined to the creation of the universe is reinstated in order to understand this universe. Whether one likes it or not, a god is a requisite part of the idea of determinism — and this is a harsh irony."

This preoccupation with time in Valéry is not an isolated phenomenon in the early part of this century. We may quote in disorder Proust, Bergson, Teilhard, Freud, Peirce or Whitehead.

As we have mentioned, the verdict of science seemed final. Time is an illusion. Still again and again the question was asked: how is this possible? Do we have really to make a tragic choice between a timeless reality which leads to human alienation or an affirmation of time which seems to brade with scientific rationality?

Most of European philosophy from Kant to Whitehead appears as an attempt to overcome in one way or another the necessity of this choice.[9] We cannot go into detail, but obviously Kant's distinction between a noumenal world and a phenomenal one was a step in this direction, as is Whitehead's idea of process philosophy. None of these attempts has met with more than a mitigated success. As a result, we have seen a progressive decay of "philosophy of nature." I agree completely with Leclerc when he writes: "In the present century we are suffering the consequences of the separation of science and philosophy which followed upon the triumph of Newtonian physics in the eighteenth century. It is not only the dialogue between science and philosophy which has suffered."[10]

Here is one of the roots of the dichotomy into "two cultures." There is an irreducible opposition between classical *reason* with its nontemporal vision and our *existence* with its vision of time as this *twirl* which Nabokov describes in *Look at the Harlequins.*[11] But something very dramatic is happening in science — something as unexpected as the birth of geometry, or the grandiose vision of the cosmos as expressed in Newton's work. We become progressively more and more conscious of the fact that, on all levels

[9] I. Prigogine and I. Stengers, *La Nouvelle Alliance* (Paris: Gallimard, 1979); German trans. Piper, Italian trans. Einaudi, English translation to appear in 1983.

[10] *The Nature of Physical Existence,* p. 31.

[11] New York: McGraw-Hill, 1981; cf. M. Gardner, *The Ambidextrous Universe* (New York: Charles Scribner's Sons, 1979).

from elementary particles up to cosmology, science is rediscovering time.

We are still embedded in this process of reconceptualization of physics—we still don't know where it will lead. But certainly it opens a new chapter in the dialogue between men and nature. In this perspective the problem of the relation between science and human values, the central subject of the Tanner Lectures, can be seen in a new perspective. A dialogue between natural sciences, human sciences, including arts and literature, may take a new start and perhaps develop into something as fruitful as it was during the classical period of Greece or during the seventeenth century, at the time of Newton and Leibniz.

II

To understand the changes which are going on in our time, it may be useful to start with our scientific heritage from the nineteenth century. I believe that this heritage included *two basic contradictions* or at least *two basic questions* to which no answer was provided.

As you know, the nineteenth century was essentially the century of evolution. Think about the work of Darwin in biology, of Hegel in philosophy, or of the formulation of the famous entropy law in physics.

Let us start with *Darwin.* The present year is the centenary of the death of Darwin. Beyond the importance of *The Origin of Species,* published in 1859, for biological evolution proper, there is a general element involved in Darwin's approach which I want to emphasize.[12] His approach combines *two* elements: the assumption of spontaneous *fluctuations* in biological species, which then through selection from the medium lead to *irreversible* biological evolution. Therefore, his model combines two elements to which

[12] M. Peckham, *Charles Darwin; The Origin of Species, in the Variorum Text* (Philadelphia: University of Pennsylvania Press, 1959).

we shall very often return in this lecture: the idea of *fluctuations,* or randomness, of stochastic processes, and the idea of evolution, of *irreversibility.* Let us emphasize that on the level of biology this association leads to evolution corresponding to increasing complexity, to self-organization.

This is in complete contrast to the meaning which is generally associated with the law of *entropy* increase as formulated by Clausius in 1865.[13] The basic element in this law is the distinction between reversible and irreversible processes. Reversible processes do not know any privileged direction of time. You may think about a spring oscillating in a frictionless medium or about planetary motion. On the other hand, irreversible processes involve an arrow of time. If you bring together two liquids they tend to mix, but the unmixing is not observed as a spontaneous process. All of chemistry corresponds to irreversible processes. This distinction is taken up in the formulation of the second law, which postulates the existence of a function, entropy, which in an isolated system can only increase because of the presence of irreversible processes while itself remaining unchanged through reversible processes. Therefore, in an isolated system, entropy will finally reach its maximum whenever the system has come to equilibrium and the irreversible processes to a final halt.

It is the work of one of the greatest theoretical physicists of all time, Ludwig Boltzmann, that gave a first microscopic interpretation to this increase of entropy. He turned to kinetic theory of gases with the idea that the mechanism of change, of "evolution" is then described in terms of collisions between molecules. His main conclusion was that entropy S closely related to *probability* P. Everybody has heard quoted the famous formula $S = k \ln P$, which was engraved on Boltzmann's tombstone after his tragic suicide in 1906.[14] Here k is a universal constant named

[13] See Prigogine and Stengers, *La Nouvelle Alliance.*

[14] I. Prigogine, *From Being to Becoming* (San Francisco: W. E. Freeman, 1980).

after Boltzmann by Planck. Again, as with Darwin, evolution and probability, randomness, are closely related. However, Boltzmann's result is different and even contradictory to that of Darwin. Probability will reach its maximum when *uniformity is achieved.* Think about a system formed by two boxes which may communicate through a small hole. Equilibrium will obviously be achieved when the number of particles in the two boxes is the same. Therefore, the approach to equilibrium corresponds to the destruction of privileged initial conditions, to the forgetting of initial structures, in contrast to Darwin, where evolution means the creation of new structures.

Thus we come to the first question, to the first contradiction which we have inherited from the nineteenth century: *how can Boltzmann and Darwin both be right?* How can we describe both the destruction of structures and processes involving self-organization? Still, as I have already emphasized, both approaches use common elements: the idea of probability (expressed in Boltzmann's theory in terms of the collisions between particles) and irreversibility emerging as a result of this probabilistic description. Before I shall explain how both Boltzmann and Darwin can be right, let us describe the second contradiction which we had to face.

III

The problematics to which we come now lie much deeper than the opposition between Boltzmann and Darwin. The prototype of classical physics is classical mechanics, the study of motion, the *description of trajectories* leading a point from position A to position B. Two of the basic characteristics of the dynamical description are its deterministic and *reversible* character. Once appropriate initial conditions are given, we can predict the trajectory rigorously. Moreover, the direction of time does not play any role: prediction and retro-prediction are identical. Therefore, on the fundamental dynamic level there seems to be no place for randomness or for irreversibility. To some extent the situation remains the same in quantum theory, where we speak of wave function rather than trajectories. Again the wave function evolves according to reversible deterministic law.

Consequently, the universe appears as a vast automaton. We have already mentioned that for Einstein, time in the sense of directed time, of irreversibility, was an illusion. Quite generally, as it appears in innumerable books and publications, the classical attitude in respect to time has been some form of distrust. For example, in his monograph *The Ambidextrous Universe,* Martin Gardner writes that the second law only makes certain processes *improbable,* never impossible. In other words, the law of increase of entropy refers only to a *practical* difficulty without any deep foundation. Similarly, in his classic book *Chance and Necessity,* Jacques Monod expresses the view that life is only an *accident* in the history of nature.” It is a kind of fluctuation which for some not very clearly understood reasons is able to maintain itself.

It is certain that, whatever our final apprehension of these complex problems, our universe has a pluralistic, complex character. Structures may disappear, as in a diffusion process, but structures may appear, as in biology and, even more clearly, in social processes. Some phenomena are, so far as we know, well described by deterministic equations, as is the case for planetary motions; but some, like biological evolution, likely involve stochastic processes. Even a scientist convinced of the validity of deterministic descriptions would probably hesitate to imply that at the very moment of the Big Bang the date of this lecture was already inscribed in the laws of nature.

How then to overcome the apparent contradiction between these concepts? We are living in a *single universe.* As we shall see, we begin to appreciate the meaning of these problems; we begin to see that irreversibility, life, are inserted in the basic laws,

[15] *Le Hasard et la nécessité* (Paris: Seuil, 1970), pp. 194–95.

even on the microscopic level. Moreover, the importance which we give to the various phenomena we may observe and describe is quite different from, I would even say opposite to, what was suggested by classical physics. There the basic processes, as I mentioned, were considered *deterministic* and *reversible.* Processes involving randomness or irreversibility were considered to be exceptions, mere artifacts. Today *we see everywhere the role of irreversible processes, of fluctuations.* The models considered by classical physics appear to us now to correspond only to limited situations which we can create artificially, for example by putting matter into a box and waiting for it to reach 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 passive, as described in the mechanical world view, but is associated with spontaneous activity. This change is so deep that I believe we can really speak about a *new dialogue of man with nature.*

IV

Of course, it has taken many unexpected developments both in theoretical concepts and experimental discoveries to go from the classic description of nature to the new one which is emerging. In brief, we were looking for all-embracing schemes, for symmetries, for immutable general laws, and we have discovered the mutable, the temporal, the complex. Examples abound. As you know, quantum theory predicts a *remarkable symmetry,* the one which should exist between matter and antimatter, but our world does not have this symmetry. Matter dominates greatly over antimatter. This is quite a happy circumstance, as otherwise the annihilation between matter and antimatter would mean the end of all massive particles. The discovery of a large number of *unstable* particles is another example; it may even be that all particles are unstable. Anyway, the idea of an unchanging, permanent substrate for matter has been shattered.

Who could have predicted that (in contrast to the views of Giordano Bruno) the concept of evolution would be applicable to the world as a whole; and, as a matter of fact, astrophysical discoveries, and especially the famous residual black body radiation, leave little doubt that the world as a whole has undergone a remarkable evolution.

How to speak, then, about immutable, eternal laws? We certainly cannot speak about laws of life at a moment when there was no life. The very concept of law which emerged at the time of Descartes and Newton, a time of absolute monarchies, has to be revised.

Of special importance in the context of this lecture are experiments dealing with macroscopic physics, with chemistry — in other words, with nature on our own scale. The classical view (remember our discussion of Boltzmann's interpretation of the second law of thermodynamics) focused its interest on the transition from order to disorder. Now we find everywhere transitions from disorder to order, processes involving *self-organization* of matter. If you had asked a physicist a few years ago what exactly physics explains and what remains open, he might have answered that we obviously do not sufficiently understand elementary particles or cosmological features of the universe as a whole, but in between, our knowledge is pretty satisfactory. Today a growing minority (to which I belong) would not share this optimistic view. I am, on the contrary, convinced that we are only at the beginning of a deeper understanding of the nature around us, and this seems to me of outstanding importance for the embedding of *life in matter as well as of man in life.*

V

We shall now briefly review the way in which the two contradictions which we have mentioned can be approached today. First of all, how can we describe the origin of structures, of self-organization? This problem has been the object of many publications, and I may be quite brief.[16] Once we attach entropy to a physical system, we may distinguish between equilibrium or near equilibrium on one hand and situations corresponding to *far from equilibrium* on the other. What has been shown is that near equilibrium matter indeed conforms to Boltzmann's paradigm; structures are destroyed. If we perturb such a system, the system responds by restoring its initial condition; such systems are therefore stable. In a sense, such systems are always able to develop mechanisms which make them *immune to perturbation.* However, these properties do not extend to far-from-equilibrium conditions. The key words there are *nonlinearity, instability, bifurcation.* In brief, this means that if we drive a system sufficiently far from equilibrium, its state may become unstable in respect to perturbation. The exact point at which this may happen is called the *bifurcation point.* At this point, the old solution becoming unstable, new solutions emerge which may correspond to quite different behavior of matter. A spectacular example is the appearance of chemical clocks in far-from-equilibrium conditions. The experimental demonstration of the existence of chemical clocks is today a routine experiment which is performed in most courses in chemistry at colleges and universities. It is a very simple experiment, and, still, I believe it is perhaps one of the most important experiments of the century. Let me briefly explain why I think so.

In this experiment we have basically two types of molecules. Let us call one species A (the red molecules), the other B (the blue molecules). When we think about some chaotic collisions going on at random, we expect that the interchange between A and B would lead to a uniform color with occasional flashes of red or blue, This is not what happens with appropriate chemicals in far-from-equilibrium conditions. The whole system becomes

[16] See, for example, G. Nicolis and I. Prigogine, *Self-Organization in Non-equilibrium Systems* (New York, London, Sydney, Toronto: Wiley Interscience, 1977); also, P. Glansdorff and I. Prigogine, *Thermodynamic Theory of Structure, Stability and Fluctuations* (London, New York, Sydney, Toronto: Wiley Interscience, 1971).

red, then blue, and again red. This shows that molecules may *communicate* over large, macroscopic distances and over macroscopic times. They have means to signal each other their state in order to react together. This is very unexpected behavior indeed. We always thought that molecules interacted only through short-range forces; each molecule would only know its direct neighbors. Here, on the contrary, the system acts as a whole. Such behavior was traditionally associated with biological systems, and here we see it already arising in relatively simple nonliving systems.

A second aspect I want to emphasize is the idea of *symmetry breaking* associated with some of the bifurcations. The equations of reaction and diffusion are highly symmetrical; if we replace the geometric coordinates *x, y*, *z* by *-x, -y, -z,* which corresponds to space inversion, these equations would not change. Still, after bifurcation we may have different solutions, each of which has a broken symmetry. Of course, if we had, say, a "left" solution, we would also have a "right" solution, but it may happen that in nature we observe for some reason only one of the solutions. Everyone has observed that shells often have a preferential chirality. Pasteur went so far as to see in the breaking of symmetry the very characteristic of life. Again we see in nonlife a precursor of this property. Here I want to emphasize that solutions of symmetrical equations may have less symmetry than the equations themselves. This will be an essential point when we discuss the roots of time in nature.

Finally, the appearance of bifurcations in far-from-equilibrium conditions leads to an irreducible stochastic random element on the macroscopic level. Deterministic theories are of no help in permitting us to predict which of the branches arising at the bifurcation point will be followed at the bifurcation point. We have here an example of the essential role of *probability.* You may remember that in quantum mechanics probability already plays an essential role; this is the essence of the famous Heisenberg uncertainty relation. There one could object by saying that we living beings are made of so many elementary particles that quantum effects are being washed out by the laws of large numbers. However, this is no longer possible when we speak about bifurcation of chemical systems far from equilibrium. Here irreducible probabilistic effects appear on our *own level.* Clearly there is a relation with the role of fluctuations and the Darwinian theory of the origin of species. Again you see why I mentioned earlier that in the present perspective life appears much less isolated, as having much deeper roots in the basic laws of nature.

VI

We come now to the second problem, which, I have to tell you immediately, is vastly more difficult. The second law of thermodynamics belongs traditionally to macroscopic physics, but, curiously, its meaning has some elements in common with microscopic theories like quantum theory and relativity. Indeed, all these theoretical constructs have one element in common: they indicate some limit to our manipulation of nature. For example, the existence of the velocity of light as a universal constant indicates that we cannot transmit signals with a speed greater than that of light in a vacuum. Similarly, the existence of the quantum-mechanical constant h, Planck's constant, indicates that we cannot measure simultaneously the momentum and position of an elementary particle. In the same spirit, the second law of thermodynamics indicates that we cannot realize certain types of experiments despite the fact that they are compatible with all other known laws of physics. For example, we cannot drive a thermal engine using the heat of a single heat source, such as the ocean. That is the meaning of the impossibility of a "perpetuum mobile of the second kind."

I believe that this does not mean, however, that physics now becomes a subjectivistic physics, some result of our preferences or convictions, but is indeed a physics subjected to intrinsic constraints that identify us as a part of the physical world we are describing. It is this physics which presupposes an observer situated in the world that is confirmed by experiment. Our dialogue with nature is successful only if carried on from *within* nature.

But how to understand irreversibility, no longer in terms of macroscopic physics, but in terms of the basic laws, be they classical or quantum? I have already mentioned the bold attempt of Boltzmann to relate irreversibility to probability theory. But, in turn, what can probability mean in a world in which particles or wave functions evolve according to deterministic laws? In his beautiful book *Unended Quest,* Popper has described the tragic struggle of Boltzmann and the way in which he was finally obliged to retreat and to admit that there would be no intrinsic arrow of time in nature.[17] Again we come back to Einstein's lapidary conclusion: Time is an illusion.

We can now take up Boltzmann's quest because we have a much better understanding of dynamics, as a result of the work of great mathematicians such as Poincaré, Lyapounov, and, more recently, Kolmogorov.[18] Without their work this problem would still be a question of conjecture. Let us first observe that irreversibility *is not a universal.* We have already mentioned that there are systems, like an isolated spring, for which entropy has no relevance, its motion being entirely reversible. Therefore, we cannot hope that irreversibility may be a property of *all* dynamical systems. What we have to do is to identify dynamical systems of the right complexity, systems for which a formulation of the second law on a microscopic basis becomes possible.

We can of course not go into technical detail here; however, the main point is the recent discovery of *highly unstable dynamical systems.* In such systems the trajectories starting with two points as near to each other as we want diverge exponentially in time. But then the concept of trajectory ceases to be meaningful. We can only reach finite accuracy.

[17] K. Popper, *Unended Quest* (La Salle, Ill,: Open Court, 1976).

[18] A. N. Kolmogorov, *La théorie générale des systémes dynamiques et la mécanique classique,* Amsterdam Congress I (1954), pp. 315–33.

In spite of the fact that we start with deterministic equations, the solutions appear "chaotic." Some authors speak of "deterministic chaos." Curiously, strong probability elements appear in the core of dynamics.

We can only speak of average behavior. Such systems can be called *intrinsically random.* Indeed, as has been shown by my colleagues Misra and Courbage and myself, their behavior is so stochastic that they can be mapped into a probabilistic process called a Markov process, reaching equilibrium either for $t \rightarrow +\infty$ in the distant future or $t \rightarrow -\infty$ in the distant past.[19]

So we have already justified one of Boltzmann's basic institutions. It is indeed meaningful to speak of probabilities even in the frame of classical mechanics, but *not for all systems, only for highly unstable systems for which the concept of a trajectory loses its meaning.* Now, how can we go further and go from intrinsically random to *intrinsically irreversible* systems?

This requires supplementary conditions. We need representations of dynamics which have less symmetry than the full time-inversion symmetry of the basic equations. For example, in hard spheres, a possible situation is one in which for distant past the velocities of a group of particles were really parallel and for distant future the distribution becomes random as required by equilibrium. The time-inversion symmetry requires that there would also exist a situation in which in the distant past velocities were random and in a distant future they would tend to be parallel. One situation is obtained through the velocity inversion of the other. In fact only the first situation is observed, while the second is not. The second law of thermodynamics on the macroscopic level expresses precisely the exclusion of one of the two situations which are velocity inverses one of the other.

[19] B. Misra and I. Prigogine, "Time, Probability and Dynamics," in *Long-Time Prediction in Dynamics,* C. W. Horton, L. E. Reichl, and A. G. Szebehely, eds. (New York: Wiley, 1983). Also see M. Courbage and I. Prigogine, "Intrinsic randomness and intrinsic irreversibility in classical dynamical systems," *Proceedings of the National Academy of Sciences* 80 (1983), pp. 2412–16.

Irreversibility can have a microscopic meaning only if there are representations of dynamics which are not invariable in respect to time inversions, in spite of the fact that the initial equations are.

Let us emphasize the remarkable analogy between such situations and the symmetry-breaking bifurcations we mentioned earlier. There also in some cases we may derive from a symmetrical equation two solutions, one "left," one "right" — each of which taken separately breaks the space symmetry of the equation. We may now make precise what the second law may mean on the microscopic level. It states that only situations which go to equilibrium in the future may be prepared or observed in nature. This means that the second law is an *exclusion principle* which excludes situations in which in the distant past the velocities of colliding spheres would have been distributed uniformly, while in the distant future they would tend to parallel velocities. On the contrary, the situation in which we start in the distant past particles with nearly parallel velocities which are then randomized by collisions is an experiment which we can perform easily.

I have used here *physical* images. But the important point is that the existence of these representations of dynamics with broken time symmetry can be proved rigorously for highly unstable systems.

For such systems we may associate to each initial condition expressed by a distribution function in phase space a number measuring the information necessary to prepare this state. The initial conditions which are excluded are those for which this information would be infinite.[20]

Note also that the entropy principle cannot be derived from dynamics; it appears as a supplementary condition which has to

[20] I. Prigogine and Cl. Georges, "The second law as a selection principle: the microscopic theory of dissipative processes in quantum systems," *Proceedings of the National Academy of Science* 80 (1983), pp. 4590-94. Also see B. Misra and I. Prigogine, "Irreversibility and Nonlocality," *Letters in Mathematical Physics* 7 (1983), pp. 421-29.

be tested experimentally as any other law of physics. The basic point, however, is that this exclusion principle is not contradictory to dynamics, once it is admitted that at a given time it is *propagated* by dynamics.

The probability interpretation of Boltzmann is only possible because there exists this exclusion principle which provides us with an arrow of time.

Irreversibility as in the theory of Darwin, or also as in the theory of Boltzmann, is an even stronger property than randomness. I find this quite natural. Indeed, what could irreversibility mean in a deterministic concept of the universe in which tomorrow is already potentially present today? Irreversibility presupposes a universe in which there are limitations in the prediction of the future. I want again to emphasize that, in the spirit of this explanation, *irreversibility is not a universal property.* However the world as a whole seems to belong to these complex systems, intrinsically random, for which irreversibility is meaningful, and it is to this category of systems with broken time symmetries that all phenomena of life belong and, as a consequence, all human existence.

You may be astonished that I have spoken little about cosmological theories. Certainly the global state of our universe plays an essential role. It provides the nonequilibrium environment which makes the formation of structures possible. However, I do not believe that the existence of the expanding universe and of the initial Big Bang can by themselves provide an explanation of irreversibility. We observe, as already indicated, both reversible and irreversible processes despite the fact that all processes, reversible or not, are embedded in the expanding universe.

VII

The microscopic interpretation of the second law is very recent. I am personally convinced that it will lead to profound changes in our conception of matter. Some preliminary results have been worked out by my colleagues and myself, but what I shall say now is to some extent an anticipation which may or may not be confirmed by later developments.

If we take the second law together with its probabilistic interpretation seriously, we have to associate equilibrium with maximum probability. Now maximum probability in terms of particles means chaotic uncorrelated motion similar to the way the Greek atomists imagined the physical world. Inversely, we may define particles as the units which are uncorrelated and behave in a chaotic way in thermodynamic equilibrium. What is then the effect of nonequilibrium? It is to create *correlations* between these units, to create order out of the chaotic motions arising in the equilibrium state. This description of nature, in which order is generated out of chaos *through nonequilibrium conditions* provided by our cosmological environment, leads to a physics which is quite similar in its spirit to the world of "processes" imagined by Whitehead." It leads to a conception of matter as active, as in a continuous state of becoming. This picture deviates significantly from the classical description of physics, of change in terms of forces or fields. It is a momentous step to leave the royal road opened by Newton, Maxwell, and Einstein. But I believe that the unification of dynamics and thermodynamics paves the way to a radically new description of temporal evolution of physical systems, a description which again, to my mind, is much closer to what we see on the macroscopic level, be it in the nonliving or the living world.

We may quote as examples the highly correlated distribution of nucleotides in the fundamental biological molecules, and perhaps even the distribution of letters which are assembled in words to form our language.

[21] A. N. Whitehead, *Process and Reality; An Essay in Cosmology* (New York: Macmillan Co., The Free Press, 1969), p. 20.

VIII

Over all my scientific career, the attitude I have taken has been to consider the law of entropy increase, the second law of thermodynamics, as a basic law of nature. I was following the views Planck expressed in the following text:

> The impracticability of perpetual motion of the second kind is granted, yet its absolute impossibility is contested, since our limited experimental appliances, supposing it were possible, would be insufficient for the realization of the ideal processes which the line of proof presupposes. This position, however, proves untenable. It would be absurd to assume that the validity of the second law depends in any way on the skill of the physicist or chemist in observing or experimenting. The gist of the second law has nothing to do with experiment; the law asserts briefly that *there exists in nature a quantity which changes always in the same sense in all natural processes.* The proposition stated in this general form may be correct or incorrect; but whichever it may be, it will remain so, irrespective of whether thinking and measuring beings exist on the earth or not, and whether or not, assuming they do exist, they are able to measure the details of physical or chemical processes more accurately by one, two, or a hundred decimal places than we can. The limitations to the law, if any, must lie in the same province as its essential idea, in the observed Nature, and not in the Observer. That man's experience is called upon in the deduction of the law is of no consequence; for that is, in fact, our only way of arriving at a knowledge of natural law.[22]

However, Planck's views remained isolated. As we have noticed, most scientists considered the second law to be the result of approximation, or the intrusion of subjective views into the exact laws of physics. Our attitude is the opposite: we have looked for the limits which the second law brings into the world of dynamics.

[22] M. Planck, *Treatise on Thermodynamics* (New York: Dover Publications, 1945), p. 106.

In other words, our goal is to unify dynamics and thermodynamics. It is clear that in such a view randomness, fluctuations, and irreversibility will play an essential role at the microscopic level quite different from the marginal role they played in the traditional descriptions of nature. This goal is far from being realized, but on the road we have been led to a series of surprising findings, some of which I have summarized in this lecture.

I remain stunned by the variety of non-equilibrium structures which have been discovered experimentally, some of which we may now describe theoretically. Still, we are only at the level of 'taxonomy'.

We have already mentioned the work of great mathematicians such as Poincaré or Kolmogorov in classical mechanics. As its result, we know that classical dynamics may lead to situations in which the concept of trajectories loses its meaning, and in which we can only make probabilistic statements. Curiously, chemistry is now also going through a comparable reconceptualization. In many instances, we have to go beyond the deterministic approach of chemical kinetics and to take into account fluctuation and randomness, even in systems formed of a large number of molecules. At the microscopic level, irreversibility emerges as symmetry-breaking in systems reaching a sufficient degree of randomness.

The second law limits what is observable. It appears as an exclusion principle propagated by classical or quantum mechanics.

Perhaps the most unexpected aspect is that at all levels order, coherence, emerges from chaos for non-equilibrium conditions: An equilibrium world would be chaotic; the non-equilibrium world achieves a degree of coherence which, at least for me, is a source of surprise.

IX

In this lecture I have discussed some steps in the rediscovery of time in the physical sciences. We have seen that time in the sense of duration, of irreversibility, is basically related to the role of randomness, in full accord with the genial intuition of Boltzmann.

Since the discovery of quantum mechanics, in which probability plays an essential role, the meaning of randomness has led to many controversies. It appears today that deterministic schemes which make predictions valid in each individual case are inaccessible to us in a wide range of phenomena from microscopic physics up to the level of molecules and of life. Of course this situation may change, but we see no sign for such a change to occur over the next years.

In this context let us emphasize that we don't know how to describe reality as it would appear to an observer who in some sense would be situated outside this world. We can only deal with the problems of determinism or randomness as they are included in the schemes we formulate to describe our experience with the world and us.

One is reminded of the dialogue between Einstein and Tagore.[23] In this most interesting dialogue on the nature of reality Einstein was emphasizing that science has to be independent of the existence of any observer. As I mentioned at the beginning of this lecture, his realism led him to paradoxes. Time and therefore human existence become illusions. To the contrary, Tagore emphasized that even if absolute truth could have a meaning it would be inaccessible to the human mind. I found this dialogue so interesting that I have reproduced it as an appendix to this paper.

The controversy between Einstein and Tagore is only meaningful if man is supposed to be separated from nature. If the imbedding of man in nature is taken into account, human truths become truths of nature. Curiously enough, the present evolution of science goes in the direction stated by the great Indian poet. Whatever we call reality, it is only open to us through constructs

[23] R. Tagore, "The Nature of Reality," *Modern Review* XLIX (Calcutta 1931), pp. 42–43.

of our minds. This has been concisely expressed by D. S. Kothari: "The simple fact is that no measurement, no experiment or observation is possible without a relevant theoretical framework."[24]

In a more sophisticated form this phenomenon appears in quantum theory through the intervention of "operators" which are associated with physical quantities.

The problems of the limits of determinism, randomness, irreversibility and the notion of reality are closely connected, and we begin to see their relations.

As we are able to find the roots of time in nature, time ceases to be the concept which separates men from nature. It now expresses our belonging to nature, not our alienation.

The visions of the world around us and of the world in us converge. As I deliver this lecture in Delhi, why not stress that this type of convergence, of synthesis of the external world around us and the internal world inside us, is one of the recurrent themes of Indian philosophy.

We now overcome the temptation to reject time as an illusion. Far from that, we are back to Valéry's anticipation: "Durée est construction, vie est construction."[25] In a universe in which tomorrow is not contained in today, time is to be constructed. Valéry's sentence expresses our responsibility in this construction of the future — not only *our* future, but the future of mankind. With this conclusion the problem of human values, of ethics, even of art takes a new form. We may now see music with its elements of expectation, of improvisation, with its arrow of time as an allegory of becoming, of physics in its etymological Greek sense.

The dialectic between what is *in* time and what is *out* time, between external truths and time-oriented existence, will probably continue forever.

[24] D. S. Kothari, *Some Thoughts on Truth,* Anniversary Address, Indian National Science Academy, Bahadur Shah Zafar Marg, New Delhi, 1975, p. 5.

[25] Paul Valéry, *Oeuvres* II, Bibliothèque de la Pléiade (Paris: Editions Gallimard, 1960), p. 768.

But perhaps we are now in a privileged moment where we begin to perceive a little better the junction, the passage between stillness and motion, time arrested and time passing.

It is this moment with its incertitudes, its open questions, but also its hopes for a more integrated human world which I have tried to describe in this lecture.

APPENDIX

THE NATURE OF REALITY

A conversation between Rabindranath Tagore and Albert Einstein on the afternoon of July 14, 1930, at Professor Einstein's residence in Kaputh, published in the Modern Review *XLIX (1931), Calcutta.*

E: Do you believe in the Divine as isolated from the world?

T: Not isolated. The infinite personality of Man comprehends the Universe. There cannot be anything that cannot be subsumed by the human personality, and this proves that the truth of the Universe is human truth.

I have taken a scientific fact to explain this. Matter is composed of protons and electrons, with gaps between them, but matter may seem to be solid without the links in spaces which unify the individual electrons and protons. Similarly humanity is composed of individuals, yet they have their inter-connection of human relationship, which gives living unity to man's world. The entire universe is linked up with us, as individuals, in a similar manner; it is a human universe.

I have pursued this thought through art, literature, and the religious consciousness of man.

E: There are two different conceptions about the nature of the Universe:

1. The world as a unity dependent on humanity.
2. The world as a reality independent of the human factor.

T: When our universe is in harmony with man, the eternal, we know it as truth, we feel it as beauty.

E: This is the purely human conception of the universe.

T: There can be no other conception. This world is a human world — the scientific view of it is also that of the scientific man. Therefore, the world apart from us does not exist; it is a relative world, depending for its reality upon our consciousness. There is some standard of reason and enjoyment which gives it truth, the standard of the Eternal Man whose experiences are through our experiences.

E: This is a realization of the human entity.

T: Yes, one eternal entity. We have to realize it through our emotions and activities. We realized the Supreme Man who has no individual limitations through our limitations. Science is concerned with that which is not confined to individuals; it is the impersonal human world of truths. Religion realizes these truths and links them up with our deeper needs; our individual consciousness of truth gains universal significance. Religion applies values to truth, and we know truth as good through our own harmony with it.

E: Truth, then, or Beauty is not independent of Man?

T: No.

E: If there were no human beings any more, the Apollo of Belvedere would no longer be beautiful.

T: No!

E: I agree with regard to this conception of Beauty, but not with regard to Truth.

T: Why not? Truth is realized through man.

E: I cannot prove that my conception is right, but that is my religion.

T: Beauty is in the ideal of perfect harmony which is in the Universal Being. Truth the perfect comprehension of the Universal mind. We individuals approach it through our own mistakes and blunders, through our accumulated experiences, through our illumined consciousness — how, otherwise, can we know Truth ?

E: I cannot prove that scientific truth must be conceived as a truth that is valid independent of humanity; but I believe it firmly.

I believe, for instance, that the Pythagorean theorem in geometry states something that is approximately true, independent of the existence of man. Anyway, if there is a *reality* independent of man, there is also a truth relative to this reality; and in the same way the negation of the first engenders a negation of the existence of the latter.

T: Truth, which is one with the Universal Being, must essentially be human; otherwise whatever we individuals realize as true can never be called truth, at least the truth which is described as scientific and which only can be reached through the process of logic, in other words, by an organ of thought which is human. According to Indian philosophy there is Brahman, the absolute Truth which cannot be conceived by the isolation of the individual mind or described by words but can only be realized by completely merging the individual in its infinity. But such a truth cannot belong to Science. The nature of truth which we are discussing is an appearance, that is to say, what appears to be true to the human mind and therefore is human, and may be called *Maya* or illusion.

E: So according to your conception, which may be the Indian conception, it is not the illusion of the individual but of humanity as a whole.

T: In science we go through the discipline of eliminating the personal limitations of our individual minds and thus reach that comprehension of truth which is in the mind of the Universal Man.

E: The problem begins whether Truth is independent of our consciousness.

T: What we call truth lies in the rational harmony between the subjective and objective aspects of reality, both of which belong to the super-personal man.

E: Even in our everyday life, we feel compelled to ascribe a reality independent of man to the objects we use. We do this to connect the experiences of our senses in a reasonable way. For instance, if nobody is in this house, yet that table remains where it is.

T: Yes, it remains outside the individual mind but not the universal mind. The table which I perceive is perceptible by the same kind of consciousness which I possess.

E: Our natural point of view in regard to the existence of truth apart from humanity cannot be explained or proved, but it is a belief which nobody can lack — no primitive beings even. We attribute to Truth a super-human objectivity; it is indispensable to us, this reality which is independent of our existence and our experience and our mind — though we cannot say what it means.

T: Science has proved that the table as a solid object is an appearance and therefore that which the human mind perceives as a table would not exist if that mind were naught. At the same time it must be admitted that the fact that the ultimate physical reality of the table is nothing but a multitude of separate revolving centres of electric force also belongs to the human mind.

In the apprehension of truth there is an eternal conflict between the universal human mind and the same mind confined in the individual. The perpetual process of reconciliation is being carried on in our science, philosophy, in our ethics. In any case, if there be any truth absolutely unrelated to humanity, then for us it is absolutely non-existing.

It is not difficult to imagine a mind to which sequence of things happens not in space but only in time, like the sequence of notes in music. For such a mind its conception of reality is akin to the musical reality in which Pythagorean geometry can have no meaning. There is the reality of paper, infinitely different from the reality of literature. For the kind of mind possessed by the moth which eats that paper literature is absolutely non-existent, yet for Man's mind literature has a greater value of truth than the paper itself. In a similar manner, if there be some truth which has no sensuous or rational relation to human mind, it will ever remain as nothing so long as we remain human beings.

E: Then I am more religious than you are!

T: My religion is in the reconciliation of the super-personal man, the Universal human spirit, in my own individual being. This was the subject of my Hibbert Lectures, which I called "The Religion of Man."